LD-SAFE

Laser Dismantling Environmental and Safety Assessment

GENERIC SAFETY ASSESSMENT

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1. GENERIC SAFETY ASSESSMENT FRAMEWORK

1.1. CONTEXT OF THE GENERIC SAFETY ASSESSMENT

The safety assessment supports the final decommissioning plan of the nuclear facility, for which an immediate or deferred dismantling strategy is selected. The decommissioning plan is required by the General Safety Requirements Part 6 [Ref. 19] of the International Atomic Energy Agency (IAEA), and it is part of the decommissioning and release of the site from regulatory control authorization. The safety assessment is developed for ensuring decommissioning activities can be performed safely, as per the risk analysis, and as considered in the decommissioning plan.

Under the Laser Dismantling Environmental and Safety Assessment (LD-SAFE) project of the Horizon 2020 European Union program, a generic safety assessment is performed for the implementation of the laser cutting technology in the dismantling of nuclear reactors. The generic safety assessment aims at facilitating the future development of site-specific safety assessments considering laser cutting, and thus, reducing the associated licensing effort.

The generic safety assessment is performed under Work Package 4 (WP4), Safety assessment, which includes the following tasks:

- Task 4.1: Risk analysis with regards to safety, which included the report D4.1, Risk Analysis [Ref. 35], submitted in January 2021.
- Task 4.2: Compilation of results from WP2 and WP3, being WP2, Laboratory tests and calculations (residual laser beam, aerosols and hydrogen generation), and WP3, Protection of the workers and environment. It included the report D4.2, Summary of Risks Identified during WP2 and WP3 [Ref. 43], submitted in May 2022 (first version) and revised in 2023.
- Task 4.3: Generic Safety Assessment, which includes the submittal of this report.
- Task 4.4: Independent review of the generic safety assessment, which was performed by the IRSN. Their findings and recommendations (for the Generic Safety Assessment, Industrial Demonstrator, and End Users) were compiled in the report D4.4, Independent Review of the Generic Safety Assessment [Ref. 41]. The recommendations applicable to the Generic Safety Assessment were implemented within this document. All recommendations, including those to potential End Users, are shown in Annex VIII.

The information included within this document is based on a study of laser system configurations and conditions for cutting Reactor Pressure Vessel (RPV) and Reactor Vessel Internals (RVI) of Nuclear Power Plants (NPPs) under decommissioning, as well as previous cutting experiences using mechanical or other types of thermal cutting techniques (i.e., feedback from Chooz A plasma cutting operations) in the decommissioning of NPPs.

The structure of this document follows the steps of the IAEA Safety Report Series No. 77, Safety Assessment for Decommissioning [Ref. 17], which is the reference document for performing Safety Assessments for decommissioning of nuclear facilities.

This generic safety assessment includes notes, comments, and remarks for facilitating potential End Users to adjust it to their actual conditions and configurations of laser cutting activities.

1.2. SCOPE OF THE GENERIC SAFETY ASSESSMENT

This generic safety assessment is focused on the implementation of the laser cutting technology for dismantling the nuclear reactor of an NPP in normal state after shutdown (thus, excluding harsh plant and reactor conditions as a result of an accident). The activities considered in this evaluation include:

- Preparatory activities for the installation of the laser cutting technology. Relocation of components to be cut and adequation of auxiliary systems, structures and components required for segmentation activities (i.e., cutting of concrete structures for gaining cutting space, installation of additional water cleaning systems, etc.) will be out of the scope of this document, as it greatly depends on plant-specific configurations. That is, all activities performed prior to laser equipment installation or when the laser is not in use (i.e., in a shutdown mode), for instance during the RPV handling operations, are excluded from the generic safety assessment.
- Segmentation of components using the laser cutting technology and placement of segmented pieces into appropriate containers. Subsequent handling, conditioning, storage, and disposal of waste packages will be considered out of the scope of this generic safety assessment.
- Uninstallation of the laser cutting technology and re-conditioning of the area. Re-adequation of auxiliary systems is considered out of the scope of this document, as it greatly depends on plant-specific configurations.

The complexity of the above activities and their associated hazards can considerably vary based on the specific components to be cut and potential laser cutting configurations, and therefore, a framework is established for this generic safety assessment. The following boundary conditions are applicable:

- Most complex activities to be considered for laser cutting are the segmentation of the RPV and RVI of Pressurized Water Reactors (PWR) and Boiling Water Reactors (BWR). Detailed information is included in sections 2.2 and 2.5.

  This evaluation considers the segmentation of the above components and, when necessary, indicates if any of the hazards or protective measures are applicable only for specific components. This evaluation provides recommendations to adjust its content, as needed, to the specific components and conditions of a specific nuclear facility.

Since the RPV and RVI characteristics (mechanical and radiological) are plant-specific, a reference case is used for this generic safety assessment, but only for illustrative purposes, using the information from NUREG/CR-0130 [Ref. 48], NUREG/CR-5884 [Ref. 52], NUREG/CR-0672 [Ref. 49], and NUREG/CR-6174 [Ref. 53].

- Two laser cutting configurations are considered, that is, in-air or underwater. This will affect the laser specific design, such as the air flow supply and the potential systems for dust and aerosols collection. Detailed information is included in section 2.5.

  This evaluation considers the segmentation process in such configurations and, when necessary, indicates if any of the hazards or protective measures are only applicable under certain circumstances. This evaluation provides recommendations to adjust its content, as needed, to the specific laser cutting configurations and conditions of a specific nuclear facility.

  It is important to remark that laser cutting of the RPV and RVI of nuclear reactors depends on the capabilities of the laser technology for cutting high thicknesses in air or underwater, for which state of the art has certain limitations. Cutting capabilities shall be adequately adjusted and demonstrated for actual segmentation plan requirements (subject to specific plant conditions and configurations). In this regard, this document considers the deployment of a 14-kW laser power source. However, in-air cutting of thicknesses higher than 200 mm may require the deployment of more powerful laser sources (i.e., laser cutting of steel up to 300 mm thickness has been achieved using a 30-kW laser source [Ref. 38, 30]).

Boundary conditions consider the outcomes of WP1, Analysis of reactor dismantling with laser cutting of the LD-SAFE project [Ref. 33, 34], as well as the feedback provided by the Advisory Board through Technical Workshops and associated questionnaires [Ref. 39, 36]. In this regard, section 6.2 describes the main uncertainties within the boundary conditions.

The evaluation of other decommissioning tasks, as well as the treatment, conditioning, storage, and disposal of radioactive waste is not within the scope of this document.

The safety assessment has been conducted for normal operation, as well as abnormal and accidental situations. Regarding normal operation, the objective is to identify possible design options or actions aiming at reducing the impact of normal operation on workers, the public, and the environment. For abnormal and accidental situations, safety measures are identified and addressed considering only three levels of defence-in-depth: prevention, detection, and mitigation. All levels of defence-in-depth principle are not covered as it is estimated that off-site emergency response is not necessary considering the low impact on the public for any addressed accidental situation.

Regarding environmental impact assessment, the outcomes of the generic safety assessment are aimed at estimating a representative source term to be considered to support the development of impact calculations. Impact calculation methodology is not part of the generic safety assessment.

The generic safety assessment will mainly address internal hazards arisen from the use of the laser technology. External hazards shall be covered by the existing safety assessment of the host facility. In this matter, their analysis is not relevant in this document, so they are not discussed herein after.

Nevertheless, specific attention should be provided regarding following topics:

- Selection of premises (control room, system supply premises) protected against external hazards,
- Consistency of premises and systems for the cutting equipment with the host facility safety requirements. Especially, reference earthquake to be considered shall be the one identified during latest periodic safety review,
- A graded approach can be implemented considering several mitigating factors (e.g., short duration of operations, ensuring an equivalent level of safety of the existing facility, etc).

1.3. OBJECTIVES

The main objectives of this generic safety assessment are:

- Identifying and assessing the radiological and non-radiological hazards from normal laser cutting operations and those that may arise from accident situations.
- Identifying safety measures, systems, and controls for the identified hazards during laser cutting activities, following defence-in-depth principle and with the final objective of reducing residual risks to As Low As Reasonably Achievable (ALARA).
- Demonstrating that laser cutting of components under the configurations within the scope of this document can be performed safely and complying with international regulatory requirements.
- Allowing laser cutting technology to be included in safety analyses at early stages of design of decommissioning projects. Potential End Users may adjust the Generic Safety Assessment to their specific plant and national regulatory conditions, for which notes, comments and remarks are available throughout the document.

1.4. TIMEFRAMES

Timeframes relevant for the safety assessment of the entire nuclear facility decommissioning are based on the planned end state of the facility, for instance, the release from regulatory control without restrictions (as the preferred strategy for the IAEA [Ref. 21]). In this case, relevant times would be the time required for releasing the site for regulatory control and the time when un-restricted use of buildings is achieved.

Those times are based on the schedule for implementing all decommissioning activities. Among these, the segmentation of the RPV and RVI are noteworthy.

For this evaluation, timeframes for segmenting the reactor are estimated based on cutting performances (previous laser cutting experiences) and considering previous cutting experiences using mechanical or other types of thermal cutting techniques in the decommissioning of NPPs (great variability on timings) [Ref. 8, 51, 53]. Timeframes are summarized in Table 1.1.

Table 1.1. Timeframes for Segmentation Activities

Type	Component	Activity	Duration (Months)	Total Duration (Months) (1)
PWR	RVI	Onsite Preparatory Activities	0.5	6
		Segmentation	5	
		Post-segmentation Activities	0.5	
	RPV	Onsite Preparatory Activities	0.5	11
		Segmentation	10	
		Post-segmentation Activities	0.5	
BWR	RVI	Onsite Preparatory Activities	0.5	9
		Segmentation	8	
		Post-segmentation Activities	0.5	
	RPV	Onsite Preparatory Activities	0.5	12
		Segmentation	11	
		Post-segmentation Activities	0.5	

(1) Timeframes do not include mobilization time, as it is not relevant for the analysis.

NOTE: Segmentation times were estimated based on information about cutting speed limits (refer to Tables 2.12 and 2.13) and the specific segmentation plan provided by NUREGs [Ref. 52, 53]. This information should be adjusted based on actual plant conditions and cutting configurations.

Segmentation activities will be conservatively considered to start after 3.5 years from final shutdown. This includes 2.5 years for planning and preparatory activities [Ref. 52, 53] plus 1 additional year for activities needed before segmentation activities are completed and mobilization of dedicated personnel. Consequently, time for radioactive decay will be limited (3.5 years), setting conservative boundary conditions within this evaluation. Timeframes may be adjusted as needed by potential End Users.

1.5. END POINTS AND END STATE OF THE DECOMMISSIONING

The end point of the nuclear facility is based on its planned strategy, and as it is indicated before, that might involve the release from regulatory control without restrictions. In this situation, all reactor nuclear and auxiliary systems are removed, and buildings are below release levels.

The implementation of the activities within the scope of this document supports the achievement of the NPP end state. As for this evaluation, the end point is the removal of the RPV and RVI and any associated segmentation equipment. Segmented pieces are placed on appropriate containers, as per national regulations. These containers are managed in subsequent activities not considered within this evaluation.

1.6. REGULATORY REQUIREMENTS AND CRITERIA

The safety assessment should be based on regulatory requirements and criteria applicable to the decommissioning activities, for which compliance shall be demonstrated. International requirements are identified within this document, and potential End Users may add national requirements as needed. Although dose limits and constraints are defined, exposures shall be optimized in order to be as low as reasonably achievable (ALARA).

Additionally, the dose restriction concept may be applied (administrative restrictions), for which nuclear facilities may self-impose, during planning activities, lower values than those of sections 1.6.1 and 1.6.2. These restrictions are usually a fraction of regulatory limits and may be considered for the safety evaluation.

The ALARA program shall ensure the application of the Radiation Protection optimization principle, emphasizing not only on the reduction of individual doses but also on the reduction of the number of people exposed and the probability of radiation exposures occurrences.

1.6.1 Workforce criteria from normal activities

During decommissioning, the presence of residual radiological activity in contaminated or activated areas, systems or components remains a risk of exposure for people and, to a greater extent, for workers carrying out decommissioning work.

In this regard, radiation exposure of workers during decommissioning activities shall comply with the criteria established by the IAEA [Ref. 18]:

- An effective dose of 20 mSv per year averaged over five consecutive years (100 mSv in 5 years) and of 50 mSv in any single year.
- An equivalent dose to the lens of the eye of 20 mSv per year averaged over five consecutive years (100 mSv in 5 years) and of 50 mSv in any single year.
- An equivalent dose to the extremities (hands and feet) or to the skin of 500 mSv in a year.

The above criteria do not necessarily match the ALARA principle, so dose constraints should be set accordingly by the End User, as described in section 1.6.

1.6.2 Public criteria from normal activities

For the relevant members of critical groups (the public), the following limits and constraints are considered [Ref. 18]:

- An effective dose of 1 mSv in a year.
- The dose constraint for the entire site is 0.3 mSv/year [Ref. 14]. This constraint shall be divided between any unit under decommissioning and, if there are, waste management facilities.
- An equivalent dose equivalent to the lens of the eye of 15 mSv in a year.
- An equivalent dose equivalent to the skin of 50 mSv in a year.

1.6.3 Accident criteria

The generic safety assessment is based on consequence-based, defence-in-depth criteria, as it is considered more adequate than using risk-based criteria due to the following:

- Short-term one-off activities are assessed, for which consequence-based criteria is more suited.
- The potential consequences of the radiological accident analysis reinforce the use of a consequence-based criteria, as per graded approach considerations.

Table 1.2 presents the defence-in-depth criteria applicable to the generic safety assessment. Despite these criteria, work (and the associated safety measures) shall be planned to optimize safety so that the identified risks and their potential consequences can be demonstrated to be ALARA.

Table 1.2. Defence-in-depth Criteria [Ref. 17]

Unmitigated[1] Consequences[2]	Number of Independent[3] Complete Safety Measures Required
Higher > 20 mSv to a worker > 1 mSv to the public critical group	Two
Significant 2 to 20 mSv to a worker 0.01 to 1 mSv to the public critical group	One
Insignificant < 2 mSv to a worker < 0.01 mSv to the public critical group	None

1.6.4 Clearance values

For the scope of this evaluation, clearance of materials or site release from regulatory control is not considered a key aspect. However, some details will be mentioned for providing the overall decommissioning picture.

The IAEA provides guidance on clearance levels that may be adopted by Member States [Ref. 13]. Additionally, clearance levels expressed in terms of activity concentration (Bq/g) or surface activity concentration (Bq/cm^2) were published by the European Commission [Ref. 10]. National regulations may establish different clearance criteria. Potential End users may refer to their applicable criteria.

For site release, dose constraints listed in section 1.6.2 are applicable. These criteria, although relevant for the complete decommissioning process, is not directly related to the activities within the scope of this document. In any case, the removal of the RPV and RVI will result in a positive contribution to reach the planned end state of the site.

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[1] 'Unmitigated' assumes failure of safety controls.
[2] All doses are effective dose equivalent.
[3] An independent complete safety measure must be:

- Independent of the initiating event and of any other complete safety measures;
- Capable of detecting a failure (the initiating event), deciding what must be done, and terminating or suitably mitigating the accident scenario. This may for example require an equipment safety control (such as an alarm) to detect a failure, an operator deciding what needs to be done in response to the alarm, and another equipment safety control used by the operator to terminate or mitigate the scenario. 'Suitably mitigating' means that the consequences are reduced to below the low end of the relevant consequence range, meaning that more than one mitigating safety control may be required just for the mitigation part of a single independent complete safety measure.

1.6.5 Waste management

Waste management during decommissioning activities is based on the IAEA waste classification [Ref. 16]. In this regard, the IAEA classifies radioactive waste into six categories according to the activity and half-life of radionuclides and disposal solutions:

- Exempt waste (EW): waste that meets the criteria for clearance, exemption or exclusion from regulatory control for radiation protection purposes.
- Very short-lived waste (VSLW): waste that can be stored for decay over a limited period of up to a few years and subsequently cleared from regulatory control.
- Very low level waste (VLLW): waste that does not necessarily meet the criteria of EW, but that does not need a high level of containment and isolation and, therefore, is suitable for disposal in near surface landfill type facilities with limited regulatory control.
- Low level waste (LLW): waste that is above clearance levels, but with limited amounts of long-lived radionuclides. Such waste requires robust isolation and containment for periods of up to a few hundred years and is suitable for disposal in engineered near surface facilities.
- Intermediate level waste (ILW): waste that, because of its content, particularly of long-lived radionuclides, requires a greater degree of containment and isolation than that provided by near surface disposal. However, ILW needs no provision, or only limited provision, for heat dissipation during its storage and disposal.
- High level waste (HLW): waste with levels of activity concentration high enough to generate significant quantities of heat by the radioactive decay process or waste with large amounts of long lived radionuclides that need to be considered in the design of a disposal facility for such waste.

The activities considered within this evaluation includes the segmentation of components (RPV and RVI) using the laser cutting technology and the placement of segmented pieces into containers. The waste material generated during the decommissioning of the RPV and RVI will be mainly scrap metal, which will be cut to the appropriate size according to approved containers. The largest volumes of waste will mainly be ILW and LLW, but HLW may also be expected in the most activated parts. In any case, the produced waste packages shall meet the national criteria (i.e., total activities, specific activities, and dose rates) for handling, transport, storage, and disposal of radioactive waste, as needed.

The total estimated radiological inventory is detailed in section 2.3. Segmentation of components shall be planned in order to generate packages to meet the regulatory requirements, while seeking for a reduction of radioactive waste management costs (i.e., by obtaining high filling grades of waste packages and adequately segregating waste based on their activity levels).

1.6.6 Chemical and other industrial safety considerations

The control of effects to workers from non-radiological hazards, such as chemical and other industrial safety considerations, is also applied by mean of national occupational health and safety regulations.

Decommissioning activities involve a progressive change in the relevance of industrial versus radiological risks. As an example, the use of work equipment or chemicals may be the initiators of a hazardous event, so any potential risk to the safety and health of workers is identified within this document. However, detailed accident analysis within this document will be focused on the potential radiological consequences to workers and the public.

1.7. ANALYSIS OUTPUTS

The outputs of the generic safety evaluation are the following:

- Identification of radiological and non-radiological hazards for different laser cutting configurations.
- Qualitative evaluation of the risks during normal and accident situations.
- Quantitative evaluation of the risks during normal and accident situations, based on reference cases included for illustrative purposes.

1.8. GENERIC SAFETY ASSESSMENT APPROACH

The approach is based on the steps of the safety assessment framework of Figure 1.1 [Ref. 15, 17]. The evaluation was performed in a deterministic manner by establishing generic conservative hypothesis that create a safe envelope to a different range of specific conditions of configurations of potential End Users.

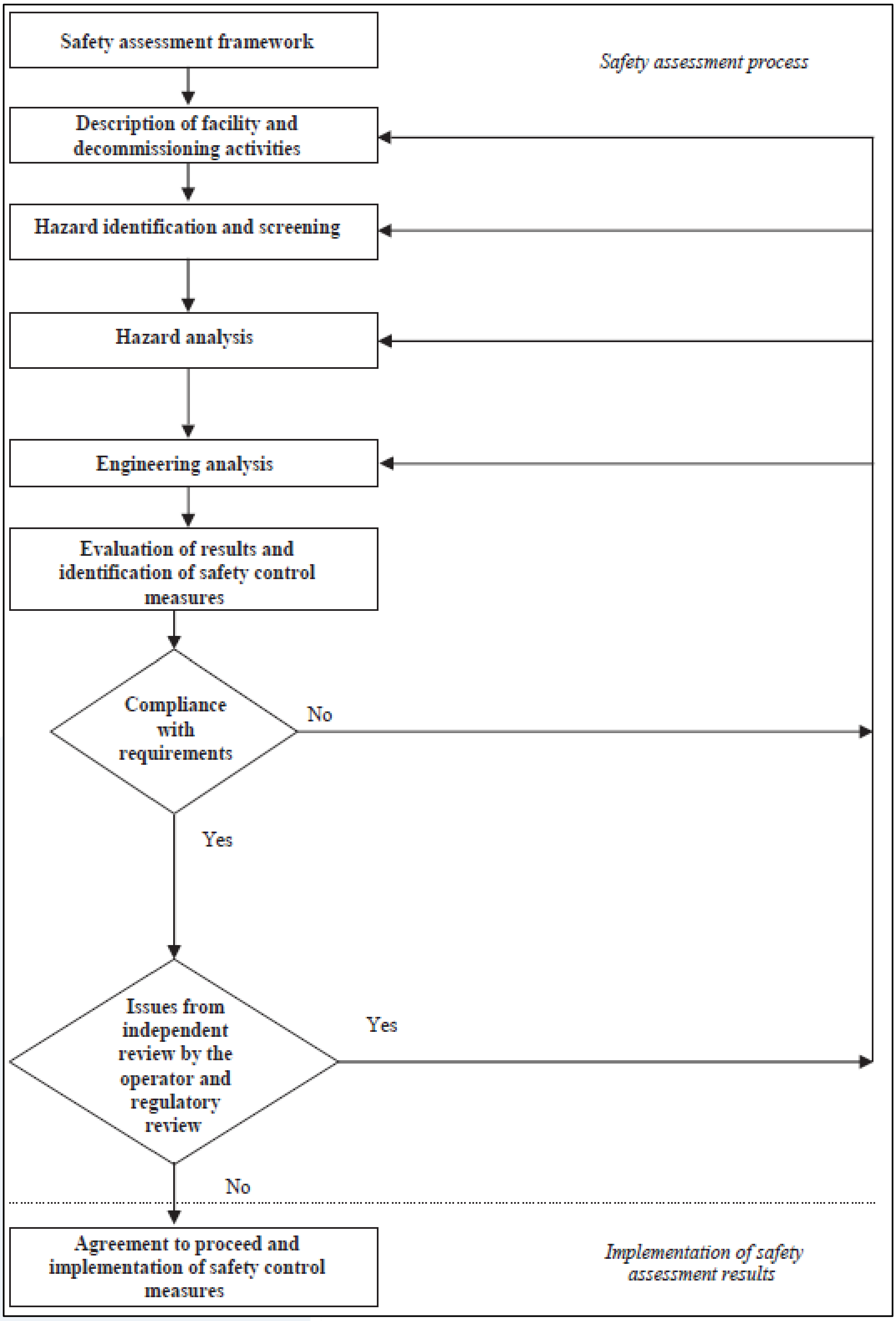


Figure 1.1. Safety Assessment Process [Ref. 17]

Hazards were identified by combining the use of checklists [Ref. 15, 17] for evaluating planned cutting activities and identifying potential accident conditions, and the Hazard and Operability Analysis (HAZOP) methodology for assessing potential deviations from normal conditions.

The characteristics of the implemented HAZOP method are the following:

- It is a systematic and structured process focused on the potential deviations from planned activities and conditions.
- It is conducted by a multidisciplinary team that identifies credible deviations, potential hazards, and safety measures to prevent or mitigate accident situations.
- It is mainly a qualitative analysis, although some quantifications are performed (i.e., personnel exposures derived from unplanned events).
- Screening techniques are used for selecting credible situations and accident situations that set bounding conditions, in order to provide an adequate level of protection. Situations with very low consequence or frequency are eliminated since they do not significantly contribute to the overall risk.

Further details about the hazard analysis methodology are presented in section 3.

1.9. EXISTING SAFETY ASSESSMENTS

No previous safety assessments are available for the laser cutting activities and configurations within the scope of this document. Nevertheless, this evaluation has considered previous cutting experiences using mechanical or other types of thermal cutting techniques in the decommissioning of NPPs.

1.10. SAFETY MANAGEMENT MEASURES

For the development of the generic safety assessment, it has been assumed that a management system for decommissioning is in place, including among others:

- Organizational structure with definition of responsibilities and authorities.
- Change control, work control, maintenance and other relevant procedures.
- Training program and trained personnel.
- Radiation protection and ALARA programs and procedures.
- Occupational safety programs and procedures.
- Emergency preparedness and response programs and procedures.
- Quality assurance program.

- Adequate safety culture.

The above considerations are considered key elements for a successful and safe decommissioning of the nuclear facility, including the performance of the activities within the scope of this document.

2. DESCRIPTION OF THE FACILITY AND DECOMMISSIONING ACTIVITIES

The sections below provide detailed information on the assumptions made for this generic safety assessment, in order to generate a "safety envelope" for most of the potential plant conditions and segmentation configurations.

Potential End Users may adjust the information to their specific situation.

2.1. SITE DESCRIPTION AND LOCAL INFRASTRUCTURE

Site and local infrastructure depend on specific site/plant conditions. Potential End Users may include site-specific data, as considered necessary, about the following:

- Site description
- Local infrastructure
- Population distribution and critical group
- Meteorology
- Hydrology
- Geology
- Seismology
- Natural resources

For this generic evaluation, conservative assumptions will be made on relevant parameters to guarantee a safe envelope for a wide range of case-specific conditions.

2.1.1 Site description

Site boundary dimensions will affect public dose estimations. Site boundary dimensions range from a few hundred of meters for small NPPs (less than 500 MWe) to around 1 km for larger NPPs (1 MWe or higher). Evaluations will be performed at 100, 250, 500 and 1,000 meters from the reactor, with the safety evaluation based on the most conservative result (100-meter distance).

Potential End Users may adjust the calculation distances as needed. In this regard, it is important to remark that for stack releases, the maximum ground-level concentration in a sector may occur beyond the site boundary, so different distances may need to be evaluated for accounting for this aspect.

2.1.2 Population distribution and critical group

Members of the public are assumed to spend 24 hours every day a year in their houses, eating vegetables, meat and milk which were cultivated at the boundary.

For accident scenarios, the calculations will be performed for two different groups of the public, that is, adults and 1- to 2-year-old children, so the critical individual can be identified.

2.1.3 Meteorology

Atmosphere dispersion factors are highly dependent on specific site meteorological conditions (e.g., wind speed, precipitation, and atmosphere stability). As for the purpose of this analysis, sufficiently conservative parameters will be used to limit dispersion, as this will serve as an envelope to other site-specific conditions. Those will be the following:

- Wind speed of 1 m/s, which can be considered a relatively low wind speed that will limit atmospheric dispersion.
- Pasquill-Gifford Stability Class F, which refers to a high stable atmosphere, and thus, limiting atmospheric dispersion.

2.2. FACILITY DESCRIPTION

2.2.1 Description of the NPP

This evaluation considers a typical light water reactor (PWR or BWR) under decommissioning, after all spent fuel has been removed from the reactor (for the scope of this document it is irrelevant if the spent fuel is in the spent fuel pool or under dry storage on- or off-site).

The plant is assumed to have active systems adequately maintained, including:

- Ventilation with filtration means. Two release models may be used based on release type: release through building ventilation system (mostly in PWR designs) and stack releases (mostly in BWR designs and certain PWR designs). A conservative approach will be used, by not accounting for the possibility of a stack release (thus, using lower dispersion factors).
- Fire protection system, including monitoring and mitigation means (i.e., reactor building spray system or area sprinkles).
- Radiation monitoring system, including area radiation monitoring in the reactor building and process radiation monitoring (i.e., ventilation, water).

- Water filtration means for cleaning the reactor cavity during and after the segmentation process. Normal plant systems may be supported by supplementary clean-up systems.

There are still contaminated and activated components in the reactor building, including the RPV and RVI, that will be dismantled. The radioactive inventory is detailed in section 2.3 and the dismantling process in section 2.5.

For maintenance and decontamination of the laser cutting and manipulator systems, an appropriate workshop is assumed to be on site.

2.2.2 Description of the RPV and RVI

RPV and RVI from PWR and BWR have similarities, but also different characteristics. Main details are described in next sections (PWR and BWR, respectively). Further information can be found in main references [Ref. 33, 48, 49].

2.2.2.1. RPV and RVI from a PWR

The RPV is a cylindrical component with two hemispherical heads. The bottom head is welded, and the upper head (hereinafter referred as the RPV head) is removable (attached with studs and nuts to the flange of the cylindrical part). As per NUREG/CR-0130 [Ref. 48], the RPV is assumed to be manufactured with SA533 carbon steel, having the internal surfaces in contact with primary coolant a weld overlaid with stainless steel or Inconel (minimum of 3.96 mm). The exterior of the RPV is insulated with removable insultation modules.

The internals (RVI), located within the RPV, are composed of three differentiated parts [Ref. 48]: lower core support structure (core barrel, core baffle, lower core plate and support columns, neutron shield pads, and core support that is welded to the core barrel), the upper core support structure and the in-core instrumentation support structure. RVI were designed to support the core, align the fuel and imped its movement, and direct water flow through them. All major components are 304 stainless steel.

As per NUREG/CR-0130 [Ref. 48] "the lower core support structure is supported at its upper flange from a ledge in the reactor vessel head flange and its lower end is restrained from transverse motion by a radial support system attached to the vessel wall". RVI parts are bolted and attached among them or directly to the RPV, or by use of "keyways", with no welding points.

Since the core was located within the RPV/RVI, its neutron flux produced the activation of the surrounding materials. Radioactive inventory is detailed in section 2.3.

Figures 2.1 to 2.3 show typical constructive characteristics of RPVs and associated RVIs. The dimensions are representative of a PWR of 3500 MW(t) [1175 MW(e)] [Ref. 48], which was taken as a reference for this evaluation.

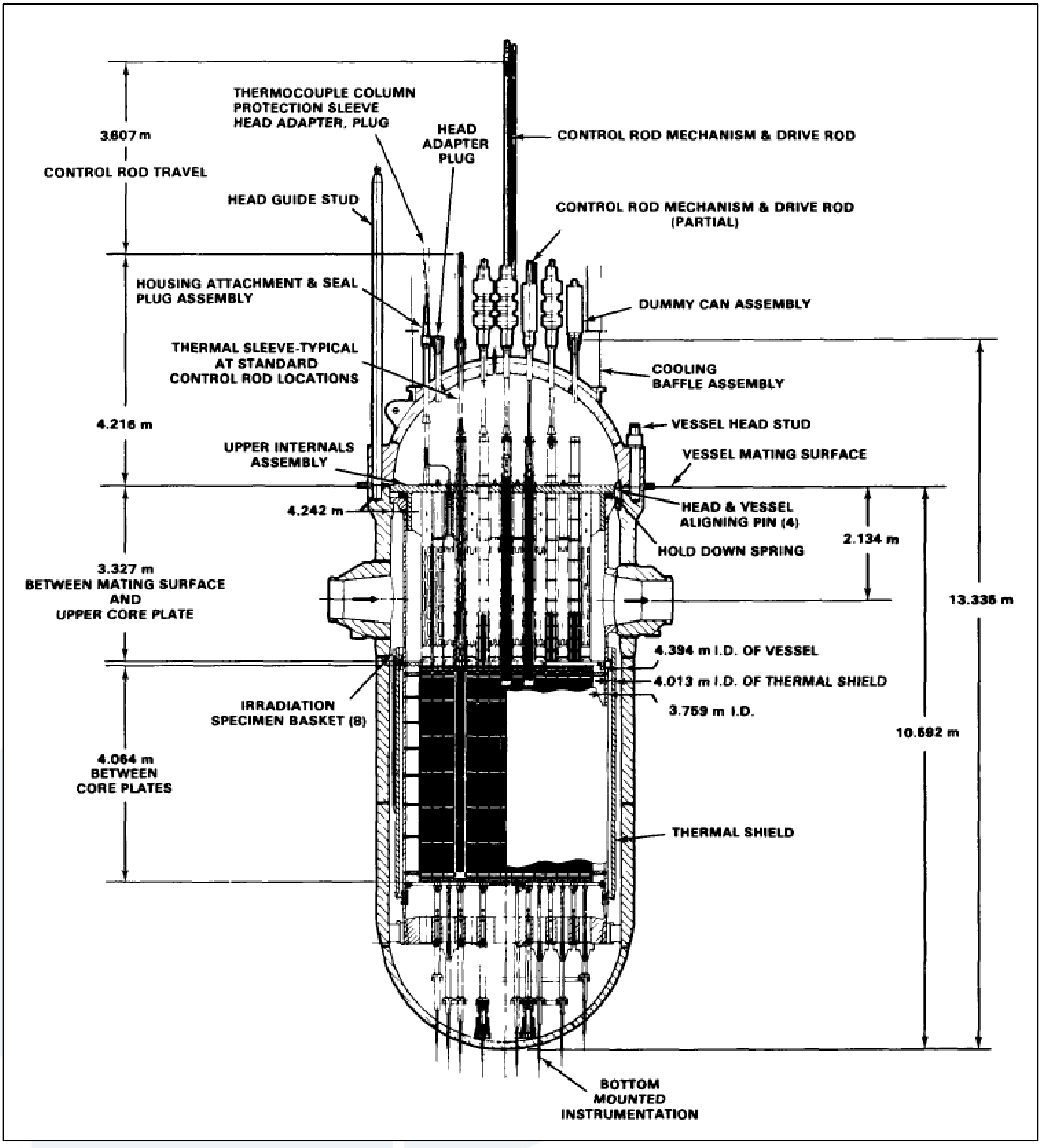


Figure 2.1. RPV and RVI Components and Reference Dimensions for a PWR [Ref. 48]

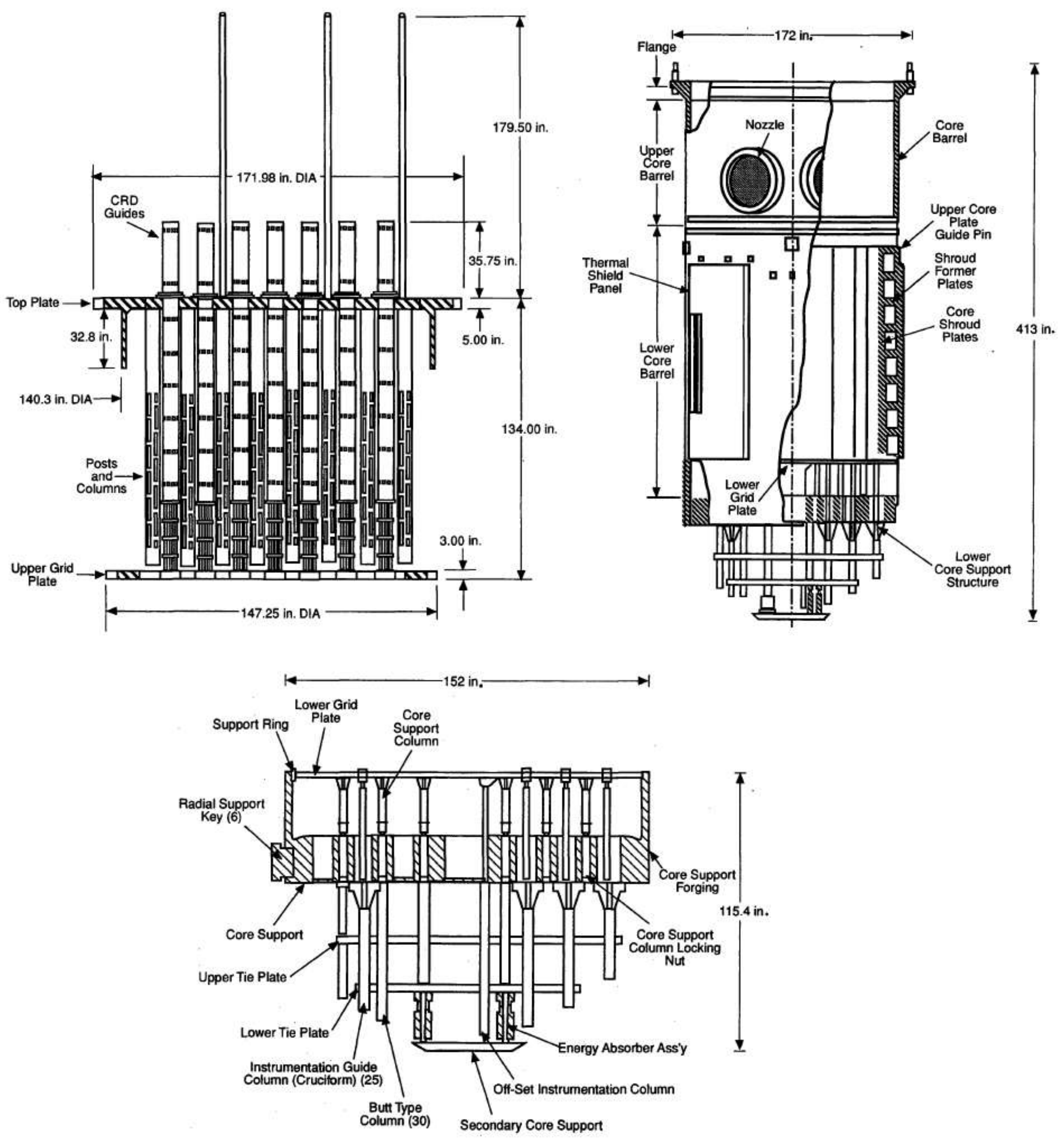


Figure 2.2. Upper Core Assembly (Upper left), Lower Core Assembly (Upper right), Lower Core Support Structure (Bottom). Reference Dimensions [Ref. 48]

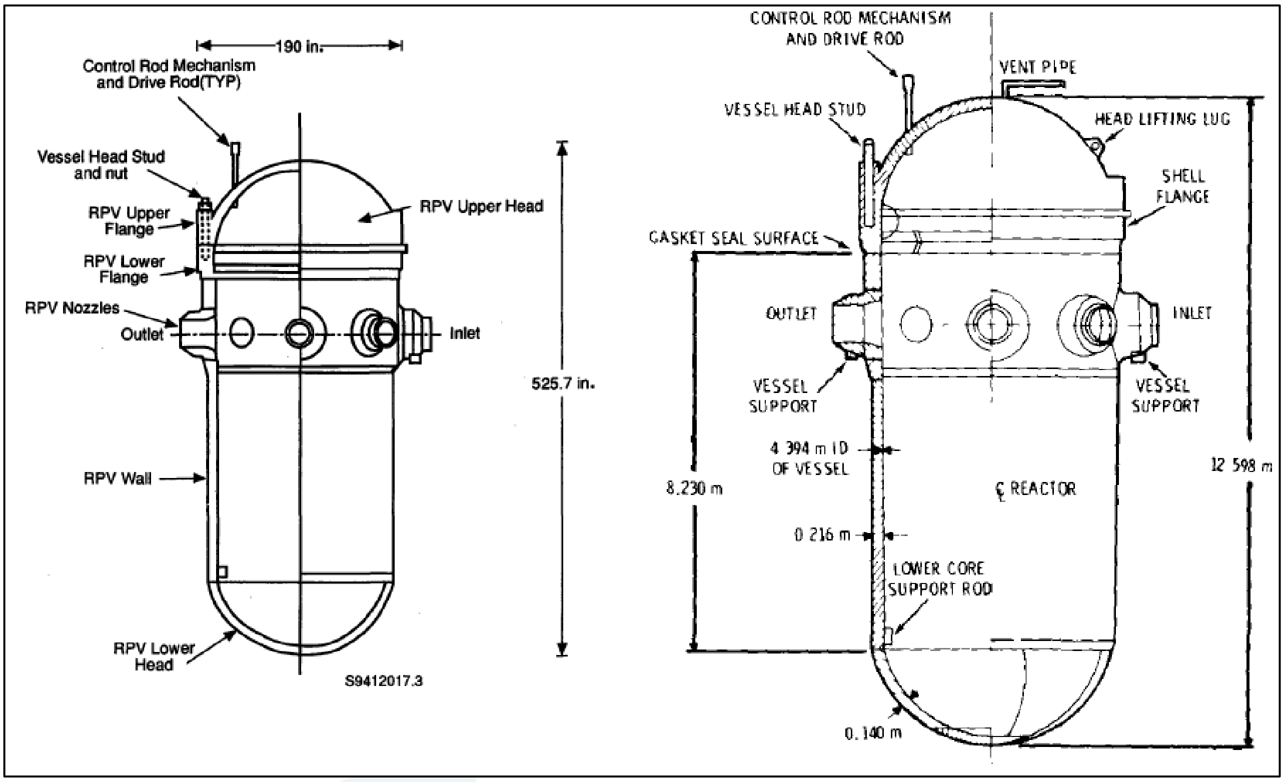


Figure 2.3. RPV Outline and Reference Dimensions [Ref. 48]

2.2.2.2. RPV and RVI from a BWR

The RPV is a cylindrical component with two hemispherical heads. The bottom head is welded, and the upper head (hereinafter referred as the RPV head) is removable (attached with studs and nuts to the flange of the cylindrical part). As per NUREG/CR-0672 [Ref. 49], the RPV is assumed to be manufactured with SA533 carbon steel and has an internal clad of 304 stainless steel (except for the top head, nozzles, and nozzle weld zones, which are unclad). The RPV contains the core and supporting structures.

The internals (RVI), located within the RPV, are composed of core shroud, shroud support plate, core support plate, top fuel guide, control rod guide tubes, jet pumps, shroud head and steam separator assembly, steam dryer assembly, feedwater spargers, core spray lines, top head cooling spray nozzle, differential pressure and liquid control line, and in-core flux monitor guide tubes [Ref. 49]. These components are made of stainless steel and include welded points to the RPV, although some parts are attached within each other by means of bolt connections.

Since the core was located within the RPV/RVI, its neutron flux produced the activation of the surrounding materials. Radioactive inventory is detailed in section 2.3.

Figure 2.4 show typical constructive characteristics of RPVs and associated RVIs. The dimensions are representative of a BWR of 3320 MW(t) [1155 MW(e)] [Ref. 49], which was taken as a reference for this evaluation.

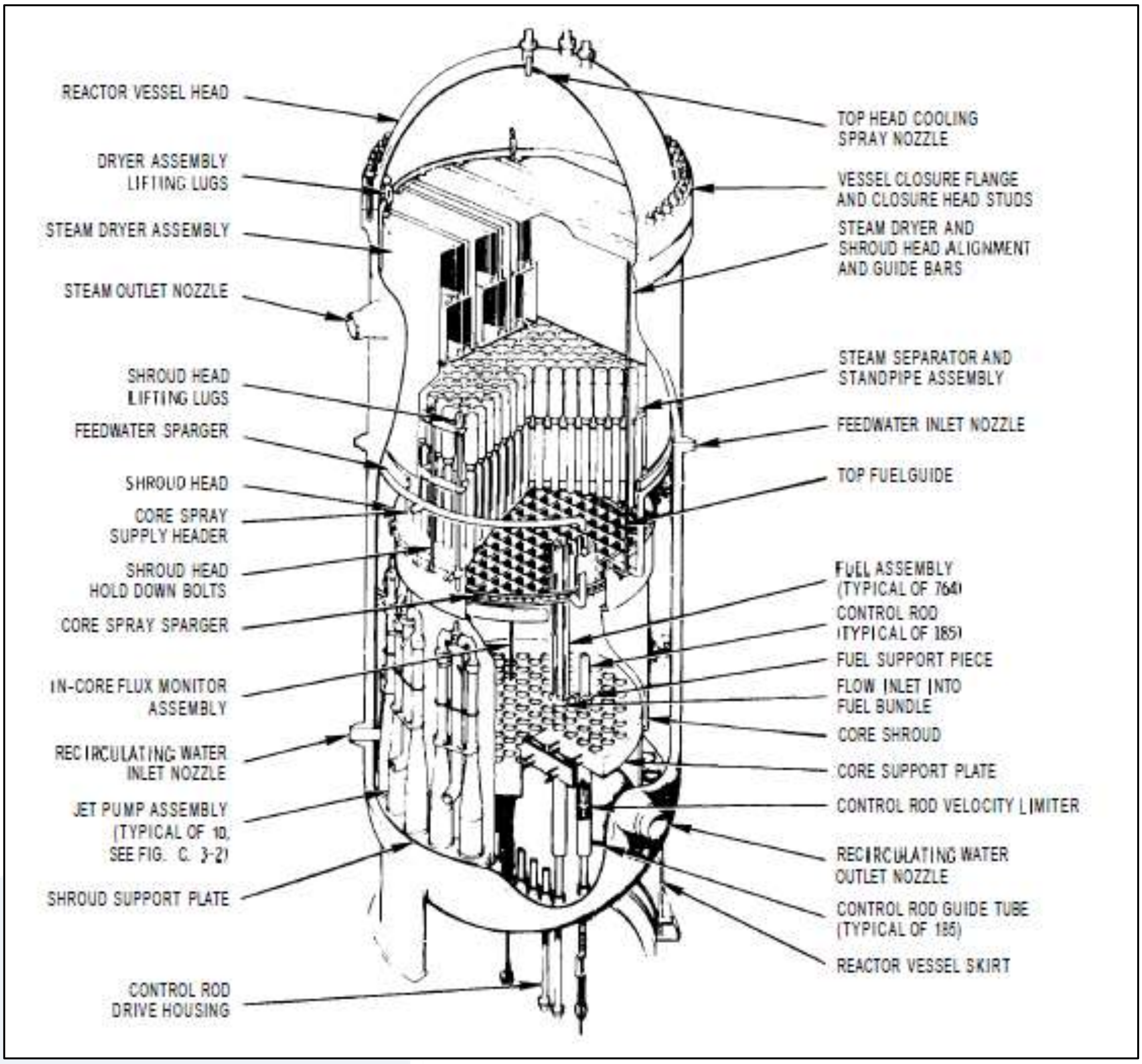


Figure 2.4. RPV and RVI Components and Reference Dimensions for a BWR [Ref. 49]

2.3. RADIOACTIVE INVENTORY

When the reactor is shut down and after removing the irradiated spent fuel, residual activity remains in the materials of the plant. This residual activity comes from two different phenomena: materials activation and contamination.

As per the above, radionuclide inventories are of two types:

- Neutron-activated components in and around the reactor core. The activation levels in the RPV and RVI greatly vary with proximity to the fuelled region of the reactor.
- Surface contamination by fission and activated corrosion products deposited inside piping systems and equipment and on structural surfaces of the site.

The radiological inventory per radionuclide differs according to these mechanisms of production and its origin (surfaces or components). The activation inventory corresponds to most of the residual activity within the plant, but the material is limited to those in and around the reactor core. This radioactive inventory will be considered within this evaluation, which is focused on the segmentation of two components, RPV and RVI, that were close to the reactor core during the plant operation.

RPV and RVI will also be contaminated when segmentation activities start. Activated corrosion products from the structural components and fission products leaking from the fuel will generate surface contamination in system, structures, and components. Differences between constructive materials will imply differences on the inventory of activated corrosion products, and these differences can be appreciated between PWR and BWR designs. This contamination will also depend on the number of leaking fuel elements, and this is related to the operating history of the plant.

It should be remarked that implementing primary system decontamination cycles after final shutdown will reduce RPV/RVI surface contamination. This is a process that optimizes the doses received by the workers, among others, during RPV and RVI cutting activities. This decontamination process may also reduce the potential consequences of postulated accidents, such as drop of loads where contamination can be dispersed.

The above plant specific conditions will determine the specific radioactive inventory to be considered for RPV/RVI segmentation activities. For defining the radioactive inventory of this evaluation, reference values from NUREG/CR-0130 and NUREG/CR-0672 will be used [Ref. 48, 49]. Those references consider, respectively, a PWR of 3500 MW(t) [1175 MW(e)] and a BWR of 3320 MW(t) [1155 MW(e)], which are assumed to be sufficiently representative. However, it should be remarked that the radioactive inventory detailed within this document is unique for this reference reactors, and they are not directly applicable to others. Information should be adjusted based on plant-specific characterization data.

RPV and RVI segmentation activities will be considered to start after 3.5 years from final shutdown of the NPP (refer to section 1.4), and thus, radioactive inventory will be adjusted with radioactive decay using the radioactive decay law equation, where the activity, A, of a radioactive substance decreases exponentially with time:

$$A = A_0 \cdot e^{-\lambda \cdot t} \qquad \text{Eq. 2.1.}$$

Where:

- A is the activity, in Bq, or specific activity, in Bq/cm^3 or Bq/g, after the assumed decay period (for this analysis, 3.5 years).
- A_0 is the activity, in Bq, or specific activity, in Bq/cm^3 or Bq/g, at time of reactor shutdown.
- λ is the decay constant, which is equal to Ln(2)/Half-life.
- t is the decay time (for this analysis, 3.5 years after plant shutdown).

2.3.1 PWR radioactive inventory

The radioactive inventory of the RPV and RVI of a PWR of 3500 MW(t) [1175 MW(e)] 3.5 years after plant shutdown is estimated by using the reference information from NUREG/CR-0130 [Ref. 48]. It is important to remark that the revised analysis of NUREG/CR-5884 [Ref. 52] maintained the activation and contamination assumptions of NUREG/CR-0130, as it was considered still representative.

2.3.1.1. RPV and RVI activation inventory

Table C.1-3 from NUREG/CR-0130 [Ref. 48] presents the levels of radioactivity in major activated reactor components at time of reactor shutdown after 30 effective full power years of operation.

Tables 2.1 to 2.4 provide the activity concentrations (peak and average values) and Table 2.5 the total activity of most relevant radionuclides in the neutron-activated steel components of the reactor vessel and internals in the axial mid-plane of the fuel core, after adjusting the reference information with decay time. Activated components included in the list are the following:

- Shroud
- Lower 4.72 m of Core Barrel
- Thermal Shields
- Vessel Inner Cladding
- Lower 5.02 m of Vessel Wall
- Upper Grid Plate
- Lower Grid Plate

The reference document considered the distribution of neutron flux and the influence on the axial regions indicated in the column headings to calculate average-to-peak ratios and the total inventory. Those ratios were also used within this document to derivate average concentrations. The following tables, for which activities in curies were converted to Becquerels, were generated:

- Table 2.1, Core Mid-Plane "Peak" activities (Bq/cm^3) by converting the radioactivity in Curies/m^3 to Bq/cm^3.
- Table 2.2, Core Mid-Plane "Average" activities (Bq/cm^3) by applying the Average/Peak factor.
- Tables 2.3 and 2.4, in Bq/g, by converting tables 2.1 and 2.2 using the density of stainless steel (8.038E3 kg/m^3 [Ref. 48]).
- Table 2.5, Core Mid-Plane activities (Bq), by multiplying average activity concentrations (Bq/g) by the material mass of each component.

The activation inventory used as reference contains 7.605E+16 Bq, which is considered a relatively conservative value. For instance, EPRI [Ref. 8], indicates that a decommissioned RPV/RVI for a PWR normally contains radioactive materials with a total activity in the range of 1.85E+16 to 7.4E+16 Bq.

Within the radioactive inventory at final shutdown, certain radionuclides such as C-14, Fe-55, Co-60, Ni-59, Ni-63, Nb-94, and Mo-93, may be especially relevant during decommissioning due to their production process, mode of radioactive decay, and radioactive emissions. However, after 3 years of decay, most significant radionuclides in the activated components of a PWR will be Fe-55, Co-60, and Ni-63.

It is important to remark that for Fe-55 and Co-60, activity concentrations saturate after about 16 and 22 years, respectively, at full power, so their activity levels are relatively independent of the years of operations (i.e., operating life extensions). However, activity levels of Ni, Nb, and C continue to increase almost linearly with years of reactor operation. For this study, the 30 effective full power years of operation will be considered as it is considered sufficiently representative.

2.3.1.2. RPV and RVI contamination inventory

Table C.4-5 from NUREG/CR-0130 [Ref. 48] presents the levels of contamination from corrosion products deposition. Based on that, for a surface of RPV and RVI of approximately 5.7E2 m^2, the specific activity is considered approximately of 8.51E+5 Bq/cm^2 (0.23 Ci/m2) and a total activity of approximately 4.81E+12 Bq (130 Ci). External contamination of the RPV will be considered negligible, due to the presence of the insulation during the operation of the reactor.

However, this information does not provide specific activity per nuclide and does not include contamination from fuel leakage. Thus, additional assumptions will be made.

As per NUREG/CR-0672 [Ref. 49], contamination from corrosion products will be assumed to be about 93% of total surface contamination. Fuel leakage will contribute to 7% of the total surface contamination, that is, 6.41E+4 Bq/cm^2 (0.02 Ci/m^2) and 3.62E+11 Bq (9.78 Ci). Total surface contamination will be of 9.15E+5 Bq/cm^2 (0.25 Ci/m^2) and 5.17E+12 Bq (140 Ci).

For obtaining the surface contamination per radionuclide, the following will be performed:

- Contamination from corrosion: 9.15E+5 Bq/cm^2 will be multiplied by the contribution (%) of each radionuclide to the total activation of Table C.1-3 from NUREG/CR-0130 [Ref. 48], and by the contribution of corrosion products to total surface contamination (93%). Then, activity levels are decayed to 3.5 years after shutdown.
- Contamination from fuel leakage: 9.15E+5 Bq/cm^2 will be multiplied by the contribution (%) of fuel leakage radionuclides from Table E.2-1 from NUREG/CR-0672 [Ref. 49], and by the contribution of fuel leakage to total surface contamination (7%). Radionuclides considered will be Ru-103, Ru-106, Cs-134, Cs-137, Ce-141, and Ce-144. Then, activity levels are decayed to 3.5 years after shutdown.

The results are shown in Table 2.6.

Table 2.1. Core Mid-Plane "Peak" Activities (Bq/cm^3), t=3.5 years, RPV/RVI of PWR

Nuclide	Half-Life (y)	λ (y^{-1})	Shroud (Bq/cm^3)	Lower 4.72 m of Core Barrel (Bq/cm^3)	Thermal Shields (Bq/cm^3)	Vessel Inner Cladding (Bq/cm^3)	Lower 5.02 m of Vessel Wall (Bq/cm^3)	Upper Grid Plate (Bq/cm^3)	Lower Grid Plate (Bq/cm^3)
Nb-95	9.60E-02	7.22E+00	7.88E-04	2.99E-06	1.38E-06	2.21E-09	6.70E-10	7.88E-04	7.88E-04
Fe-59	1.23E-01	5.63E+00	4.64E+00	4.44E-01	2.02E-01	1.01E-02	2.73E-03	4.64E+00	4.64E+00
Co-58	1.97E-01	3.52E+00	2.50E+04	1.66E+03	7.65E+02	5.49E+01	1.10E+00	2.50E+04	2.50E+04
Zr-95	1.78E-01	3.89E+00	4.92E-03	2.77E-04	1.30E-04	8.94E-06	3.22E-05	4.92E-03	4.92E-03
Zn-65	6.71E-01	1.03E+00	1.20E+05	1.10E+03	4.98E+02	6.67E-01	3.49E-02	1.20E+05	1.20E+05
Mn-54	8.22E-01	8.43E-01	1.32E+08	7.16E+06	3.29E+06	2.32E+05	9.10E+04	1.32E+08	1.32E+08
Fe-55	2.70E+00	2.57E-01	1.96E+10	2.26E+09	1.01E+09	5.27E+07	1.08E+07	1.96E+10	1.96E+10
Co-60 (1)	5.27E+00	1.31E-01	2.24E+10	2.17E+09	1.10E+09	5.84E+07	1.75E+06	2.24E+10	2.24E+10
Ni-63	1.00E+02	6.93E-03	4.33E+09	5.42E+08	2.46E+08	1.30E+07	1.37E+05	4.33E+09	4.33E+09
Mo-93	3.00E+03	2.31E-04	1.33E+04	1.92E+03	8.87E+02	4.44E+01	4.81E+01	1.33E+04	1.33E+04
C-14	5.75E+03	1.21E-04	5.55E+06	6.66E+05	3.07E+05	1.48E+04	7.03E+02	5.55E+06	5.55E+06
Nb-94	2.00E+04	3.47E-05	2.00E+05	9.62E+03	4.44E+03	3.51E+02	0.00E+00	2.00E+05	2.00E+05
Ni-59	8.00E+04	8.66E-06	2.74E+07	4.81E+06	1.85E+06	1.11E+05	1.18E+03	2.74E+07	2.74E+07
Sum (Bq/cm^3)			4.650E+10	4.986E+09	2.358E+09	1.245E+08	1.283E+07	4.650E+10	4.650E+10
Total "Peak" Specific Activity (Bq/cm^3)			1.470E+11						

(1) Upper bound of Co-60 is considered based on Co-59 contaminant in the materials.

Table 2.2. Core Mid-Plane "Average" Activities (Bq/cm³), t=3.5 years, RPV/RVI of PWR

Nuclide	Half-Life (y)	λ (y-1)	Shroud (Bq/cm³)	Lower 4.72 m of Core Barrel (Bq/cm³)	Thermal Shields (Bq/cm³)	Vessel Inner Cladding (Bq/cm³)	Lower 5.02 m of Vessel Wall (Bq/cm³)	Upper Grid Plate (Bq/cm³)	Lower Grid Plate (Bq/cm³)
Nb-95	9.60E-02	7.22E+00	5.95E-04	1.91E-06	3.96E-05	5.19E-08	1.58E-08	4.14E-04	1.10E-02
Fe-59	1.23E-01	5.63E+00	3.51E+00	2.83E-01	2.63E+00	1.08E-01	2.90E-02	1.10E+00	2.95E+01
Co-58	1.97E-01	3.52E+00	1.88E+04	1.06E+03	3.46E+03	2.03E+02	4.06E+00	2.06E+03	5.49E+04
Zr-95	1.78E-01	3.89E+00	3.71E-03	1.77E-04	7.07E-04	3.99E-05	1.44E-04	4.90E-04	1.31E-02
Zn-65	6.71E-01	1.03E+00	9.03E+04	6.98E+02	6.49E+02	7.13E-01	3.72E-02	2.85E+03	7.60E+04
Mn-54	8.22E-01	8.43E-01	9.94E+07	4.56E+06	3.90E+06	2.25E+05	8.83E+04	2.85E+06	7.61E+07
Fe-55	2.70E+00	2.57E-01	1.48E+10	1.44E+09	8.93E+08	3.82E+07	7.86E+06	3.17E+08	8.45E+09
Co-60 (1)	5.27E+00	1.31E-01	1.69E+10	1.38E+09	9.12E+08	3.97E+07	1.19E+06	3.40E+08	9.08E+09
Ni-63	1.00E+02	6.93E-03	3.27E+09	3.45E+08	1.92E+08	8.31E+06	8.77E+04	6.18E+07	1.65E+09
Mo-93	3.00E+03	2.31E-04	1.00E+04	1.22E+03	6.90E+02	2.83E+01	3.06E+01	1.89E+02	5.05E+03
C-14	5.75E+03	1.21E-04	4.19E+06	4.24E+05	2.39E+05	9.42E+03	4.48E+02	7.89E+04	2.10E+06
Nb-94	2.00E+04	3.47E-05	1.51E+05	6.13E+03	3.45E+03	2.24E+02	0.00E+00	2.84E+03	7.58E+04
Ni-59	8.00E+04	8.66E-06	2.07E+07	3.06E+06	1.44E+06	7.07E+04	7.54E+02	3.89E+05	1.04E+07
Sum (Bq/cm³)			3.511E+10	3.176E+09	2.002E+09	8.653E+07	9.226E+06	2.152E+14	1.835E+14
Total "Average" Specific Activity (Bq/cm³)			3.987E+14						

(1) Upper bound of Co-60 is considered based on Co-59 contaminant in the materials.

Table 2.3. Core Mid-Plane "Peak" Activities (Bq/g), t=3.5 years, RPV/RVI of PWR

Nuclide	Half-Life (y)	λ (y^{-1})	Shroud (Bq/g)	Lower 4.72 m of Core Barrel (Bq/g)	Thermal Shields (Bq/g)	Vessel Inner Cladding (Bq/g)	Lower 5.02 m of Vessel Wall (Bq/g)	Upper Grid Plate (Bq/g)	Lower Grid Plate (Bq/g)
Nb-95	9.60E-02	7.22E+00	9.80E-05	3.73E-07	1.72E-07	2.74E-10	8.33E-11	9.80E-05	9.80E-05
Fe-59	1.23E-01	5.63E+00	5.78E-01	5.53E-02	2.51E-02	1.26E-03	3.39E-04	5.78E-01	5.78E-01
Co-58	1.97E-01	3.52E+00	3.10E+03	2.07E+02	9.52E+01	6.83E+00	1.37E-01	3.10E+03	3.10E+03
Zr-95	1.78E-01	3.89E+00	6.12E-04	3.45E-05	1.61E-05	1.11E-06	4.00E-06	6.12E-04	6.12E-04
Zn-65	6.71E-01	1.03E+00	1.49E+04	1.36E+02	6.20E+01	8.30E-02	4.34E-03	1.49E+04	1.49E+04
Mn-54	8.22E-01	8.43E-01	1.64E+07	8.91E+05	4.09E+05	2.89E+04	1.13E+04	1.64E+07	1.64E+07
Fe-55	2.70E+00	2.57E-01	2.44E+09	2.81E+08	1.26E+08	6.56E+06	1.35E+06	2.44E+09	2.44E+09
Co-60 (1)	5.27E+00	1.31E-01	2.79E+09	2.70E+08	1.37E+08	7.26E+06	2.18E+05	2.79E+09	2.79E+09
Ni-63	1.00E+02	6.93E-03	5.39E+08	6.74E+07	3.06E+07	1.62E+06	1.71E+04	5.39E+08	5.39E+08
Mo-93	3.00E+03	2.31E-04	1.66E+03	2.39E+02	1.10E+02	5.52E+00	5.98E+00	1.66E+03	1.66E+03
C-14	5.75E+03	1.21E-04	6.90E+05	8.28E+04	3.82E+04	1.84E+03	8.74E+01	6.90E+05	6.90E+05
Nb-94	2.00E+04	3.47E-05	2.49E+04	1.20E+03	5.52E+02	4.37E+01	0.00E+00	2.49E+04	2.49E+04
Ni-59	8.00E+04	8.66E-06	3.41E+06	5.98E+05	2.30E+05	1.38E+04	1.47E+02	3.41E+06	3.41E+06
Sum (Bq/g)			5.786E+09	6.203E+08	2.934E+08	1.549E+07	1.596E+06	5.786E+09	5.786E+09
Total "Peak" Specific Activity (Bq/g)			1.829E+10						

(1) Upper bound of Co-60 is considered based on Co-59 contaminant in the materials.

Table 2.4. Core Mid-Plane "Average" Activities (Bq/g), t=3.5 years, RPV/RVI of PWR

Nuclide	Half-Life (y)	λ (y^{-1})	Shroud (Bq/g)	Lower 4.72 m of Core Barrel (Bq/g)	Thermal Shields (Bq/g)	Vessel Inner Cladding (Bq/g)	Lower 5.02 m of Vessel Wall (Bq/g)	Upper Grid Plate (Bq/g)	Lower Grid Plate (Bq/g)
Nb-95	9.60E-02	7.22E+00	7.40E-05	2.37E-07	1.33E-07	1.75E-10	5.31E-11	1.39E-06	3.72E-05
Fe-59	1.23E-01	5.63E+00	4.36E-01	3.52E-02	1.95E-02	8.00E-04	2.16E-04	8.22E-03	2.19E-01
Co-58	1.97E-01	3.52E+00	2.34E+03	1.32E+02	7.41E+01	4.35E+00	8.70E-02	4.42E+01	1.18E+03
Zr-95	1.78E-01	3.89E+00	4.62E-04	2.20E-05	1.25E-05	7.09E-07	2.55E-06	8.70E-06	2.32E-04
Zn-65	6.71E-01	1.03E+00	1.12E+04	8.68E+01	4.82E+01	5.29E-02	2.76E-03	2.11E+02	5.64E+03
Mn-54	8.22E-01	8.43E-01	1.24E+07	5.67E+05	3.18E+05	1.84E+04	7.21E+03	2.33E+05	6.21E+06
Fe-55	2.70E+00	2.57E-01	1.84E+09	1.79E+08	9.77E+07	4.18E+06	8.60E+05	3.47E+07	9.24E+08
Co-60 (1)	5.27E+00	1.31E-01	2.11E+09	1.72E+08	1.06E+08	4.63E+06	1.39E+05	3.97E+07	1.06E+09
Ni-63	1.00E+02	6.93E-03	4.07E+08	4.29E+07	2.38E+07	1.03E+06	1.09E+04	7.67E+06	2.04E+08
Mo-93	3.00E+03	2.31E-04	1.25E+03	1.52E+02	8.59E+01	3.52E+00	3.81E+00	2.35E+01	6.28E+02
C-14	5.75E+03	1.21E-04	5.21E+05	5.28E+04	2.97E+04	1.17E+03	5.57E+01	9.81E+03	2.62E+05
Nb-94	2.00E+04	3.47E-05	1.88E+04	7.62E+02	4.30E+02	2.79E+01	0.00E+00	3.53E+02	9.42E+03
Ni-59	8.00E+04	8.66E-06	2.57E+06	3.81E+05	1.79E+05	8.80E+03	9.38E+01	4.84E+04	1.29E+06
Sum (Bq/g)			4.368E+09	3.952E+08	2.282E+08	9.865E+06	1.017E+06	8.227E+07	2.194E+09
Total "Average" Specific Activity (Bq/g)			7.279E+09						

(1) Upper bound of Co-60 is considered based on Co-59 contaminant in the materials.

Table 2.5. Core Mid-Plane Activities (Bq), t=3.5 years, RPV/RVI of PWR

Nuclide	Half-Life (y)	λ (y^{-1})	Shroud (Bq)	Lower 4.72 m of Core Barrel (Bq)	Thermal Shields (Bq)	Vessel Inner Cladding (Bq)	Lower 5.02 m of Vessel Wall (Bq)	Upper Grid Plate (Bq)	Lower Grid Plate (Bq)
Nb-95	9.60E-02	7.22E+00	9.11E+02	6.36E+00	1.39E+00	3.63E-04	1.30E-02	6.45E+00	1.47E+02
Fe-59	1.23E-01	5.63E+00	5.37E+06	9.43E+05	2.03E+05	1.66E+03	5.30E+04	3.80E+04	8.64E+05
Co-58	1.97E-01	3.52E+00	2.89E+10	3.53E+09	7.71E+08	9.02E+06	2.14E+07	2.04E+08	4.65E+09
Zr-95	1.78E-01	3.89E+00	5.69E+03	5.88E+02	1.31E+02	1.47E+00	6.26E+02	4.03E+01	9.15E+02
Zn-65	6.71E-01	1.03E+00	1.38E+11	2.33E+09	5.02E+08	1.10E+05	6.79E+05	9.79E+08	2.23E+10
Mn-54	8.22E-01	8.43E-01	1.52E+14	1.52E+13	3.32E+12	3.82E+10	1.77E+12	1.08E+12	2.45E+13
Fe-55	2.70E+00	2.57E-01	2.27E+16	4.80E+15	1.02E+15	8.67E+12	2.11E+14	1.60E+14	3.65E+15
Co-60 (1)	5.27E+00	1.31E-01	2.59E+16	4.61E+15	1.11E+15	9.60E+12	3.41E+13	1.84E+14	4.17E+15
Ni-63	1.00E+02	6.93E-03	5.01E+15	1.15E+15	2.48E+14	2.14E+12	2.67E+12	3.55E+13	8.07E+14
Mo-93	3.00E+03	2.31E-04	1.54E+10	4.08E+09	8.94E+08	7.29E+06	9.35E+08	1.09E+08	2.48E+09
C-14	5.75E+03	1.21E-04	6.42E+12	1.41E+12	3.09E+11	2.43E+09	1.37E+10	4.54E+10	1.03E+12
Nb-94	2.00E+04	3.47E-05	2.31E+11	2.04E+10	4.47E+09	5.78E+07	0.00E+00	1.64E+09	3.72E+10
Ni-59	8.00E+04	8.66E-06	3.17E+13	1.02E+13	1.86E+12	1.82E+10	2.30E+10	2.24E+11	5.10E+12
Sum (Bq)			5.378E+16	1.058E+16	2.377E+15	2.046E+13	2.497E+14	3.807E+14	8.657E+15
Total "Average" Radioactivity (Bq)			7.605E+16						

(1) Upper bound of Co-60 is considered based on Co-59 contaminant in the materials.

Table 2.6. Surface Contamination, t=3.5 years, RPV/RVI of PWR

Nuclide	Half-Life (y)	λ (y^{-1})	Total Cont. (Bq/cm^2)	Total Cont. Activity (Bq)
Nb-95	9.60E-02	7.22E+00	5.72E-09	3.26E-02
Fe-59	1.23E-01	5.63E+00	3.99E-05	2.27E+02
Co-58	1.97E-01	3.52E+00	2.03E-01	1.16E+06
Zr-95	1.78E-01	3.89E+00	4.26E-08	2.43E-01
Zn-65	6.71E-01	1.03E+00	8.77E-01	5.00E+06
Mn-54	8.22E-01	8.43E-01	1.06E+03	6.02E+09
Fe-55	2.70E+00	2.57E-01	1.73E+05	9.88E+11
Co-60 (1)	5.27E+00	1.31E-01	1.92E+05	1.10E+12
Ni-63	1.00E+02	6.93E-03	3.87E+04	2.21E+11
Mo-93	3.00E+03	2.31E-04	1.27E-01	7.27E+05
C-14	5.75E+03	1.21E-04	4.93E+01	2.81E+08
Nb-94	2.00E+04	3.47E-05	1.57E+00	8.97E+06
Ni-59	8.00E+04	8.66E-06	2.62E+02	1.49E+09
Ru-103	1.02E+00	6.77E-01	1.97E+02	1.12E+09
Ru-106	1.08E-01	6.43E+00	4.34E-07	2.47E+00
Cs-134	2.07E+00	3.36E-01	5.37E+03	3.06E+10
Cs-137	3.02E+01	2.29E-02	2.87E+04	1.64E+11
Ce-141	8.90E-02	7.78E+00	4.06E-09	2.31E-02
Ce-144	7.81E-01	8.88E-01	3.31E+02	1.89E+09
TOTAL			4.40E+05	2.51E+12

(1) Upper bound of Co-60 is considered based on Co-59 contaminant in the materials.

2.3.2 BWR radioactive inventory

The radioactive inventory of the RPV and RVI of a BWR of 3320 MW(t) [1155 MW(e)] 3.5 years after plant shutdown is estimated by using the reference information from NUREG/CR-0672 [Ref. 49]. It is important to remark that the revised analysis of NUREG/CR-6174 [Ref. 53] maintained the activation and contamination assumptions of NUREG/CR-0672, as it was considered still representative.

2.3.2.1. RPV and RVI activation inventory

Table E.1-1 and Table E.1-2 of the above-mentioned document [Ref. 49] present the levels of radioactivity in major activated reactor components at time of reactor shutdown after 30 effective full power years of operation. Table E.I-6 [Ref. 49] describes the concentration of radioactivity averaged by volume (Ci/m^3), the estimated radioactivity (Ci) and the estimated volume (m^3) calculated for each RVI and RPV activated structural component.

Table 2.7 provides the activity concentrations (peak and average values) and Table 2.8 the total activity of most relevant radionuclides in the neutron-activated components of the reactor vessel and internals in the axial mid-plane of the fuel core, after adjusting the reference information with decay time. Activated components are 304 stainless steel and SA533 carbon steel [Ref. 49].

Activated stainless steel components of the RVI are the following:

- Core Shroud
- Jet Pump Assembly
- Reactor Vessel-Cladding

The carbon steel RPV is listed as Reactor Vessel-Shell Wall.

The reference document considered the distribution of neutron flux and the influence on the axial regions indicated in the column headings to calculate average-to-peak ratios and the total inventory. Those ratios were also used within this document to derivate average concentrations. The following tables, for which activities in curies were converted to Becquerels, were generated:

- Table 2.7, Specific Activity (Bq/cm^3).
- Table 2.8, Total Activity (Bq), by multiplication of the estimated volume of each component.

In addition to the major radionuclides from the activation of the principal components of the materials, the activation products are considered which, even in small quantities, have a long half-life and can contribute to the external dose rate after about 100 years of decay, as is the case of Nb-94.

After final shutdown of the BWR, many of the radionuclides present in neutron-activated structures have high levels of specific radioactivity but, because of their decay half-lives, or decay processes, or both, they do not contribute significantly to the radiation dose rate during decommissioning. Other radionuclides have lower levels of specific radioactivity but contribute greatly to the external dose rate because they are high-energy gamma ray emitters. Within the radioactive inventory at time of final shutdown, certain radionuclides such as C-14, Fe-55, Co-60, Ni-59, Ni-63, Nb-94, Mo-93, Ag-108m, Eu-152, and Eu-154, may be especially relevant during decommissioning due to their production process, mode of radioactive decay, and radioactive emissions. However, after 3 years of decay, most significant radionuclides in the activated components of a BWR will be Fe-55, Co-60, and Ni-63.

It is important to remark that for Fe-55 and Co-60, activity concentrations saturate after about 16 and 22 years, respectively, at full power, so their activity levels are relatively independent of the years of operations (i.e., operating life extensions). However, activity levels of Ni, Nb, and C continue to increase almost linearly with years of reactor operation. For this study, the 30 effective full power years of operation will be considered as it is considered sufficiently representative.

2.3.2.2. RPV and RVI contamination inventory

Table E.2-1 from NUREG/CR- 0672 [Ref. 49] presents the reference inventory for surface contamination, and Table E.2-7 [Ref. 49] provides the total surface contamination and total surface activity of the RPV and RVI.

Combining the above information, the surface contamination per radionuclide at time of shutdown can be obtained. Then, activity levels are decayed to 3.5 years after shutdown. The results are shown in Table 2.9.

Table 2.7 Specific Activity (Bq/cm³), t=3.5 years, RPV/RVI of BWR

Nuclide	Half-Life (y)	λ (y-1)	Core Shroud (Bq/cm³)	Jet Pump Assembly (Bq/cm³)	Reactor Vessel-Cladding (Bq/cm³)	Reactor Vessel-Shell Wall (Bq/cm³)
H-3	1.23E+01	5.63E-02	1.41E+01	1.41E+01	1.41E+01	0.00E+00
Be-10	1.39E+06	5.00E-07	9.73E-02	9.73E-02	9.73E-02	0.00E+00
C-14	5.75E+03	1.21E-04	3.88E+06	3.88E+06	3.88E+06	2.50E+02
P-32	3.90E-02	1.78E+01	4.02E-21	4.02E-21	4.02E-21	3.33E-23
P-33	6.90E-02	1.00E+01	1.33E-08	1.33E-08	1.33E-08	0.00E+00
S-35	2.40E-01	2.89E+00	8.34E+01	8.34E+01	8.34E+01	2.66E-02
Cl-36	3.01E+05	2.30E-06	9.95E+00	9.95E+00	9.95E+00	0.00E+00
Cr-51	7.60E-02	9.12E+00	7.40E-04	7.40E-04	7.40E-04	8.93E-10
Mn-54	8.22E-01	8.43E-01	1.64E+07	1.64E+07	1.64E+07	2.05E+04
Fe-55	2.70E+00	2.57E-01	1.39E+10	1.39E+10	1.39E+10	5.05E+06
Fe-59	1.23E-01	5.63E+00	2.77E+00	2.77E+00	2.77E+00	9.53E-04
Co-58	1.97E-01	3.52E+00	3.49E+03	3.49E+03	3.49E+03	2.48E-01
Co-60	5.27E+00	1.31E-01	7.85E+09	7.85E+09	7.85E+09	1.52E+05
Ni-59	8.00E+04	8.66E-06	2.35E+07	2.35E+07	2.35E+07	5.40E+02
Ni-63	1.00E+02	6.93E-03	3.16E+09	3.16E+09	3.16E+09	6.25E+04
Zn-65	6.71E-01	1.03E+00	3.22E+04	3.22E+04	3.22E+04	1.87E-03
Zr-93	1.53E+06	4.53E-07	3.02E-01	3.02E-01	3.02E-01	0.00E+00
Zr-95	1.78E-01	3.89E+00	6.30E-04	6.30E-04	6.30E-04	7.24E-06
Nb-93m	1.61E+01	4.30E-02	4.30E+03	4.30E+03	4.30E+03	1.24E+01
Nb-94	2.03E+04	3.41E-05	5.55E+04	5.55E+04	5.55E+04	3.07E-02
Nb-95	9.60E-02	7.22E+00	4.73E-05	4.73E-05	4.73E-05	1.48E-10
Mo-93	3.50E+03	1.98E-04	1.21E+04	1.21E+04	1.21E+04	3.47E+01
Tc-99	6.85E-04	1.01E+03	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Ag-108m	1.27E+02	5.46E-03	2.67E+03	2.67E+03	2.67E+03	0.00E+00
Ag-108	4.50E-06	1.54E+05	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Ag-109m	1.26E-06	5.50E+05	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Cd-109	1.26E+00	5.50E-01	1.85E+04	1.85E+04	1.85E+04	0.00E+00
Ag-110m	6.85E-01	1.01E+00	8.62E+03	8.62E+03	8.62E+03	0.00E+00
Ag-110	7.81E-07	8.87E+05	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Sm-151	8.88E+01	7.80E-03	7.27E+06	7.63E+02	7.63E+02	0.00E+00
Eu-152	1.33E+01	5.21E-02	6.54E+02	3.45E+01	3.45E+01	0.00E+00
Eu-154	8.60E+00	8.06E-02	3.13E+01	8.71E+04	8.71E+04	0.00E+00
Tb-160	1.98E-01	3.50E+00	5.52E-01	1.68E-04	1.68E-04	0.00E+00
Ho-166m	1.20E+03	5.78E-04	3.50E+01	2.89E+01	2.89E+01	0.00E+00
Sum (Bq/cm³)			2.495E+10	2.494E+10	2.494E+10	5.283E+06
Total Specific Activity (Bq/cm³)			7.484E+10			5.283E+06

Table 2.8. Estimated Activity (Bq), t=3 years, RPV/RVI of BWR

Nuclide	Half-Life (y)	λ (y-1)	Core Shroud (Bq)	Jet Pump Assembly (Bq)	Reactor Vessel-Cladding (Bq)	Reactor Vessel-Shell Wall (Bq)
H-3	1.23E+01	5.63E-02	3.73E+07	7.56E+05	4.26E+06	0.00E+00
Be-10	1.39E+06	5.00E-07	2.78E+03	5.62E+01	3.17E+02	1.36E-02
C-14	5.75E+03	1.21E-04	6.17E+13	1.25E+12	7.04E+12	3.13E+11
P-32	3.90E-02	1.78E+01	5.21E+16	1.06E+15	5.95E+15	7.70E+13
P-33	6.90E-02	1.00E+01	1.04E+07	2.10E+05	1.18E+06	1.45E+04
S-35	2.40E-01	2.89E+00	1.31E+10	2.66E+08	1.50E+09	3.78E+06
Cl-36	3.01E+05	2.30E-06	2.94E+16	5.96E+14	3.36E+15	2.31E+12
Cr-51	7.60E-02	9.12E+00	8.82E+13	1.79E+12	1.01E+13	8.24E+09
Mn-54	8.22E-01	8.43E-01	1.18E+16	2.40E+14	1.35E+15	9.53E+11
Fe-55	2.70E+00	2.57E-01	1.21E+11	2.45E+09	1.38E+10	2.86E+04
Fe-59	1.23E-01	5.63E+00	1.13E+06	2.29E+04	1.29E+05	0.00E+00
Co-58	1.97E-01	3.52E+00	2.36E+03	4.79E+01	2.70E+02	1.11E+02
Co-60	5.27E+00	1.31E-01	1.61E+10	3.27E+08	1.84E+09	1.89E+08
Ni-59	8.00E+04	8.66E-06	2.08E+11	4.22E+09	2.38E+10	4.69E+05
Ni-63	1.00E+02	6.93E-03	1.77E+02	3.59E+00	2.02E+01	2.26E-03
Zn-65	6.71E-01	1.03E+00	4.52E+10	9.16E+08	5.16E+09	5.30E+08
Zr-93	1.53E+06	4.53E-07	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Zr-95	1.78E-01	3.89E+00	1.00E+10	2.03E+08	1.14E+09	0.00E+00
Nb-93m	1.61E+01	4.30E-02	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Nb-94	2.03E+04	3.41E-05	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Nb-95	9.60E-02	7.22E+00	6.92E+10	1.40E+09	7.90E+09	0.00E+00
Mo-93	3.50E+03	1.98E-04	3.23E+10	6.55E+08	3.69E+09	0.00E+00
Tc-99	6.85E-04	1.01E+03	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Ag-108m	1.27E+02	5.46E-03	2.73E+13	5.80E+07	3.27E+08	0.00E+00
Ag-108	4.50E-06	1.54E+05	2.45E+09	2.62E+06	1.48E+07	0.00E+00
Ag-109m	1.26E-06	5.50E+05	1.17E+08	6.62E+09	3.73E+10	0.00E+00
Cd-109	1.26E+00	5.50E-01	2.07E+06	1.28E+01	7.18E+01	0.00E+00
Ag-110m	6.85E-01	1.01E+00	1.31E+08	2.20E+06	1.24E+07	0.00E+00
Ag-110	7.81E-07	8.87E+05	3.73E+07	7.56E+05	4.26E+06	0.00E+00
Sm-151	8.88E+01	7.80E-03	2.78E+03	5.62E+01	3.17E+02	1.36E-02
Eu-152	1.33E+01	5.21E-02	6.17E+13	1.25E+12	7.04E+12	3.13E+11
Eu-154	8.60E+00	8.06E-02	5.21E+16	1.06E+15	5.95E+15	7.70E+13
Tb-160	1.98E-01	3.50E+00	1.04E+07	2.10E+05	1.18E+06	1.45E+04
Ho-166m	1.20E+03	5.78E-04	1.31E+10	2.66E+08	1.50E+09	3.78E+06
Sum (Bq)			9.356E+16	1.896E+15	1.068E+16	8.062E+13
Total Estimated Radioactivity (Bq)			1.061E+17			8.062E+13

Table 2.9. Surface Contamination, t=3.5 years, RPV/RVI of BWR

Nuclide	Half-Life (y)	I (y^{-1})	Total Cont. (Bq/cm^2)	Total Cont. Activity (Bq)
Cr-51	7.59E-02	9.13E+00	3.68E-10	9.62E-03
Mn-54	8.22E-01	8.43E-01	2.72E+04	7.09E+11
Fe-59	1.23E-01	5.63E+00	9.09E-05	2.37E+03
Co-58	1.97E-01	3.52E+00	5.57E-02	1.45E+06
Co-60	5.27E+00	1.31E-01	3.95E+05	1.03E+13
Zn-65	6.71E-01	1.03E+00	2.19E+02	5.71E+09
Zr-95	1.78E-01	3.89E+00	6.44E-03	1.68E+05
Nb-95	9.60E-02	7.22E+00	5.67E-08	1.48E+00
Ru-103	1.02E+00	6.77E-01	2.86E+02	7.48E+09
Ru-106	1.08E-01	6.43E+00	6.32E-07	1.65E+01
Cs-134	2.07E+00	3.36E-01	7.82E+03	2.04E+11
Cs-137	3.02E+01	2.29E-02	4.18E+04	1.09E+12
Ce-141	8.90E-02	7.78E+00	5.91E-09	1.54E-01
Ce-144	7.81E-01	8.88E-01	4.82E+02	1.26E+10
TOTAL			4.73E+05	1.23E+13

2.4. OPERATIONAL HISTORY

There is no specific information about operational history, as this document is a generic evaluation. Plant specific information may be added as necessary.

Operational history may affect the radioactive inventory (reference values defined within section 2.3). This includes, among others, number of years of operation, water chemistry, abnormal events occurred during operation, and the decontamination of the primary system after plant final shutdown.

2.5. DECOMMISSIONING ACTIVITIES AND TECHNIQUES

The decommissioning activities considered within this document are the segmentation of the RPV and/or RVI of a PWR or BWR using laser cutting technologies.

2.5.1 Laser cutting technology

Segmentation of components will be performed using laser cutting technology. This will be comprised of the following main elements:

- Laser cutting system (laser source, coupler, laser-cutting head, and fluid distribution system).

  The laser source generates the laser beam and sends it through the optical fibre to the cutting head. The laser source is water-cooled by a dedicated refrigeration unit. Different laser powers can be used, for which a minimum of 10 kW source is recommended for decommissioning purposes (the power can be then modulated as needed).

  The laser coupler is necessary to connect two sections of optical fibre with minimum loss of power. The coupler shall be water-cooled by a dedicated refrigeration unit, and it is usually located far (100m or the maximum length of the 400µm fibre) from the laser source.

  The cutting head contains optical elements to channel the laser beam to allow cutting and it is designed to blow dry air through a nozzle during the cutting process, so the molten material is moved away. For underwater cutting, an air-cone is also generated around the cutting zone through an additional air nozzle, for maintaining optimal cutting conditions.

  The fluid distribution unit contains a compressor and a water pump for supplying the cutting head with the necessary dry air and cooling water.

  The cutting performances are summarized in the table below.

Table 2.10. Laser Cutting Performances

Configuration	Material	Thickness (mm)	Laser Power (kW) vs. Cutting Speed Limit (mm/min)				
			4	6	8	10 (1)	14 (1)
In-Air	Steel and Stainless Steel	10	600	800	1000	No feedback	No feedback
		20	175	300	350	500	700
		30	75	125	175	275	400
		40	20	75	125	150	225
		60	Not cutting	20	40	55	120
		80	Not cutting	Not cutting	20	35	82
		100	Not cutting	Not cutting	7.5	15	45
		120	Not cutting	Not cutting	Not cutting	8.5	32.5
		180	Not cutting	Not cutting	Not cutting	Not cutting	7.5
		200	Not cutting	Not cutting	Not cutting	Not cutting	2.5
Underwater	Stainless Steel	40 (2)	No feedback	No feedback	70	No feedback	100

(1) Most values are estimated based on projections.

(2) Greater thickness to be tested.

Based on the cutting speed limit for a laser power of 14 kW, cutting speed ranges are approximated (order of magnitude). For stainless steel cutting underwater, values are extrapolated considering the cutting performances profile of in-air laser cutting.

Table 2.11. Laser Cutting Performances Approximation

Thickness Range (cm)	In-Air Steel Cutting Speed (cm/min) for RPV	Underwater Stainless-Steel Cutting Speed (cm/min) for RVI
0-3	70	12.5
3-5	22.5	10
5-7	12	6
7-9	8.2	3
9-11	4.5	2
11-13	3.25	1
13-19	0.75	0.3
19-40	0.25	0.125

NOTE: Cutting performance ranges have been approximated based on the projected cutting speed limit for a 14-kW laser power source. Cutting speeds used in this document are TENTATIVE, since operational cutting speeds are highly dependent on actual configurations. These speeds should be updated based on the capabilities of the laser technology deployed at the site.

Additionally, in-air cutting of thicknesses higher than 200 mm may require the deployment of more powerful laser sources. It should be remarked that laser cutting of steel up to 300mm thickness has been achieved using a 30-kW laser source [Ref. 38, 30]. In the same line, underwater cutting thicknesses and multi-thickness limitations should be observed.

- Manipulator system (arm or robot), for controlling the position and movement of the laser-cutting head.

  The system should be able to produce smooth movements with a stable cutting speed and repeat these movements accurately. It should also be equipped with force feedback features for collision detection and be able to follow shapes, notably for underwater and non-emerging cuts.

- Control unit, for controlling remotely the operation of the laser-cutting and manipulator systems, including multiple cameras and screens to provide a clear picture of the cutting operation.

- Dust and fumes collection system.

  The dust and fumes collection systems for in-air cutting and underwater cutting differ substantially. The following are examples of contamination control arrangements that can be deployed:

  - The dust and fumes collection system for in-air cutting can be integrated within the "global" laser cutting system, and it may consist of a collection head, which collects the aerosols generated during cutting operations, collection lines, and a first level of aerosol capture (for a certain diameter of particles). Its design should consider the potential effect of the residual laser beam.

  - When components are laser cut underwater, bubbles, aerosols, and particles are released. Bubbles and aerosols rise to surface, and aerosols will scatter into the environment. The dust and fumes collection system for underwater cutting may consist of a spray system (driving aerosols back into the water) or above water extraction hoods, since collection close to the cutting point is not considered feasible. Water filtration will be necessary.

  The results from a Fukushima research project show that, especially for in-air collection, approximately 80% to 99% of the particles are collected (aerosols range: 4,5nm to 1000nm). For instance, for Steel/Zirconia the aerosols collection efficiency is estimated to be 98-99% at 20 mm stand-off for mass fractions of aerosols lower than 1 μm. In this safety assessment, an efficiency of 80% will be assumed.

  The implementation of the collection system will depend on the environment itself (closed/open), the presence of local ventilation, and the accessibility of the cutting area. Within this evaluation, contamination control arrangements are recommended following the graded approach of ISO 16647:2018 [Ref. 29] (refer for Annex VI for further details). It should always be considered that risks are to be reduced to ALARA (safety optimization).

- For facilitating transport and installation of the manipulator and cutting system, a transporter/carrier will be used.

The system is deployed in three differentiated on-site locations for increased flexibility:

- The dismantling area where RPV/RVI is cut, where the laser head and manipulator will be installed.

- The laser cutting system control room, which can be far away from the radiation-controlled area or at least in a low radiation zone. It will include all the control and visualization systems. Segmentation activities will be remotely operated.

- The utilities room or area that will host major components for keeping the laser cutting system operational (laser source, coupler, fluid distribution unit, and additional utilities). These components can be placed outside the radiation-controlled area.

The installation of the laser technology in these differentiated areas will facilitate maintenance tasks. The design of the laser head will be robust as to minimize maintenance and repair activities, and maintenance tasks will not be considered necessary. In line with this approach, the in-air laser head could be managed as a consumable, by replacing it in case of malfunction. The underwater laser head could be uninstalled and repaired in a hot workshop if necessary. Maintenance or repairs in the cutting area are not expected.

The laser cutting system shall be designed considering operational safety, regardless of the components to be cut and the specific plant conditions. For this purpose, safety provisions should be in place, such as:

- Operation of the equipment by at least two persons (operator and supervisor) for implementing double verifications during cutting activities.
- Manual (and not automatic) trigger of the laser beam, requiring a continuous and deliberate action from the operator (if the trigger is stopped, the laser beam will be switched off).
- Availability of emergency stop buttons (manually and automatically triggered).
- Programmed stop mechanisms to avoid unintentional cuts or unwanted collateral aggressions. I.e., Laser beam switched off when moving for too long while the laser is still active, in order to avoid damaging the surroundings of the intervention zone.
- Fibre control, avoiding the storage of burnable material close to the laser source, coupler, and fibre.
- Fibre protections from physical damage such as crushing, squeezing, shocks and tearing.
- Electrical sensor in the laser fibre that will detect any rupture and automatically stop the laser source.
- Safe stop of the laser in case of anormal sensors indications. I.e., temperature in case of loss of cooling (fire risk), low flow in dust/aerosols collection system, temperature of the laser head, pressure of the air flow, etc. The laser system shall be designed following the fail-safe approach.

Other safety controls will include the protection from the laser beam (the laser head shall be placed in a closed environment or shielded by a double bend, since even the reflected light can potentially be harmful to the personnel exposed) and access restrictions to laser source and cutting areas and adequate training of personnel (i.e., training with mock-ups).

The design of the laser cutting system will also consider the maintainability characteristics, for facilitating installation, maintenance (avoiding maintenance and repair works in the cutting area) and removal for reuse. Besides the inherent design of the system, maintenance and inspection checks should be periodically performed (i.e., laser source power check using a calorimeter). Nuclear environment compatibility shall be considered, including for the safety provisions (i.e., electrical sensors in the laser fibre).

Human factors and human machine interface will also be taken into account through ergonomics, software design, and cameras positioning. In this regard, it is important to remark that mock-up tests and process qualifications carried out on laser cutting performance help designing operating parameters (power, cutting speed, cutting distance, orientation of the cutting head, trajectories, etc.) using tools such as 3D virtual reality. Additionally, mock-up tests and process qualifications allow actual experience feedback to be gathered for the operators and improving work organization (composition of teams and distribution of tasks). For this reason, mock-up tests and process qualifications are recommended for obtaining feedback about operational parameters definition, as well as human factors and human machine interface issues, and this should be considered within the demonstrator.

2.5.2 Segmentation process and associated activities

Segmentation and packaging of the RPV and RVI is a complex process that requires detailed planning according to specific conditions and associated hazards. It should be remarked that the components are highly activated which imply high dose rates in the area if they are not adequately shielded (refer to Annex V for further information). For minimizing personnel exposure, segmentation will be done with remotely operated equipment. Constructive characteristic, as well as the different levels of activation among components and their parts, will define the segmentation and packaging plan. The segmentation plan shall be defined by the End User, considering external constraints such as national radioactive waste regulatory requirements, radioactive waste categories, types of packaging (i.e., sizes of pieces), storage conditions, etc.

Based on the hazards, RVI segmentation is usually performed underwater [Ref. 33], which involves cutting and handling tools capable to work several meters under water in intense radiation fields due to the highly activated components, while the RPV is usually cut in-air. In both cases, contamination control (i.e., due to aerosols dispersion) should be in place, such as contamination control envelopes or dust and aerosols collection and filtration systems [Ref. 42] (refer to Annex VI for further information). These cutting configurations will be assumed within this generic safety assessment.

It is important to remark that the underwater laser cutting system at CEA laboratory was tested with a 5-meter water column. Operation at higher depths should be tested (watertightness and cutting rates). As an alternative, water levels could be adjusted at the cutting location, or the cutting table may include an elevation system so the components could be raised while lower parts are being cut, with a top-to-down segmentation process.

The segmentation process has similarities for both PWR and BWR, so the activities will be presented together specifying any relevant difference between them. Potential End Users should adjust the segmentation process to their actual conditions and cutting configurations (i.e., in-air/underwater, cutting location, number of cuts, length of cuts, etc.).

The segmentation process will be as follows [Ref. 51, 52]:

- The RPV Head and the Upper Core Support (PWR) or Steam Separator and Dryer Assemblies (BWR) will be removed and placed in the normal storage locations within the reactor containment area, and the reactor will be defueled.
- The laser cutting system will be installed in the Refuelling Cavity (PWR) or Dryer/Separator Storage Pool (BWR), place where the RVI will be segmented. The manipulator/cutting system may be placed in the refuelling bridge, end of Refuelling Cavity (PWR), end of Dryer/Separator Storage Pool (BWR), or any location considered most adequate for cutting activities. A cutting table will also be available in this area. For preparatory activities, 2 weeks (in two shifts) are considered.

  Alternatively, the RVI could be cut directly within the RPV without need for their relocation. The safety implications will be assimilable to the ones addressed within this generic safety assessment, excepting the potential damage to the RPV from the residual laser beam power but only for in-air laser cutting of the (in this Generic Safety Assessment, in-air laser cutting of the internals is no considered an optimized cutting configuration due to the potential dose rates in surrounding areas that may add operational constraints, but ad-hoc studies could be performed based on actual plant conditions and needs).
- The Reactor Coolant System (RCS) water is deionized, and the Refuelling Cavity (PWR) or Dryer/Separator Storage Pool (BWR) filled.
- For a PWR, Upper Core Support parts will be dismantled by unfastening or breaking the bolts. Upper internals to be subsequently cut will be placed into a cutting table located in the Refuelling Cavity. Then, the Lower Core Assembly will be removed from the RPV and relocated in its stand in the Refuelling Cavity. The Lower Core Assembly will be laser cut and pieces will be placed in adequate containers.
- For a BWR, RVI components will be sequentially moved to the Dryer/Separator Storage Pool and laser cut underwater, in the following tentative order: Steam Separator and Dryer Assemblies, Core Spray and Feed Water Ring Headers, Lower Core Support and Core Shroud, Control Rod Guide Tubes (not need for segmentation, only removal and packaging), and Jet Pumps.

- The Refuelling Cavity (PWR) or Dryer/Separator Storage Pool (BWR) will be drained and decontaminated, and the laser cutting system and manipulator uninstalled. For post-segmentation activities, two weeks (in two shifts) are considered.

- For cutting the RPV, some preparatory activities may be required. First, a supporting structure will have to be located underneath, in order to support the vessel once the RCS piping is cut at the nozzles. The RPV insulation will be removed prior initiating segmentation activities.

- The laser cutting system will be installed in a suitable location. For preparatory activities, 2 weeks (in two shifts) are considered.

- The RPV will be laser cut in air within the biological shielding (Reactor Cavity, PWR) or Concrete/Steel Sacrificial Shield (BWR), with deionized water level just below the cutting operations. Laser cutting of the vessel could be performed from the inside or outside, as to reduce the issues associated with the residual laser beam. The potential exists for moving the RPV to another location for segmentation, but its safety implications will be assimilable to the ones addressed within this generic safety assessment.

- The water will be drained and decontaminated, and the laser cutting system and manipulator uninstalled. For post-segmentation activities, two weeks (in two shifts) are considered.

> NOTE: Alternative segmentation processes may be considered, including alternative cutting locations and configurations. The flexibility of the laser cutting technology may allow to consider it as the main RPV and RVI cutting tool, or, for instance, as a cutting tool to be used in a confined cutting area for further segmenting big cut pieces.
>
> It is important to remark that associated risks and recommended safety measures and controls mainly depend on the overall cutting condition (in-air vs. underwater) and radioactive inventory.

During underwater and in-air cutting operations, contamination control means shall be in place. Those measures will be implemented in accordance with the safety analysis and ALARA principle. In this regard, a contamination control envelope with local high-efficiency particulate air (HEPA) filtration will be considered (refer to Annex VI for further information), and the consequences of its rupture during dismantling activities will be evaluated.

For a PWR, many of the RVI parts are attached with bolts or nuts, which can be removed with long extension socket with an impact wrench or similar tool. Depending on the system used, the time needed for unfastening the bolts can be estimated from 2 to 6 minutes. In case a bolt cannot be removed with the impact wrench, then a nutcracker may be used, which will require 10 minutes per bolt. According to NUREG/CR-5884 [Ref. 52], this will result in 252 hours for bolt removal. Bolts removal efforts could be potentially saved if the RVI are cut directly within the RPV.

During segmentation operations, the sequence will involve the positioning of the laser cutting system and grappling the piece to be cut (estimated in 20 minutes per cut), performing the laser cut (time will depend on the length of cut, thickness of material, and performance of the laser), and placing the piece into the appropriate container (estimated in 20 minutes, but the next positioning could be performed when the piece is half way of its movement, which implies only 10 additional minutes) [Ref. 52, 53]. The operating time (Toj, in minutes), which will be the base for dose calculations, will be estimated will the following formulae:

$$Toj = 30Nj + SUM (Lij / Rij) \qquad \text{Eq. 2.2. [Ref. 52, 53]}$$

Where Nj is the number of cuts for each component, Lij, are the length of cut and Rij are the cutting performances (m/min), and SUM (Lij /Rij) is the cutting time (Tc). Number of cuts and associated length depends on the segmentation and packaging plan, which is also related to the activation of components and containers specifications. This evaluation uses the same assumptions as NUREG/CR-5884 and NUREG/CR-6174 [Ref. 52, 53], including their segmentation plans (refer to Appendix E of those documents).

The effective time (Te) will consider personnel preparatory activities, such as dressing/undressing to get into the radiation-controlled area, Radiation Protection and ALARA briefings, work breaks, etc. This will result in a 57.4% of time increase [Ref. 52, 53].

Preventive maintenance activities of the laser cutting system and manipulator, as well as the performance of periodic inspection of tests of the equipment will be assumed to result in a 10% increase of the required time. Since it is considered that no major tasks will be performed in the cutting area, additional occupational doses will be considered negligible.

Activities are assumed to be performed with two shifts per day, with the following crew per shift:

- 1 Supervisor
- 2 Laser Cutting and Manipulator System Operators and 1 Handling System Operator
- 7 Technician for supporting and maintenance activities
- 2 Radiation Protection Technicians

The following tables summarize the required time for the segmentation activities (PWR and BWR):

Table 2.12. Segmentation Activities Planning for a PWR

Component	Thickness (cm)	No. Of Cuts	Total Length (cm)	Laser Cutting Rate (cm/min)	Cutting Time, Tc (min)	Operating Time, To (min)	Effective Time, Te (min)
RPV Internals Removal and Sectioning							
Equipment Setup/Testing and Post-Use Removal	4 weeks						
Upper Core Assembly							
Top Plate	6.4-12.7	7	897	3.0	298.9	509	1170
CRD Guides	1.3	122	7437	12.5	595.0	4255	9786
Support Columns	1.3	79	4816	12.5	385.3	2755	6337
Upper Grid Plate	7.6	18	5372	3.0	1790.7	2331	5361
Lower Core Assembly							
Upper Barrel	6.4	23	5309	6.0	884.8	1575	3622
Lower Barrel	6.4	123	31171	6.0	5195.1	8885	20436
Shroud Plates	1.9	91	15865	12.5	1269.2	3999	9198
Former Plates	3.2	26	800	10.0	80.0	860	1978
Lower Grid Plate	5.1	30	5781	6.0	963.5	1864	4286
Thermal Shields	7.1	34	7112	3.0	2370.7	3391	7799
Lower Forging	5.1-15.2	83	4216	2.0	2108.2	4598	10576
Tie Plates	7.6	20	203	3.0	67.7	668	1536
Support Columns	8.9	121	853	3.0	284.5	3914	9003
Insulation	1.3	113	23625	12.5	1890.0	5280	12144
Subtotal	-	890	-	-	18183	44883	103232
				In hours	*303*	*748*	*1721*
Reactor Pressure Vessel Removal and Sectioning							
Equipment Setup/Testing and Post-Use Removal	4 weeks						
Top Penetrations	8.9	63	610	8.2	74.3	1964	3693
Top Flange	22.9-35.6	14	1013	0.25	4053.8	4474	8411
Top Dome	16.5	24	5207	0.25	20828.0	21548	40510
Lower Flange	22.9-38.1	14	960	0.25	3840.5	4260	8010
Nozzles	21.6	8	2113	0.25	8453.1	8693	16343
Vertical Wall	21.6	50	14686	0.25	58745.1	60245	113261
Lower Dome	14.0	42	6726	0.75	8967.9	10228	19228
Lower Penetrations	3.8	58	221	22.5	9.8	1750	3290
Subtotal	-	273	-	-	104973	113163	212746
				In hours	*1750*	*1886*	*3546*
TOTAL	-	1163	-	-	123156	158046	315978
				In hours	*2053*	*2634*	*5266*

Table 2.13. Segmentation Activities Planning for a BWR

Component	Thickness (cm)	No. Of Cuts	Total Length (cm)	Laser Cutting Rate (cm/min)	Cutting Time, Tc (min)	Operating Time, To (min)	Effective Time, Te (min)
RPV Internals Removal and Sectioning							
Equipment Setup/Testing and Post-Use Removal	4 weeks						
Core Shroud	5.1	178	47216	6.0	7869.3	13209	20210
Top Fuel Guide	1.0	665	20269	12.5	1621.5	21572	33004
Shroud Support	5.1-12.1	58	12799	3.0	4266.4	6006	9190
Jet Pumps & Support	0.8-5.1	224	43035	10.0	4303.5	11024	16866
Core Support Plate	2.3-5.1	329	4437	10.0	443.7	10314	15780
CR Guides	0.4	185	15870	12.5	1269.6	6820	10434
CR Drive Housings	1.3	185	9822	12.5	785.8	6336	9694
Inst. Guides	0.5-1.3	165	2771	12.5	221.7	5172	7913
Steam Separator	0.4-5.1-7.6	584	28016	10.0	2801.6	20322	31092
Steam Dryer	1.3-2.5	29	18933	12.5	1514.7	2385	3649
Subtotal	-	2602	-	-	25098	103158	157831
				In hours	*418*	*1719*	*2631*
Reactor Pressure Vessel Removal and Sectioning							
Equipment Setup/Testing and Post-Use Removal	4 weeks						
Upper Head	11.4	16	11537	3.25	3549.7	4030	5077
Upper Flange	43.2	20	1524	0.25	6096.0	6696	8437
Lower Flange	35.6	20	1829	0.25	7315.2	7915	9973
Activated Wall Sections	17.8	168	28956	0.75	38608.0	43648	54996
Non-activated Wall Sections	17.8	77	26299	0.75	35065.5	37376	47093
Nozzles	17.8	40	7823	0.75	10430.9	11631	14655
Lower Head	20.3	16	14404	0.25	57617.4	58097	73203
Skirt	5.1	19	6134	12.0	511.2	1081	1362
Skirt Ring	12.7	3	130	3.3	39.9	130	164
Collar	7.6	18	4115	8.2	501.8	1042	1313
Base Ring	7.6	2	947	8.2	115.5	176	221
Subtotal	-	399	-	-	159851	171821	216495
				In hours	*2664*	*2864*	*3608*
TOTAL	-	3001	-	-	184949	274979	374326
				In hours	*3082*	*4583*	*6239*

2.6. WASTE MANAGEMENT

During segmentation activities the following waste will be generated and should be managed appropriately:

- RPV and RVI cut pieces: activation levels in the RPV and RVI greatly vary with proximity to the fuelled region of the reactor, and thus, some cut pieces may be HLW while others ILW or LLW [Ref. 52]. Thus, the segmentation and packaging plan is key for optimizing waste management. For instance, minimizing the number of cuts will reduce the cutting time, personnel exposure, and secondary waste [Ref. 7], but it will increase the necessary volume for disposing the pieces (effecting filling grade will decrease).
- Cut pieces will be placed in approved containers based on their activity levels. These containers will have to be handled, conditioned, and disposed, which are activities out of the scope of this analysis.
- HEPA filters from the dust/aerosols collection system, local confinement, or building off-gas will be managed according to plant procedures.
- Secondary waste from decontamination will depend on the methods used for laser cutting system, manipulator, and reactor floors decontamination.
- HEPA filters, resins or other waste resulting from the water clean-up system will be managed according to plant procedures.

2.7. SUPPORTING FACILITIES

Supporting facilities, other than those for handling, conditioning, and disposing the RPV/RVI cut pieces, will not be necessary.

2.8. END-POINTS

The activities considered within the scope of this document consider the following endpoints:

- After RVI segmentation, the cut pieces will be placed in appropriate containers, which will be subsequently handled, conditioned, and disposed. The laser cutting system will be uninstalled. The Refuelling Cavity (PWR) or Dryer/Separator Storage Pool (BWR) will be emptied and decontaminated (this does not apply in case the RVI are cut directly within the RPV). Secondary waste will be managed appropriately. If the RPV is not planned to be cut right after the RVI, then the RPV head may be installed again and a certain water level within the Reactor Cavity may be kept. Radioactive inventory within the site will be considerably reduced.

- After RPV segmentation, the cut pieces will be placed in appropriate containers, which will be subsequently handled, conditioned, and disposed. The laser cutting system will be uninstalled. The Reactor Cavity (or any alternative cutting location) will be emptied and decontaminated. Secondary waste will be managed appropriately. Radioactive inventory within the site will be considerably reduced.

3. HAZARD ANALYSIS: IDENTIFICATION AND SCREENING

3.1. HAZARD IDENTIFICATION

Activities and associated conditions for the segmentation of RPV and RVI with laser cutting techniques were reviewed to identify potential hazards and initiating events. Hazards were identified by a combination of the following:

- The use of a checklist [Ref. 15, 17] for evaluating planned cutting activities and identifying potential accident conditions.
- Hazard and Operability Analysis (HAZOP) methodology for assessing potential deviations from normal conditions.

The outcomes of the HAZOP analysis were compared to those of the checklist, ensuring consistency in their results. Hazards were then screened to identify credible situations for which further analysis may be required.

3.2. APPROACHES TO HAZARD IDENTIFICATION

The process for identifying potential hazards, initiating events and scenarios which may have consequences on workers, the public or the environment during the activities considered within the scope was structured, systematic, and iterative, as it is described below:

- The foreseen activities and configurations were reviewed.
- Boundary conditions were set.
- A checklist was used for the identification of hazards and initiating events. Industrial hazards with no radiological consequences were not considered further in this safety assessment as prescribed by the methodology [Ref. 15], although typical safety measures are recommended in Annex II. This information is presented in section 3.3.1, with the identified initiating events presented in section 3.3.2.
- Risks during planned activities and potential deviations were also identified by using the HAZOP methodology. The method was adapted by using activities as nodes and the application of specific keywords (refer to Annex I for further information). Different failure

modes were evaluated, such as power loss or human error. The results were compared to those of the checklists and integrated when necessary in sections 3.3.1 and 3.3.2.

- Credible scenarios were grouped and screened for further analysis. Those scenarios are presented in section 3.4.
- The HAZOP study includes an evaluation of potential consequences and recommended safety measures (detailed in sections 4, 5 and 6). This is performed in an iterative and supplementary manner.

3.3. HAZARD ASSESSMENT AND SCREENING

3.3.1 Use of a checklist

The hazards identification, as stated above, was performed by using checklists [Ref. 15, 17] and the HAZOP study (refer to Annex I). The results are indicated in the table below.

Table 3.1. Risk Identification based on IAEA Checklists

Hazards and Initiating Events	Relevant for Planned Work	Relevant for Accidents	Comments
INTERNAL INITIATING EVENTS			
Radiological Initiating Events			
Criticality	N	N	Spent fuel removed before the start of cutting activities.
Spread of Contamination			
Loss of containment/barriers	Y	Y	• RPV/RVI cutting during planned activities. • The potential for unplanned cutting of non-intended areas is considered. However, in terms of loss of containment/barriers, this is not considered to pose a higher risk than during planned work. • Potential rupture of the contamination control envelope (airlock) or malfunction of filtration systems. • Potential rupture of the cavity liner due to drop of loads or the effect of the laser beam residual power. • Pressure increase inside the contamination control envelope due to laser air supply, potentially leading to contamination downstream filters. • Potential sublimation of ruthenium oxides to gaseous form from the contaminated surface during in-air laser cutting.
Dismantling of containment/barriers	Y	N	• RPV/RVI cutting during planned activities. • The potential for unplanned cutting of non-intended areas is considered. However, in terms of dismantling of containment/barriers, this is not considered to pose a higher risk than during planned work.

Hazards and Initiating Events	Relevant for Planned Work	Relevant for Accidents	Comments
Drop of radioactive materials, packages, and waste	N	Y	• RPV and RVI components may drop during movement to the cutting location (underwater), but this is out of the scope of this evaluation. • RPV/RVI pieces drop. Consequences may differ for underwater/in-air cutting configuration. • Packaged pieces may drop, but this is out of the scope of this evaluation. • Other potential drops of radioactive materials are case specific. I.e., drop of concrete cubes if part of the biological shielding needs to be removed for RPV/RVI cutting operations.
Clean-up of buildings (activated or contaminated)	Y	N	After cutting activities, the area should be cleaned.
External exposure			
Activated materials and equipment	Y	Y	• RPV/RVI (uncut, cut, and inside waste package) are highly activated. • The improper removal of shielding (i.e., water shielding loss) or the inadvertent entry into high radiation zones should be addressed.
Direct radiation sources	Y	Y	• RPV/RVI (uncut, cut, and inside waste package) are relevant sources of radiation. Other radioactive components in the operating areas should be considered (case-specific). • The improper removal of shielding (i.e., water shielding loss) or the inadvertent entry into high radiation zones should be addressed.
Internal exposure			
Physical and chemical state of the radioactive material	Y	Y	• Internal exposure due to aerosols dispersion during cutting activities. Consequences may differ for in-air/underwater laser cutting configurations. • Internal exposure due to contamination dispersion in case of accidents (i.e., drop loads).

Hazards and Initiating Events	Relevant for Planned Work	Relevant for Accidents	Comments
Contamination, corrosion, etc.			
Pathways (inhalation, ingestion)	Y	Y	• Inhalation due to aerosols dispersion during cutting activities. Consequences may differ for in-air/underwater laser cutting configurations. • Inhalation due to contamination dispersion in case of accidents (i.e., drop loads, failure of clean-up systems and equipment, etc.).
Contaminated materials	Y	Y	• RPV/RVI (uncut, cut, and inside waste package) are contaminated material. • Other contaminated materials are case specific. I.e., concrete cubes if part of the biological shielding needs to be removed for RPV/RVI cutting operations.
Gaseous Effluent	Y	Y	• Gas/aerosols generation during cutting activities. Effluents may differ for in-air/underwater laser cutting configurations. • For accidents, gas emissions will be assessed in terms of dose consequences (i.e., internal exposure).
Liquid Effluent	Y/N	N	• Liquid contamination due to cutting activities underwater. • Liquid effluents are not considered relevant for in-air cutting configurations. However, if a certain level of water is maintained below the cutting area, the water may become contaminated and this aspect may need to be addressed. • Potential rupture of the cavity liner. Other risks for potential cavity leakage are out of the scope of this assessment, as they are considered to affect the entire decommissioning project, to be case-specific, and not to be laser-cutting specific.
Non-Radiological Initiating Events			
Fire			

Hazards and Initiating Events	Relevant for Planned Work	Relevant for Accidents	Comments

Thermal cutting techniques (Zircalloy, etc.)	Y	Y	• For in-air cutting configurations, the residual power may be of concern.
			• For underwater cutting configurations, the risk related to the generation of hydrogen should be controlled and brought to negligible levels, as per the following:
			  • Very low production of H2 during the underwater cutting process, as shown in laboratory results (further detailed in this document). H2 monitoring will be included in the demonstrator for confirming with supporting data that the risk can be considered negligible.
			  • Availability of ventilation system that participates in the absence of local build-up of H2;
			  • The loss of ventilation which should lead to automatic stop of the laser cutting, supported with alarms for potential manual stop.
			• For in-air laser cutting, no Hydrogen production is foreseen, and neither its risk, as no water is present in the cutting process (thermolysis is negligible).
			• The laser generation module and laser head itself are potential sources of fire.

Decontamination process.	N	N	No decontamination activities are considered within the scope of this assessment.
Accumulation of combustible materials and radioactive waste	N	N	No relevant fire loads (other than the laser itself) are considered within the scope of this assessment.

Hazards and Initiating Events	Relevant for Planned Work	Relevant for Accidents	Comments

Flammable gases and liquids	Y	Y	• For underwater cutting configurations, the risk related to the generation of hydrogen should be controlled and brought to negligible levels, as per the following:
			  • Very low production of H2 during the underwater cutting process, as shown in laboratory results (further detailed in this document). H2 monitoring will be included in the demonstrator for confirming with supporting data that the risk can be considered negligible.
			  • Availability of ventilation system that participates in the absence of local build-up of H2;
			  • The loss of ventilation which should lead to automatic stop of the laser cutting, supported with alarms for potential manual stop.
			• For in-air laser cutting, no Hydrogen production is foreseen, and neither its risk, as no water is present in the cutting process (thermolysis is negligible).
			• If flammable hydraulic fluids are used in the robotic arm actuating the laser head, this risk should be considered.

Explosion			
Decontamination process	N	N	No decontamination activities are considered within the scope of this assessment.
Dust (graphite, Zircalloy, etc.)	N	N	Dust generation that may result in explosive atmospheres is not considered credible for RPV/RVI materials of a PWR/BWR.

Hazards and Initiating Events	Relevant for Planned Work	Relevant for Accidents	Comments

Radiolysis phenomena	Y/N	Y/N	• Radioactive waste disposal is out of the scope of this assessment.
			• For waste package filling, radiolysis phenomenon is not considered relevant.
			• For underwater cutting configurations, the risk related to the generation of hydrogen should be controlled and brought to negligible levels, as per the following:
			  • Very low production of H2 during the underwater cutting process, as shown in laboratory results (further detailed in this document). H2 monitoring will be included in the demonstrator for confirming with supporting data that the risk can be considered negligible.
			  • Availability of ventilation system that participates in the absence of local build-up of H2;
			  • The loss of ventilation which should lead to automatic stop of the laser cutting, supported with alarms for potential manual stop.
			• For in-air laser cutting, no Hydrogen production is foreseen, and neither its risk, as no water is present in the cutting process (thermolysis is negligible).

Compressed gases	Y	Y	• For underwater cutting configurations, compressed air is used for generating the air flow around the laser beam. • For in-air cutting configurations, an air flow is used to remove the cut particles.

Hazards and Initiating Events	Relevant for Planned Work	Relevant for Accidents	Comments
Explosive substances	Y/N	Y/N	• For underwater cutting configurations, the risk related to the generation of hydrogen should be controlled and brought to negligible levels, as per the following: • Very low production of H2 during the underwater cutting process, as shown in laboratory results (further detailed in this document). H2 monitoring will be included in the demonstrator for confirming with supporting data that the risk can be considered negligible. • Availability of ventilation system that participates in the absence of local build-up of H2; • The loss of ventilation which should lead to automatic stop of the laser cutting, supported with alarms for potential manual stop. For in-air laser cutting, no Hydrogen production is foreseen, and neither its risk, as no water is present in the cutting process (thermolysis is negligible).
Flooding			
Leak of liquid storage	N	N	Risks for potential cavity leakage are out of the scope of this assessment, as they are considered to affect the entire decommissioning project, to be case-specific, and not to be laser-cutting specific.
Leak of pipes	N	N	Leak of pipes is not considered relevant for the scope of this assessment.
Toxic and hazardous materials			
Asbestos/glass wool in thermal insulation system	Y/N	N	Asbestos and other hazardous insulation are usually removed prior cutting operations. This is usually performed under risk reduction/removal activities prior dismantling of RPV/RVI. However, it will be considered for conservative purposes.

Hazards and Initiating Events	Relevant for Planned Work	Relevant for Accidents	Comments
Lead in paint, shielding	Y/N	N	• For underwater cutting configurations, this is not considered relevant. • For in-air cutting configurations, residual beam power, distance of shielding and type of shielding material should be considered.
Beryllium and other hazardous materials	Y	N	Ozone, carbon oxides, nickel carbonyl, nitrogen oxide and toluene may be produced during cutting operations. Hexavalent chromium may be generated during cutting of stainless steel (RVI).
Polychlorinated biphenyls (PCBs)	N	N	This is not considered relevant for the scope of this assessment.
Pesticide use	N	N	This is not considered relevant for the scope of this assessment.
Biohazards	N	N	This is not considered relevant for the scope of this assessment.
Electrical hazards			
Loss of power supply	N	Y	This is considered relevant as it may result in loss of ventilation. In case of overall loss of power, the laser will stop. However, there might be situations where ventilation/filtration means were connected to different breakers/panels, and local loss of power could occur.
High voltage	Y/N	N	This may depend on the voltage used for the laser beam generation. It is considered that 400 V (3 phases) will be required.
Inadequately disconnected circuits/prevention against inadvertent connection	N	Y	Human errors are relevant in this regard, as it may result in accidents, such as electrocution.
Non-ionizing radiation hazards			

Hazards and Initiating Events	Relevant for Planned Work	Relevant for Accidents	Comments
Non-ionizing radiation sources (lasers, …)	Y	Y	Laser beam generation.
Electromagnetic radiation (e.g., microwaves)	N	N	This is not considered relevant for the scope of this assessment.
High intensity magnetic fields	N	N	This is not considered relevant for the scope of this assessment.
Working environment hazards			
Falling of heavy loads	N	Y	Falling of heavy loads may occur during laser system installation, laser system uninstallation, during RPV/RVI cut pieces handling, or a potential loss of structural integrity due to unintentional damage of components during laser cutting activities. Other drops of heavy loads are considered out of the scope, such as the potential relocation of the RPV/RVI components.
Falling loads on SSCs important for safety	N	Y/N	Falling of loads may occur during laser system installation, laser system uninstallation, during RPV/RVI cut pieces handling, or a potential loss of structural integrity due to unintentional damage of components during laser cutting activities. The potential for falling into SSCs important to safety is plant-specific and should be adjusted accordingly.
Falling loads on radioactive materials (packages)	N	Y	Falling of cut pieces into the waste package may occur during handling activities.
Collapse of structure (due to ageing)	N	N	This is not considered credible. A potential loss of structural integrity due to unintentional damage of components during laser cutting activities should be considered.
Demolition activities	N	N	This is considered out of the scope of this assessment.

Hazards and Initiating Events	Relevant for Planned Work	Relevant for Accidents	Comments
Working at heights	Y/N	Y/N	The need for working at heights is plant-specific and should be adjusted accordingly.
High noise area	Y	Y	Cutting activities may result in high noise due to equipment operation.
Inadequate illumination	N	N	This is not considered relevant for the scope of this assessment.
Inadequate ventilation	N	Y	This is considered relevant in case of accident (i.e., loss of ventilation).
Confined space	N	N	This is not considered relevant for the scope of this assessment.
Dangerous equipment, e.g. power tools, compressed gas cylinders, welding and cutting…	Y	N	Dangerous equipment may be used during installation and uninstallation of the laser system.
Excavations	N	N	This is not considered relevant for the scope of this assessment.
Vehicle traffic	N	N	This is not considered relevant for the scope of this assessment.
Pinch points, sharp objects	Y	N	Pinch points and sharp objects may be present during installation and uninstallation of the laser system.
Obstruction of passageways or exits	Y	Y	This factor is to be considered during installation of the laser system, its uninstallation, and during segmentation activities.
Physical hazards			
Kinetic energy	Y	Y	Kinetic energy may be present during installation and uninstallation of the laser system.

Hazards and Initiating Events	Relevant for Planned Work	Relevant for Accidents	Comments
Potential energy (springs, Wigner energy in graphite...)	N	N	This factor is not relevant to the specific scope of this analysis, since there are no springs, no graphite, and pipework components are not fixed in-situ.
Degraded or degrading structures, systems and components	N	N	Systems are considered to be in a good state of repair.
Steam	N	N	No systems in operation needing steam in the scope of this assessment.
Temperature extremes (high temperatures, hot surfaces, cryogenics)	N	N	This factor is not relevant to the specific scope of this analysis. Cutting activities will be performed remotely.
High pressure (pressurized systems, compressed air)	Y	Y	• For underwater cutting configurations, compressed air is used for generating the air flow around the laser beam. • For in-air cutting configurations, an air flow is used to remove the cut particles.
Human and organizational initiating events			
Operator error/violation	Y	Y	Human errors are a potential source of deviations from normal operating conditions.
Inadvertent entry into high-radiation areas	Y	Y	RPV/RVI are highly activated components.
Misidentifications	Y	Y	Misidentifications may cause inadvertent disconnection/operation of systems, incorrect waste packaging plan implementation, etc.

Hazards and Initiating Events	Relevant for Planned Work	Relevant for Accidents	Comments
Contractor and sub-contractor	Y/N	Y/N	This factor is site-specific and should be adjusted accordingly.
Performing incompatible activities	Y/N	Y/N	This factor is site-specific and should be adjusted accordingly. During segmentation activities, it is recommended to avoid performing parallel activities within the areas.
Disabling services to other facilities	Y/N	Y/N	This factor is site-specific and should be adjusted accordingly. Important systems for safety should be operative.
Poor ergonomic conditions	N	N	Laser system should be designed as to take into account ergonomic conditions.
EXTERNAL INITIATING EVENTS			
Earthquake	N	N	This factor is not relevant to the specific scope of this analysis. It should be considered in the safety analysis of the complete decommissioning process.
External flooding	N	N	See comment above.
External fire (oil storage, etc.)	N	N	See comment above.
Extreme weather conditions	N	N	See comment above.
Subsidence (formation of underground cavities from rain, waste degradation...)	N	N	See comment above.
Hazards due to industrial environment (explosion, etc.)	N	N	See comment above.
Airplane crash	N	N	See comment above.

Hazards and Initiating Events	Relevant for Planned Work	Relevant for Accidents	Comments
OTHER INITIATING EVENTS			
High temperature and pressure	N	N	This is not considered relevant for the scope of this assessment.
Corroded barriers	N	N	This is not considered credible.
Unknown or unmarked materials	N	N	This is not considered relevant for the scope of this assessment.

3.3.2 Separate identification of possible initiating events

Hazards and initiating events considered relevant for the segmentation activities were used as an input for the hazard analysis evaluation described in section 4.

Hazards and initiating events considered relevant for accidents were further screened to identify which scenarios required more in-depth analysis.

The following risks and initiating events were identified:

- Spread of contamination due to loss of containment/barriers

RPV/RVI cutting during planned activities may lead to a significant dose for workers and spread of contamination. Therefore, this hazard requires a detailed analysis from the point of view of radiological protection.

The potential for unplanned cutting of non-intended areas is considered. However, in terms of loss of containment/barriers, this is not considered to pose a higher risk than during planned work.

Additionally, the potential rupture of the cavity liner due to drop of loads or the effect of the laser beam residual power could result in loss of containment/barriers.

The potential rupture of the contamination control envelope (airlock) will be further evaluated, as the doses to workers and spread of contamination may be relevant. In this regard, airlock effectiveness could be reduced by a pressure increase due to laser air supply, which may essentially lead to contamination downstream filters.

The potential also exists for subliming ruthenium oxides from the contaminated surface by the effect of laser cutting (in-air only), and thus, the formation of metastable gaseous ruthenium tetroxide could then be a concern. The risk of spread of contamination is more complex for gaseous elements than aerosols, since HEPA filters may have limited efficiency. Main chemical elements likely to be present in the gaseous state of activity during laser cutting operations are caesium (Cs), strontium (Sr), plutonium (Pu) and ruthenium (Ru). However, due to vaporization or sublimation temperatures of these elements, only ruthenium sublimation is considered. The risk can be considered very low but it cannot be excluded [Ref. 1, 2].

- Spread of contamination due to dismantling of containment/barriers

RPV/RVI cutting during planned activities may lead to a significant dose for workers and spread of contamination. Therefore, this hazard requires a detailed analysis from the point of view of radiological protection.

The potential for unplanned cutting of non-intended areas is considered. However, in terms of dismantling of containment/barriers, this is not considered to pose a higher risk than during planned work.

- Spread of contamination due to drop of radioactive materials, packages, and waste

This hazard is relevant in case of accident. RPV/RVI cut pieces may drop, but the consequences may be different for the laser cutting configuration under water or in-air, as in the last case the contamination dispersion may be higher.

The drop of RPV/RVI components and packaged pieces can be other possible accidents, but they are considered out of the scope of this assessment.

Other possible drops of radioactive materials are specific to each case. For example, concrete cubes drop if it is necessary to remove part of the biological shielding for RPV/RVI cutting operations.

- Clean-up of buildings (activated or contaminated)

Cavities/pool where the cutting was performed shall be cleaned after activities finalization, and the concrete surfaces may be contaminated. Occupational doses for performing these activities will be considered, but no further analysis will be performed for the potential release of contaminants as not considered comparatively relevant. Typical equipment and cleaning methods include measures for preventing the spread of contamination, such as vacuum cleaners or wet cloths.

- External exposure due to activated materials and equipment

This hazard is relevant for normal cutting activities, since RPV/RVI are highly activated components.

No accident detailed analysis will be performed. Safety measures and controls will be in place to avoid high doses due to external exposure, such as radiation monitoring, water level (in the cavity/pool) monitoring, and ALARA program measures (remote operation, time reductions, installation of temporary shielding, etc.).

- External exposure due to direct radiation sources

This hazard is relevant for normal cutting activities, since RPV/RVI are highly activated and contaminated components. Other radioactive components in the operating areas should be considered (case-specific).

No accident detailed analysis will be performed. Safety measures and controls will be in place to avoid high doses due to external exposure, such as radiation monitoring, water level (in the cavity/pool) monitoring, and ALARA program measures (remote operation, time reductions, installation of temporary shielding, etc.).

- Internal exposure due to physical and chemical states of the radioactive materials

This hazard is relevant either in case of an accident or during planned segmentation activities. Aerosol dispersion during cutting activities leads to internal exposure, and the consequences may vary depending on whether the laser cutting configuration is underwater or in-air, as in last case the aerosol dispersion may be higher.

Internal exposure due to the dispersion of contamination in case of accidents (i.e., drop of loads) should be further evaluated.

- Contamination, corrosion, etc. – exposure pathways (inhalation, ingestion)

This hazard is relevant either in case of an accident or during planned segmentation activities. Aerosol dispersion during cutting activities leads to internal exposure, and the consequences may vary depending on whether the laser cutting configuration is underwater or in-air, as in last case the aerosol dispersion may be higher.

Internal exposure due to the dispersion of contamination in case of accidents (i.e., drop of loads) should be further evaluated.

- Contamination, corrosion, etc. due to contaminated materials

This hazard is relevant either in case of an accident or during planned segmentation activities because RPV/RVI are contaminated material.

Other contaminated material in the operating areas should be considered (case-specific). For example, if it is necessary to remove part of the biological shielding for RPV/RVI cutting operations the concrete cubes will be a source of contamination.

- Contamination, corrosion, etc. due to Gaseous Effluent

The generation of gaseous effluents or aerosols during cutting activities is considered relevant, due to the activated and contaminated material that may be dispersed during segmentation. The consequences may vary according to the in-air or underwater laser cutting configuration.

In the case of accidents, gas emissions will be also assessed.

- Contamination, corrosion, etc. due to Liquid Effluent

Liquid effluents due to underwater cutting activities will have to be managed, but its impact is not considered relevant for the total dose contribution. The generation of liquid effluents are not considered relevant for in-air cutting configurations. However, if a certain level of water is maintained below the cutting area, the water may become contaminated and this aspect may need to be addressed.

In the case of accidents, the potential rupture of the cavity liner is considered. Other risks due to possible leaks in the cavity are out of the scope of this assessment, as they are considered to affect the entire decommissioning project, which is specific to each case and not specific to laser cutting.

- Fire as a result of the use of thermal cutting techniques (Zircalloy, etc.)

This hazard is relevant in case of in air cutting configurations, when the residual laser beam together with inflammable materials (flexible collection system, flexible cables…) may be of concern.

In regards of the hydrogen generation in case of underwater cutting configurations, WP2 studies [Ref. 40] indicate that cutting of stainless steel will result in H_2 concentrations in the range of several hundreds of ppm (for the case of Delia vessel), which is several orders of magnitude lower than the 1 % typically tolerated value and much lower than H_2 lower flammability limit (4 %) (a scaling factor specific to each facility should be considered). Local built-up of Hydrogen is not considered credible due to air renewal flows for filtration purposes. The loss of ventilation should lead to automatic stop of the laser cutting, supported with alarms for potential manual stop. All the above should imply that risk related to the generation of hydrogen is controlled and brought to negligible levels.

H2 monitoring will be included in the demonstrator for confirming with supporting data that the risk can be considered negligible.

For in-air laser cutting, no Hydrogen production is foreseen, and neither its risk, as no water is present in the cutting process (thermolysis is negligible).

If cutting of other materials is considered (i.e., Zircaloy), the potential for hydrogen generation should be addressed. However, Zircaloy is not considered to be within the materials of the RPV and RVI.

In addition, the laser generation module and the laser head itself are potential sources of fire. In the same way, damage of the optical fibre may lead to the creation of hot areas that pose a risk of fire.

If the fire reaches the local HEPA filters, the captured radioactive material may be released, resulting in doses that should be further evaluated.

- Fire due to decontamination processes

No decontamination activities are considered within the scope of this assessment.

- Fire due to accumulation of combustible materials and radioactive waste.

No relevant fire loads (other than the laser itself) are considered within the scope of this assessment.

- Fire due to flammable gases and liquids

For hydrogen generation, see risk above.

If other materials different than steel or stainless steel is envisaged, the potential for flammable gases built-up should be addressed.

If flammable hydraulic fluids are used in the robotic arm actuating the laser head, this risk should be considered.

- Explosion as a result of decontamination process, and dust (graphite, Zircalloy, etc.)

These hazards are considered out of the scope and not credible to this assessment.

- Explosion as a result of radiolysis phenomena

This hazard is not considered relevant for in-air or underwater cutting configurations.

In regards of the hydrogen generation in case of underwater cutting configurations, WP2 studies [Ref. 40] indicate that cutting of stainless steel will result in H2 concentrations in the range of several hundreds of ppm (for the case of Delia vessel), which is several orders of magnitude lower than the 1 % typically tolerated value and much lower than H2 lower flammability limit (4 %) (a scaling factor specific to each facility should be considered). Local built-up of Hydrogen is not considered credible due to air renewal flows for filtration purposes. The loss of ventilation should lead to automatic stop of the laser cutting, supported with alarms for potential manual stop. All the above should imply that risk related to the generation of hydrogen is controlled and brought to negligible levels.

H2 monitoring will be included in the demonstrator for confirming with supporting data that the risk can be considered negligible.

For in-air laser cutting, no Hydrogen production is foreseen, and neither its risk, as no water is present in the cutting process (thermolysis is negligible).

If cutting of other materials is considered (i.e., Zircaloy), the potential for hydrogen generation should be addressed. However, Zircaloy is not considered to be within the materials of the RPV and RVI.

- Explosion as a result of compressed gases

Air flow is used for laser cutting, both in-air and underwater.

Pressure increase inside the reactor containment due to laser air supply is not considered realistic.

- Explosion due to explosive substances

For hydrogen generation, see risks above.

- Flooding due to leak of liquid storage, or leak of pipes

These hazards are not considered relevant for the scope of this assessment.

- Toxic and hazardous materials as Asbestos/glass wool in thermal insulation system

Asbestos and glass wool in thermal insulation system are usually removed before dismantling of RPV/RVI. However, they will be considered as a potential hazard.

- Toxic and hazardous materials as lead in paint, shielding

This hazard is not considered relevant for underwater cutting configurations.

Residual beam power, distance of shielding and type of shielding material should be considered for in-air cutting configurations.

- Toxic and hazardous materials as Beryllium and other hazardous materials

Ozone, carbon oxides, nickel carbonyl, nitrogen oxide and toluene may be produced during cutting operations. Hexavalent chromium (toxic) may be generated during cutting of stainless steel.

- Toxic and hazardous materials as Polychlorinated biphenyls (PCBs), Pesticide use and Biohazards

These hazards are not considered relevant for the scope of this assessment.

- Loss of power supply

Loss of power supply is considered relevant since it may result in loss of ventilation. In this case, operations should also be stopped, even if no loss of the laser beam occurs.

- High voltage

This risk will depend on the actual voltage used for the laser source. No high voltage is considered within this evaluation, since it is assumed to operate under 400 V (3 phases).

- Electrical hazards due to inadequately disconnected circuits/prevention against inadvertent connection

This hazard may be relevant because human errors may result in accidents, such as electrocution, loss of power and associated loss of ventilation or inadvertent laser beam generation.

- Non-ionizing radiation sources (lasers, ...)

Laser beam generation is a relevant risk during segmentation activities.

- Working environment hazards due to falling of heavy loads

This hazard may be relevant either in case of an accident or during planned segmentation activities, because falling of heavy loads may occur during laser system installation, laser system uninstallation, during RPV/RVI cut pieces handling, or a potential loss of structural integrity due to unintentional damage of components during laser cutting activities, resulting in personnel or equipment damage.

Falling loads may also result in contamination dispersion and associated committed doses, so further analysis is required.

- Working environment hazards due to falling loads on Structures, Systems and Components (SSCs) important for safety

This hazard should be considered to adequately planning the movement of loads as to avoid potential damage of SSCs important for safety.

- Working environment hazards due to falling loads on radioactive materials (packages)

This hazard may be relevant either in case of an accident or during planned segmentation activities. I.e., falling of cut pieces that may impact the waste package.

Falling loads may also result in contamination dispersion and associated committed doses, so further analysis is required.

- Working environment hazards due to working at heights

This hazard depends on specific work configurations. It is expected that working at heights may be a potential risk.

- Working environment hazards due to high noise area

This hazard may be relevant during planned segmentation activities. The consequences may be different for the laser cutting configuration in-air, as cutting activities may result in high noise, or underwater, as in this case is not considered relevant.

- Working environment hazards due to inadequate ventilation

This hazard may be relevant in case of accident (i.e., loss of ventilation). The consequences may be internal exposure for inhalation due to dispersion of contamination without adequate filtration, so further analysis may be required.

- Working environment hazards due to dangerous equipment, e.g., power tools, compressed gas cylinders, welding and cutting...

This hazard may be relevant during installation and uninstallation of the laser system if dangerous equipment needs to be used. The consequences may be material and/or personal damage.

- Working environment hazards due to pinch points, sharp objects

This hazard may be relevant during installation and uninstallation of the laser system. The consequences may be material and/or personal damage.

- Working environment hazards due to obstruction of passageways or exits

This risk may exist during planned activities, such as installation of the laser system, its uninstallation, and during segmentation activities. The work area should be designed as to do not obstruct passageways or exits.

- Physical hazards due to Kinetic energy

This hazard may be present during installation and uninstallation of the laser system.

- Physical hazards due to high pressure (pressurized systems, compressed air)

This hazard may be present due to the use of compressed air in the laser head.

- Human and organizational initiating events due to operator error/violation

Human errors are a potential source of deviations from normal operating conditions.

- Human and organizational initiating events due to inadvertent entry into high-radiation areas

This hazard is relevant because RPV/RVI are highly activated components, and it may result in significant external exposures. Safety controls should be in place to eliminate this risk.

- Human and organizational initiating events due to misidentifications

This hazard may be relevant because misidentifications may cause inadvertent disconnection/operation of systems, incorrect waste packaging plan implementation, etc. Cutting will be performed by two operators (double check).

- Human and organizational initiating events due to use of contractor(s) and sub-contractor(s)

The need to use of contractor(s) and sub-contractor(s) is site-specific and should be adjusted accordingly.

- Human and organizational initiating events due to incompatible activities

During segmentation activities, it is recommended to avoid performing parallel activities within the areas because the consequences may be material and/or personal damage, or the risk for internal exposure.

- Human and organizational initiating events due to disabling services to other facilities

This factor is site-specific and should be adjusted accordingly. This evaluation does not envisage disabled services. Important systems for safety should be operative.

- External initiating events and other initiating events:

External initiating events are not considered relevant to the specific scope of this analysis. They should be considered in the safety assessment of the complete decommissioning process.

3.4. OUTCOME OF HAZARD ANALYSIS AND SCREENING

Based on the hazard analysis (see section 3.3), the following radiological and non-radiological risks, for which safety measures should be in place, are identified:

Table 3.2. Summary of Risks identified

Hazard Type	Details
Radiological	
External Exposure	There are direct radiation sources in the working area, mainly, due to the highly activated components to be cut. Thus, external doses from normal planning activities should be evaluated. Besides, safety measures should aim to avoid the inappropriate removal of shielding (i.e., water shielding loss) or inadvertent entry into areas of high radiation.
Internal Exposure	Airborne releases will occur during cutting activities of the activated and contaminated components. Thus, committed doses from normal planning activities should be evaluated. Additionally, accidents may result in a significant spread of contamination, such as in case of drop of radioactive materials, fire, and explosions. These initiating events are further evaluated.
Effluents and secondary waste	Effluents (gas/liquids) and secondary waste generation should be considered, as this may result in doses to the public and to workers.
Non-Radiological	
Fire	Laser cutting, as a thermal cutting technique, involves a risk of fire for which safety measures should be in place (laser source, coupler, and laser beam and associated residual power. Additionally, fire may become an initiating event of radiological accidents, and so, it will be further analysed.
Explosion	Air flow is required for laser cutting. Additionally, explosion may become an initiating event of radiological accidents, and so, it will be further analysed.
Lead, Asbestos, etc.	Lead shielding may be used in the proximities of the components to be cut, and it may be impacted by the residual laser beam. If sufficient distance is provided between lead shielding and the laser head, this risk should be negligible. Other toxic substances are considered, such as asbestos, although it is acknowledged that they are usually removed before RPV/RVI segmentation activities start.
Other hazardous substances	Ozone, carbon oxides, nickel carbonyl, nitrogen oxide and toluene may be produced during cutting operations. Hexavalent chromium may be generated during cutting of stainless steel, for which safety measures should be in place.
Electrical hazards	400 V (3 phases) is assumed to be needed, for which adequate Health, Safety & Environment (HSE) measures should be in place, also to avoid inadvertent connection resulting in electrocution.
Laser beam and residual power	A powerful laser beam is used for laser cutting, which may result in personnel and equipment damage, including components around the cutting point. Safety controls should be in place to reduce the risk to ALARA.
Drop of heavy loads	Heavy loads are to be handled (i.e., cut pieces, laser system and manipulator components, etc.) which may result in personnel and equipment damage. Additionally, the drop of loads may become an initiating event of radiological accidents, and so, it will be further analysed.
Other industrial hazards	Working at heights, high noise areas, use of dangerous equipment (i.e., powered tools), pinch points and sharp objects, kinetic energy, compressed air (used for the laser head), etc. are risks of the activities, for which adequate safety measures should be in place.

For the screening of the events for further evaluation the following is considered:

- Radiological risks associated to normal segmentation conditions shall be evaluated within the scope of this document and cannot be screened out (refer to section 4.1).
- Non-radiological risks or initiating events that do not trigger radiological risks are screened out, as they are out the scope of the safety assessment. Those include the following: toxic material such as lead or asbestos and other hazardous substances, laser beam and residual power (since potential induced fire and drop of heavy loads are considered separately), and other industrial hazards.
- Safety measures and controls of frequent radiological risks involving external and internal exposure are usually addressed in the Radiation Protection Manual of the facility (i.e., access control, shielding, dosimeters, and other Radiation Protection (RP) procedures and controls), and thus, associated initiating events are screened out. Those include the following: inadvertent entry in high radiation or contaminated areas or inappropriate removal of shielding, and failures during waste handling.

As per the above, the following initiating events are identified for further evaluation:

- IE.1. Loss of local confinement and/or HEPA filtration during segmentation activities.
- IE.2. Fire or explosion/overpressure.
- IE.3. Drop of loads.

For ensuring completeness of accident scenarios, the above screened accidents were also compared to those included in other safety evaluations of similar RPV/RVI segmentation projects using conventional cutting techniques, and from those listed in NUREG-0586 [Ref. 54], which contains a list of radiological accidents that were considered for both PWRs and BWRs during decommissioning in early studies of NPPs decommissioning safety and cost.

4. HAZARD ANALYSIS EVALUATION

4.1. ANALYSIS OF NORMAL DECOMMISSIONING CONDITIONS

The radiological hazards resulting from the segmentation activities under normal conditions were evaluated considered the planned scenario detailed in section 2.5. The following was analysed:

- Occupational doses as a result of the activities within the scope of this document.
- Doses to the public based on main identifiable routes of exposure from the activities within the scope of this document.

4.1.1 Doses to workers

During the activities within the scope of this document, workers will be subject to radiation fields of the activated components to be dismantled and those from surrounding areas and components. Although the workers will be exposed to the risk of inhalation of radioactive aerosols generated during RPV/RVI laser cutting, the committed dose will be considered negligible based on the implementation of safety measures: remote cutting operation and, as needed, dust/aerosols collection system and local confinement and filtration. Dose constraints, as detailed in section 1.6 shall be met, and technical, organizational and personnel protection means shall be in place to reduce personnel doses to ALARA.

As per the above, occupational doses within this study correspond only to the external exposure. Safety measures as detailed in sections 6 and 7 shall be taken to control and reduce committed doses to negligible levels during the execution of the activities within the scope of this document. An additional evaluation of the committed dose is performed under certain assumptions (that is, considering some safety measures are not taken) to assess its need and justification (refer to Annex VI for further information).

Occupational doses from external exposures, as detailed in section 4.3.2, are calculated for the personnel involved in the work, accounting for the expected dose rates to which they will be subjected, and the time spent for performing the associated tasks. As described in section 2.5, the following activities are considered:

- Preparatory activities
- Remotely operated segmentation activities
- Post-segmentation activities

Doses are evaluated as described in section 4.3 for each segmentation activity, and this will facilitate the planning of tasks and, if needed, to optimize them from the safety point of view (i.e., involving more personnel, need for decontamination of the primary system, etc.) in order to meet the dose criterion of 20 mSv to individual workers, and to reduce doses to ALARA.

For minimizing doses, the ALARA program should consider, when needed, the measures listed in the following table. The implementation of those measures was assumed in the dose estimates.

Table 4.1. Typical Measures of an ALARA Program

EXTERNAL EXPOSURE	EXTERNAL/INTERNAL CONTAMINATION
• Access restrictions • Exposure time control • Use of remotely operated techniques • Use of fixed or mobile shielding, including underwater cutting (refer to section 2.5 for cutting conditions assumptions).	• Contamination close enclosures (airlock) • Integrated dust collection systems • Ventilation systems with HEPA filters • Personal protective equipment (clothing and respiratory protection) • Use of means for minimizing loose contamination

The estimated doses for planned conditions are summarized in the following table:

Table 4.2. Estimation of Occupational Doses in mSv

Personnel	PWR		BWR	
	RVI	RPV	RVI	RPV
Supervisor	3.40	6.02	5.83	8.47
Operator	3.82	7.79	7.34	11.33
Technician	5.41	9.06	8.93	12.60
RP Technician	5.41	9.06	8.93	12.60
Collective	127.16	221.88	203.54	290.55
Maximum Individual	5.41	9.06	8.93	12.60

The above occupational doses (refer to section A3.1.1 for calculation details), depend on the actual dose rates and the expended in working areas. For this purpose, the following is considered essential:

- Reducing dose rates in working areas by shielding optimization (including water level shielding the RPV/RVI) and by the evaluation of the benefits for implementing decontamination cycles to the primary system before segmentation activities begin. An increase of dose rates would have a similar effect in occupational doses.

- Reducing the time for performing the tasks, being critical those performed in high dose rate areas. For this reason, special attention should be given to the robustness of the laser system, considering its maintainability characteristics, for easing installation, maintenance, and removal for reuse, as well as the potential needs for repairs and replacements. An increase on the time devoted to maintenance and repairs in high dose rate areas will have a direct impact in occupational doses.

Since the segmentation process is assumed to be remotely, a relevant percentage of the occupational dose will result from preparatory and post-segmentation activities, and thus, the design should account for easy installation, uninstallation, and decontamination.

The above results may be contextualized by comparing them to the doses estimated to workers by the NRC [Ref. 53, 54], for which a 7-year decay period was considered.

- PWR-RPV: 176.8 mSv·person
- PWR-RVI: 639.9 mSv·person
- BWR-RPV: 350.5 mSv·person
- BWR-RVI: 1,122.2 mSv·person

Additional comparison can be performed to segmentation projects performed in other NPPs, as provided by EPRI [Ref. 8] and shown in Table 4.3.

Table 4.3. Comparison of Statistics from Various Plans, EPRI [Ref. 8]

NPP	RPV/RVI Activity (Bq)	Cutting Length (m)	Radiation Exposure (Sv-p)	Waste Volume (m^3)	Filtration Flowrate (lpm)
Yankee Rowe	3.4E+16	Segmented All Internals	1	All internals except Greater than Class C Waste shipped as waste	284
Conn Yankee	3.0E+16	550	2.05	35.4	950
Maine Yankee	7.4E+16	355	0.5	48	3,785
Songs Unit 1	1.4E+16	248	0.23	7.2	5,700
Rancho Seco	2.7E+15	Cut into Large Pieces	0.2	32	930-2,800

Committed doses due to inhalation are also calculated based on radioactive concentration on air (suspended aerosols from cutting activities) and time spent for performing the associated tasks, in case of implementing or not certain safety measures, systems, and controls (i.e., remote operation, dust/aerosols collection system, contamination envelope, etc.). Doses to workers due to ingestion, dermal uptake or open wounds are considered negligible in respect to the inhalation contribution, considering that usual Radiation Protection measures are in place. Committed doses are evaluated according to section 4.3.2, based on the generation of aerosols during cutting activities per the models of section 4.3.1. The results are summarized in the following table:

Table 4.4. Estimation of Committed Doses, in mSv, based on safety measures

Assumptions	PWR		BWR	
	RVI	RPV	RVI	RPV
Personnel in the area considering no filtration and contamination control means	3.33E+02	7.02E+00	1.23E+03	1.90E+03
Personnel in the area considering contamination control envelope	3.33E-01	7.02E-03	1.23E+00	1.90E+00
Personnel in the area considering dust/aerosols collection system	6.66E+01	1.40E+00	2.47E+02	3.81E+02
Personnel in the area considering dust/aerosols collection system and contamination control envelope	6.66E-02	1.40E-03	2.47E-01	3.81E-01

The above table is a conservative calculation of committed doses to workers in case they are continuously present at working area (but outside the local confinement). Additional measures such as remote operation with limit in stay times and radiation monitoring should bring committed doses to negligible levels following ALARA principles.

It is important to remark that safety controls will not only be aimed at worker dose reductions. The control of the contamination dispersion will also aim at reducing doses to the public and minimizing contamination of surfaces and equipment within the reactor building from airborne releases.

4.1.2 Doses to public

Doses to public resulting from the activities detailed in section 2.5 were calculated following the methodology of section 4.3.2. For this analysis, doses to public were assumed to be caused primarily by atmospheric discharges of radionuclides during segmentation, and thus, not considering water discharges. Potential End Users may perform a more detailed analysis based on specific plant conditions and as per their Offsite Doses Calculation Manual (ODCM).

For this evaluation, the following was assumed:

- Segmented pieces from RPV/RVI are put promptly into approved packages.
- Dust/aerosols collection system and contamination close enclosure HEPA filters are considered, but evaluations are also performed considering only building filtration.
- NPP ventilation with HEPA filtering system may or not may be operating.

The generation of aerosols during cutting is modelled as per section 4.3.1 and doses are calculated per the methodology detailed in section 4.3.2. The results for the critical individual (1 to 2-year-old infant) are summarized in the following table:

Table 4.5. Estimation of Doses to the public (critical individual at 100m), in mSv

Assumptions	PWR		BWR	
	RVI	RPV	RVI	RPV
No filtration means are considered (DT)	4.94E+01	7.82E-01	3.85E+01	4.37E+01
No additional measures are in place other than building filtration (DTb)	1.48E-02	2.34E-04	1.15E-02	1.31E-02
Considering a contamination control envelope and building filtration (DTcc)	1.93E-05	3.05E-07	1.50E-05	1.70E-05
Considering the dust/aerosols collection system and building filtration (DTcs)	2.97E-03	4.69E-05	2.31E-03	2.63E-03
Considering dust/aerosols collection system, contamination control envelope and building filtration (DTcc+cs)	8.89E-06	1.41E-07	6.92E-06	7.87E-06

4.1.3 Other Safety Concerns

4.1.3.1. Fire/Overpressure/Explosion

Fire and overpressure risks are identified in the hazards analysis. Fire can occur, for instance, because of the laser or the residual laser beam power or due to a potential presence of flammable hydraulic fluids in the robotic arm. Overpressure may occur from the use of the air supply for the laser cutting process.

Explosion is considered in the risk analysis, although no flammable materials are considered to be present in the segmentation process other than Hydrogen. In particular, the risk of fire/explosion caused by the generation of hydrogen could be considered controlled and brought to negligible levels. The generation peak shown in laboratory tests for stainless steel underwater cutting does not exceed 600 ppm (0.06%), which is 15 times lower to the 1% typically tolerated value and much lower than H2 lower flammability limit (4%) [Ref. 40]. Although the scaling factor of each facility should be considered, it is important to remark that typical large air volumes of the cutting environment and required air flows for contamination control make justifiable discarding any potential local build-up of hydrogen. The loss of ventilation should lead to automatic stop of the laser cutting, supported with alarms for potential manual stop. H2 monitoring will be included in the demonstrator for confirming with supporting data that the risk can be considered negligible.

Even if cutting tests revealed hydrogen very low production, laboratory tests are on-going by CEA (under the LD-SAFE Project, future update of D2.3 [Ref. 40]) to support the analysis and to understand the physicochemical mechanisms of hydrogen generation when cutting underwater SS304 by laser.

For in-air laser cutting, no Hydrogen production is foreseen, and neither its risk, as no water is present in the cutting process (thermolysis is negligible).

However, if underwater cutting of other materials such as Zirconium is considered (not addressed within the Generic Safety Assessment as it is not present in RPV/RVI of PWR/BWR), then adequate evaluations of hydrogen production shall be performed.

In the same line, if flammable materials are present in the cutting environment, then the risk of explosion shall be adequately addressed, and adequate safety measures and controls should be in place.

4.1.3.2. Residual Laser Beam

Due to the residual laser beam during in-air laser cutting, the risks of potential damage to structures and components not involved in the segmentation plan, fire, and release of toxic gases are identified.

It is important to remark that laboratory results showed damage to background structures due to the residual laser beam for in-air laser cutting. Damage to background structures and components not involved in the segmentation plan could result in unforeseen drop of loads due to loss of structural integrity, blockages interfering the segmentation process, pinching of components serving as a contamination barrier, etc. This issue shall be adequately addressed when defining a specific segmentation plan, ensuring any undesired damage to components and structures is evaluated and safety measures and controls are in place. In specific situations, laser absorbers or impact plates could be considered. For factilitating future evaluations of the risks associated to the residual laser beam, tests performed by CEA are on-going (under the LD-SAFE Project, future update of D2.1 [Ref. 38]) to estimate laser power density on Graphite and Stainless-Steel walls (characterization of the absorbed energy), and it is planned the development of an abacus for various laser cutting configurations.

The residual laser beam power for underwater cutting is considered negligible as per laboratory tests. Thus, this risk will depend in the actual cutting conditions (in-air vs. underwater), which should be optimized following ALARA principles:

- In-air cutting of RVI might not be the most suitable cutting condition due to potential dose rates, and so, this risk is not assessed here.
- Laser beam residual power might cause risks during in-air cutting of the RPV, for instance, potential damage of the liner of the Reactor Cavity (in case that reflooding would be necessary after cutting operations are finished) or of any other important component (i.e., components serving as contamination barrier).

The risks associated to the residual laser beam could be increased by a wrong positioning of the laser head before initiating the cut, as this phase is critical. This is also applicable to the final phase (end of cutting) when the component is completely cut. For these initial and final phases, special modulus for the laser cutting technology may be considered (i.e., reducing cutting power based on actual cutting condition). Human error minimization techniques and training should be in place.

For minimizing the risk associated to the residual laser beam, a relevant aspect is the optimization of the cutting speed. This speed should be the fastest as possible for reducing the impact on background structures, but without reducing the robustness of the laser cutting process. Adequate segmentation planning is essential for minimizing the risks related to the residual laser beam.

The following table provides and oversight on different cutting conditions and the associated risk:

Table 4.6. Oversight of different cutting conditions and the associated risks related to the Residual Laser Beam

Cutting Condition	Qualitative Evaluation of Risk	Comment
Cutting underwater (RPV or RVI)	Negligible	The residual laser beam power for underwater cutting is considered negligible as per laboratory tests.
RPV in-air cutting	Low-Intermediate	When cutting the RPV in-air, distances to background structures may be sufficient as to consider the associated risks low. However, attention should be paid as to avoid any pintching of a contamination containment barrier (i.e., SAS). If cutting the RPV is performed within the Reactor Cavity, pintching of the liner would not most probably have any operative implications, since reflooding of the cavity would not be further foreseen (RVI already dismantled).
RVI in-air cutting	High	Cutting of the RVI in-air would imply high risks associated to the residual laser beam, either from cutting/pintching the RPV but also as there is a potential to unintentionally cutting other pieces of the RVI, whih may imply unforeseen drop of loads due to loss of structural integrity or blockages interfering the segmentation process. It is important to remark that this cutting configuration is not considered recommended from radiation protection point of view, due to potential radiation fields.

4.1.3.3. Water Contamination

Water contamination due to segmentation activities shall be considered, as to define the necessary clean-up system requirements. In this regard, data may indicate that, as described in section 4.3.5.1, water may be contaminated with 2.65E+13 Bq, at a rate of 6.63E+12 Bq/h for a PWR and with

1.83E+13 Bq, at a rate of 4.58E+12 Bq/h for a BWR. if no clean-up systems are in place, water activity concentrations may reach, after 4 hours of uninterrupted cutting, 3.53E+10 Bq/m^3 for a PWR, and 2.44E+10 Bq/m^3 for a BWR.

This is also relevant in terms of particle suspension in water for maintaining proper visibility during cutting activities and as to minimize particle resuspension in-air because of the air injection flow. Adequate water clean-up systems should be in place to minimize these effects.

4.1.3.4. Secondary Waste Generation

Airborne releases and dross generation (refer to section 4.1.3.3) during RPV/RVI cutting will result in secondary waste (i.e., filters for airborne control and water clean-up systems, dross, etc.).

Special emphasis will be given to the deposition of molten metal on other surfaces as this may result in undesired upgrades of radioactive waste classification levels with difficult later decontamination solutions.

4.1.3.5. Attaching/Welding of Components

The risk associated to the potential attaching/welding of components during the laser cutting process is not considered of special relevance based on laboratory tests (for SS304 and when using air as assist gas), as the produced material is highly oxidized and easily removed.

4.2. ANALYSIS OF ACCIDENT SCENARIOS

Accident analysis considers the radiological consequences of potential accidents that may occur during the laser cutting of the RPV/RVI as per the scope of this document, including preparatory and post-segmentation activities.

The accident analysis does not cover expected doses from other normal decommissioning operations, on- and off-site chemical or toxic hazards, or other industrial hazards. External hazards are judged not to be relevant for the scope of the activities analysed within this document.

The process followed for the analysis of accident scenarios is as follows:

- Assessment of unmitigated consequences based on stated hypothesis.
- Identification of minimum number of independent and complete safety measures as per defence-in-depth criteria.
- Recommendation of safety controls to meet the defence-in-depth criteria and to reduce the risks to ALARA.

The detailed analysis of accident scenarios is included in Annex IV, with summary results in Table 4.7. The results show high unmitigated potential consequences for scenario IE.2 (Fire or explosion -mainly driven by the potential burning of HEPA filters-), relatively moderate unmitigated potential consequences for scenario IE.1 (Loss of local confinement and/or HEPA filtration during segmentation activities), and relatively low unmitigated potential consequences for scenario IE.3 (Drop of loads).

it is considered that no numerical frequency or probabilistic analysis are needed. Examples of frequencies of occurrence, based on expert judgement, are provided in NUREG/CR-0130 [Ref. 48] and NUREG/CR-0672 [Ref. 49], as well in Annex VII. Main conclusions from the accident analysis are described in section 7, including recommended procedural and engineered safety controls and outstanding issues. Recommendation on prevention, detection and mitigation safety measures are also provided for each accident scenario in Annex VI.

Table 4.7. Estimation of doses to the public and workers, in mSv, for the screened accident scenarios

Accident Scenario		Doses	PWR		BWR	
			RVI	RPV	RVI	RPV
IE.1. Loss of local confinement and/or HEPA filtration during segmentation activities.		Public	2.56E-04	5.36E-08	8.23E-05	7.79E-05
		Workers	3.18E+01	1.39E-02	1.13E+01	1.68E-02
IE.2. Fire or explosion[4].	Estimation Option 1	Public	1.48E-04		3.24E-05	
		Workers	2.21E+02		2.68E+01	
	Estimation Option 2	Public	1.48E-04		3.24E-05	
		Workers	3.90E+02		4.71E+01	
IE.3. Drop of loads.	Estimation Option 1	Public	6.52E-08	2.69E-07	1.78E-07	8.03E-07
		Workers	7.66E-02	4.36E-01	2.07E-01	1.29E+00
	Estimation Option 2	Public	6.52E-08	2.69E-07	1.78E-07	8.03E-07
		Workers	2.71E-02	1.54E-01	7.34E-02	4.55E-01

4.3. MODELLING AND CALCULATION OF CONSEQUENCES

4.3.1 General input data

4.3.1.1. Calculation of radioactive material release during cutting activities

When a component is cut in two pieces, a certain volume of the central part is removed, some will fall to the floor, some may migrate to water (for underwater cutting) and the rest will be released to the air.

[4] Fire or explosion event limits the potential radiological inventory of HEPA filters. Refer to Annex IV for further information.

Thus, releases can be calculated based on activity concentrations, size of kerf, and dispersion/migration factors.

For activated material, activity concentrations are considered homogenous within the component, and releases can be calculated with any of the two equations:

$$Aair_i = \sum Cv_{i,j} \cdot th_j \cdot l_j \cdot w_j \cdot fa_{i,j} \qquad \text{Eq. 4.1.}$$

$$Aair_i = \sum Cm_{i,j} \cdot th_j \cdot l_j \cdot w_j \cdot \rho_j \cdot fa_{i,j} \qquad \text{Eq. 4.2.}$$

Where:

- $Aair_i$ is the activity released to the atmosphere for each radionuclide (i), in Bq.
- $Cv_{i,j}$ is the specific activity (Bq/cm^3) for each radionuclide (i) and component (j), as per section 2.3.
- $Cm_{i,j}$ is the specific activity (Bq/g) for each radionuclide (i) and component (j), as per section 2.3.
- th_j is the component thickness, in cm.
- l_j is the length of the cut, in cm.
- w_j is the width of the cut, that will depend on the cutting technology used, in cm.
- ρ_j is the density of the component, in g/cm^3.
- $fa_{i,j}$ is the dispersion factor to the air for each radionuclide (i) and component (j).

For contaminated material, activity concentrations are considered to be uniformly distributed in the surface of the component, and releases can be calculated with the following equation:

$$Aair_i = \sum Cs_{i,j} \cdot l_j \cdot w_j \cdot fa_{i,j} \qquad \text{Eq. 4.3.}$$

Where $Cs_{i,j}$ is the specific activity in Bq/cm^2 for each radionuclide (i) and component (j). In the case of the RVI components, both sides of the component will be considered contaminated, and thus, the activity released to the air will be multiplied by 2. RPV components will be considered to be only contaminated internally.

Similar equations could be used for calculating activity migration to water, by using the associated migration factor ($fw_{i,j}$).

The above equations will be slightly simplified within this evaluation. The total mass released to the air will be calculated based on the aerosol mass flow rate generation (Amfr) obtained under WP2 and compiled in D4.2 [Ref. 43], and using estimated cutting times (Tc, in hours) from section 2.5. Thus, activity released to the air will be calculated assuming the following:

$$Aair_i = \sum Cv_{i,j} \cdot \frac{1}{\rho_j} \cdot Amfr \cdot Tc \qquad \text{Eq. 4.4.}$$

$$Aair_i = \sum Cm_{i,j} \cdot Amfr \cdot Tc \qquad \text{Eq. 4.5.}$$

$$Aair_i = \sum Cs_{i,j} \cdot \frac{1}{\rho_j} \cdot 1/th_j \cdot Amfr \cdot Tc \qquad \text{Eq. 4.6.}$$

The following values for aerosol mass flow rate generation[5] are considered:

- For underwater laser cutting, 0.93 mg/s considering a water depth of 5 m.
- For in-air laser cutting, 3.41 mg/s.

Eq. 4.4 and Eq. 4.5 are used for activity release from activated materials (with activity in Bq/cm^3 or Bq/g, respectively) and Eq. 4.6 from contaminated materials.

End Users could consider the adaptation of aerosol mass flow rate generation for each specific situation based on the information of D2.2 [Ref. 42] and the models developed by CEA [Ref. 44].

4.3.1.2. Collection and Filtration Means

Airborne releases may be reduced by collection and filtration means. The following may be considered:

- Building filtration, for offsite gaseous discharges, will be assumed to have an efficiency of 99.97%. This will be considered in all estimations of doses to the public under normal conditions.
- Local dust/aerosols collection system will be assumed to have an effectiveness of 80% (in-air), and the advantage of not dispersing the contamination within the contamination control envelope. For underwater cutting, the effectiveness of the collection system (above water extraction hoods or spray system) has not been tested and it might be assumed to be lower to that of the in-air configuration. However, as the total collection effect will be supported by the scrubbing effect of the water, 80% will also be assumed.

[5] As per D4.2 [Ref. 43], the aerosol mass flow rate generation is adjusted to only consider the mass released from the components being cut. That is, the total mass flow rate generation obtained in laboratory tests is adjusted with a factor obtained from physico-chemical analysis based on the contribution of the metallic components to the total mass (since, among others, aerosols may be in the form of oxidized compounds). That is:

- For underwater laser cutting, the total mass flow rate generation is of 1.65 mg/s. This is adjusted with the corresponding factor of 5.63E-01, resulting in a release of 0.93 mg/s from the components being cut.
- For in-air laser cutting, the total mass flow rate generation is of 6.70 mg/s. This is adjusted with the corresponding factor of 5.09E-01, resulting in a release of 3.41 mg/s from the components being cut.

Direct connection to the building exhaust is assumed (no impact to workers). The local exhaust is filtered before its connection. The remaining 20% would be dispersed into the reactor building and managed by the building ventilation system. This would result in an estimated overall filtration for the public of 99.9940% [6], considering the two different pathways (through direct exhaust and working environment) after building exhaust filtration.

- Contamination control envelope will consider that 99.9% of the released material can be contained, 0.1% of the material will leak without filtration to the reactor building. A filtration of 99.97% can be achieved in the contamination control envelope, with subsequent direct connection to the building exhaust (no impact to workers). This would result in an estimated overall filtration for the public of 99.9970% [7], considering the two different pathways (through direct exhaust and working environment) after building exhaust filtration.

  Note: NUREG/CR-0130 [Ref. 48] refers to leak ratios from 0.1 to 10%. As it is considered that negative pressure is necessary by adjusting dynamic air flows (refer to Annex VI for further information), the lowest value will be assumed.

- Combining the local dust/aerosols collection system and contamination control envelope will result in an overall filtration to the working environment of 99.98% (100% - 20% x 0.1%), since the contamination within the contamination control envelope will be reduced by the effect of the local dust/aerosols collection system, and so, reducing the activity leaking into the reactor building[9]. For the public, this would result in an estimated overall filtration of 99.9994% [10], considering the two different pathways (through direct exhaust and working environment) after building exhaust filtration.

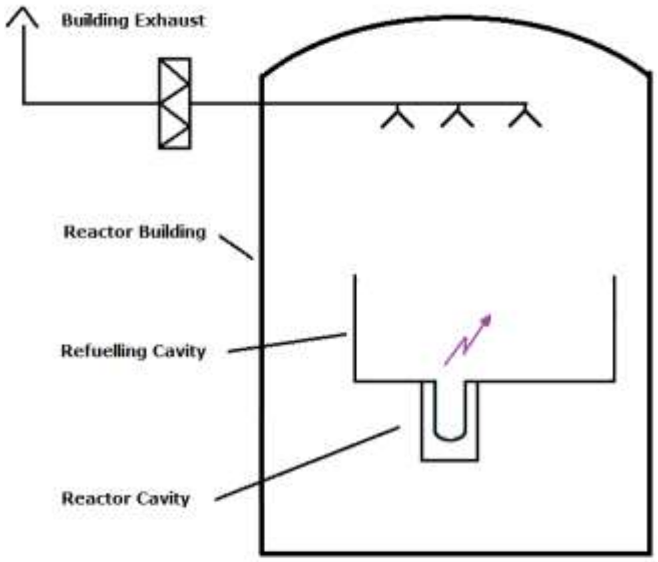
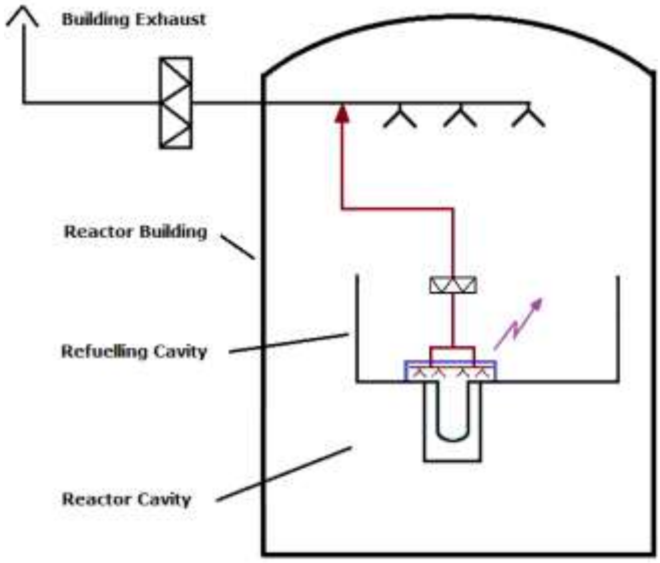
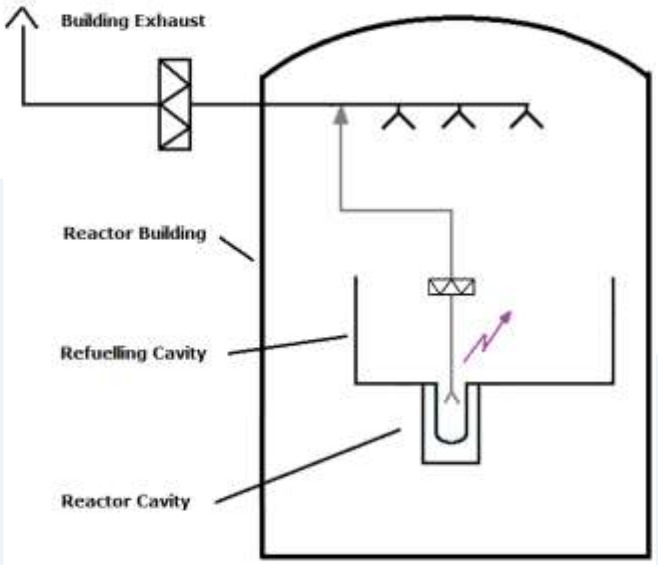
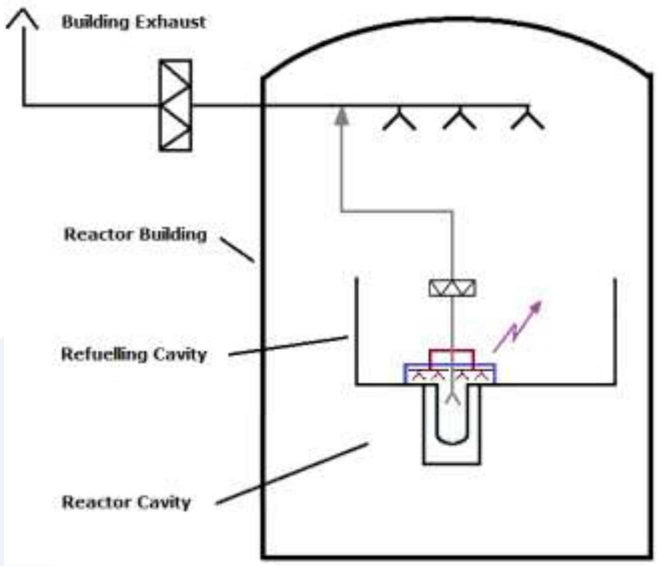
The above collection and filtration means are synthetized in Figure 4.1.

[6] Through direct exhaust before building exhaust filtration: 80% x (100% - 99.97%). Through working environment before building exhaust filtration: 20%. Total overall filtration after building exhaust filtration:
100% - [80% x (100% - 99.97%) + 20%] x (100% - 99.97%) = 99.9940%.

[7] Through direct exhaust before building exhaust filtration: 99.9% x (100% - 99.97%). Through working environment before building exhaust filtration: 0.01%. Total overall filtration after building exhaust filtration:
100% - [99.9% x (100% - 99.97%) + 0.1%] x (100% - 99.97%) = 99.9970%.

[9] The same approach could be considered for underwater cutting. For instance, by using an overall push and pull filtration system for the contamination control envelope supported by above water extraction hoods.

[10] Through direct exhaust before building exhaust filtration: (80% + 20% x 99.9%) x (100% - 99.97%). Through working environment before building exhaust filtration: 20% x 0.1%. Total overall filtration after building exhaust filtration:
100% - [[80% + 20% x 99.9%] x (100% - 99.97%) +20% x 0.1%] x (100% - 99.97%) = 99.9994%.

In-air cutting with no confinement systems	In-air cutting with contamination control envelope
	
In-air cutting with local collection system	**In-air cutting with contamination control envelope supported by local collection system**
	

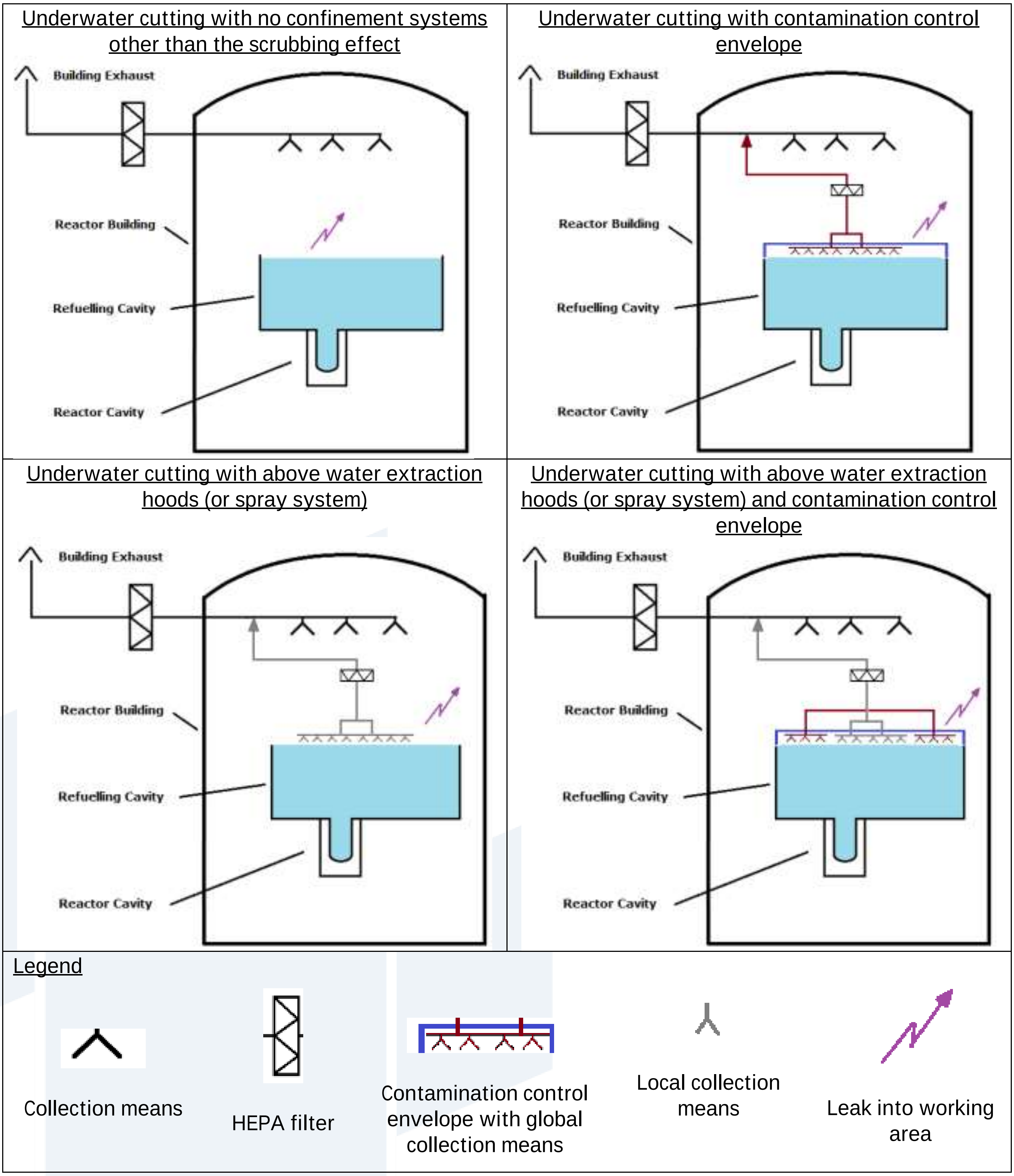


Figure 4.1. Diagrams of Collection and Filtration Systems

4.3.2 Doses to workers and to the public

Modeling of doses to workers and to the public is detailed in Annex III.

4.3.3 Dispersion Factors

For estimating atmosphere dispersion, Gaussian models are used as per the U.S. Regulatory Guide (RG) 1.145 [Ref. 49]. Procedures for calculating dispersion factors (X/Q) depend on the mode of release, that is, release through vents or other building penetrations (hereinafter referred as release at 10 m) and stack releases. For the purpose of this generic evaluation, dispersion factors for releases at 10 meters will be considered, as the results are more conservative (since it implies less atmospheric dispersion).

For this mode of release, the set of meteorological conditions for stable conditions will be used (considering the conservative values of 1 m/s and F stability class as per section 2.1). Dispersion factors will be determined using the following set of equations:

$$\frac{X}{Q} = \frac{1}{\overline{U_{10}}\cdot(\pi\cdot\sigma_y\cdot\sigma_z+A/2)} \qquad \text{Eq. 4.7.}$$

$$\frac{X}{Q} = \frac{1}{\overline{U_{10}}\cdot(3\cdot\pi\cdot\sigma_y\cdot\sigma_z)} \qquad \text{Eq. 4.8.}$$

$$\frac{X}{Q} = \frac{1}{\overline{U_{10}}\cdot(\pi\cdot\Sigma_y\cdot\sigma_z)} \qquad \text{Eq. 4.9.}$$

Where:

- X/Q is the dispersion factor, in s/m^3.
- U_{10} is the wind speed at 10 meters above plant grade, in m/s.
- σ_y is the lateral plume spread, in m, which can be obtained from figure 1 of the RG [Ref. 50]
- σ_z is the vertical plume spread, in m, which can be obtained from figure 2 of the RG [Ref. 50]
- Σy is the lateral plume spread with meander and building wake effects, in m, which can be obtained based on parameter M (figure 3 of the RG [Ref. 50]). For distances of 800 meters or less, $\Sigma y = M\cdot\sigma_y$, and for distances greater than 800 meters, $\Sigma_y = (M - 1)\cdot \sigma_{y800m} + \sigma_y]$
- A is the smallest vertical-plane cross-sectional area of the reactor building, in m^2. It will be considered as 1,000 m^2.

As per RG 1.145 [Ref. 50], X/Q values should be calculated using Equations 4.7, 4.8, and 4.9. The values from Equations 4.7 and 4.8 should be compared and the higher value selected. This value should be compared with the value from Equation 4.9, and the lower value of these two should then be selected as the appropriate X/Q value.

The results are summarized in the following table:

Table 4.8. Estimation of Dispersion Factor, X/Q, per RG 1.145 [Ref. 50]

Calculation Distances (m)	100	250	500	1,000
Wind speed (m/s)	1	1	1	1
Stability Class	F	F	F	F
σy (m) (Fig.1)	4	10	20	40
σz (m) (Fig.2)	2.5	5	8.5	15
M (Fig.3)	4	4	4	4
Σy (m)	16	40	80	130
A (m2)	1000	1000	1000	1000
X/Q (s/m^3) (1)	1.88E-03	1.52E-03	9.67E-04	4.19E-04
X/Q (s/m^3) (2)	1.06E-02	2.12E-03	6.24E-04	1.77E-04
X/Q (s/m^3) (3)	7.96E-03	1.59E-03	4.68E-04	1.63E-04
X/Q (s/m^3)	7.96E-03	1.59E-03	4.68E-04	1.63E-04

4.3.4 Doses in accident scenarios

Doses calculated to workers during accident scenarios will be estimated as indicated in Annex III, A3.1.2, based on the accident specific release.

For estimating doses to the public, the following process will be followed for each accident scenario:

- The activity (accident specific) released to the air will be subsequently released through the off-gas, for which associated filtration is considered.
- The activity will be dispersed up to the location of the group of the public considering meteorological conditions and associated dispersion factors, as per section 4.3.3.
- Doses will be calculated using dose coefficients of each group of the public, and thus, identifying the critical individual, following the same dose modelling of Annex III, A3.2.

4.3.5 Modelling of other Hazards

Due to the special relevance, certain hazards will be modelled to identify potential safety concerns. This is the case of water contamination.

4.3.5.1. Water Contamination for Underwater Cutting

Water contamination will occur during underwater cutting of activated and contaminated materials. For this evaluation, the following will be assumed:

- According to Eq. 4.1, particle release will depend on size of kerf (width of cut). This varies with cutting parameters [Ref. 3]. An approximate value for the size of kerf of 1 mm will be considered.
- As no additional information is available, it will be considered that 100% of material of kerf is contained by the water. This is quite conservative as many of the material will remain attached to the cut pieces.
- Most activated RVI components will be considered. This implies:
  - Cv_i (Bq/cm^3) for each radionuclide (i) of Core Shroud will be assumed (Table 2.1 for PWR Table 2.7 for BWR). That is in total, 4.650E+10 Bq/cm^3 for PWR, and 2.495E+10 Bq/cm^3 for BWR.
  - Thickness of RVI shroud plates of a PWR: 1.9 cm.
  - Thickness of RVI shroud plates of a BWR: 5.1 cm.
  - For the length of cut, 4 hours of uninterrupted cutting will be considered at cutting speeds of section 2.5.2 (Table 2.12 for PWR, Table 2.13 for BWR). That is, 3000 cm for a PWR at a rate of 12.5 cm/min, and 1440 cm for a BWR at a rate of 6 cm/min.
- Contamination nuclides of the shroud is considered negligible in comparison with its activation.

Applying Eq. 4.1, and after 4 hours of uninterrupted cutting of the core shroud, water contamination could reach the following if water filtration is not implemented:

- 2.65E+13 Bq, at a rate of 6.63E+12 Bq/h for a PWR.
- 1.83E+13 Bq, at a rate of 4.58E+12 Bq/h for a BWR.

The volume of the cutting cavity will be assumed to be of approximately 750 m^3 [Ref. 48], for both the Refuelling Cavity (PWR) and Dryer/separator Storage Pool (BWR). This implies that if no clean-up systems are in place, water activity concentrations may reach, after 4 hours of uninterrupted cutting, 3.53E+10 Bq/m^3 for a PWR, and 2.44E+10 Bq/m^3 for a BWR.

5. ENGINEERING ASSESSMENT

5.1. ENGINEERING ASSESSMENT METHODOLOGY

As provided in sections 1.6.3 and 4.2, engineered control measures (safety structures, systems, and components - SSCs-) are identified based on defence-in-depth criteria and to reduce the risks to ALARA.

For the identified engineered safety measures, performance requirements should be specified and demonstrated.

As provided by the IAEA [Ref. 17], SSCs are usually categorized based on their relative importance, which aims at implementing a graded approach in their implementation and maintenance. Although this evaluation is based on a deterministic approach, and thus, SSCs categories are not needed, the following categorization scheme will be used as it may provide useful information [Ref. 17]:

- Category 1: mitigation of potential consequences greater than 250 mSv to workers or greater than 10 mSv to the public.
- Category 2: mitigation of potential consequences between 20 and 250 mSv to workers or between 0.1 and 10 mSv to the public.
- Category 3: mitigation of potential consequences between 2 and 20 mSv to workers or between 0.01 and 0.1 mSv to the public.
- Category 4: mitigation of potential consequences lower than 2 mSv to workers or lower than 0.01 mSv to the public.

Other categorizations may be used by Potential End Users, based on their actual practices. In any case, defence in depth should be applied, and physical barriers should be effectively maintained as to separate radioactive sources from workers, the public and the environment.

5.2. ENGINEERING MEASURES DERIVED FROM THE GENERIC SAFETY ASSESSMENT

As per the evaluation, the SSCs listed in Table 5.1 were identified.

Table 5.1. Safety Structures, Systems, and Components (SSCs)

ID.	SSCs Description	Category	Performance Requirements	Associated Risk
1	Fire detection and mitigation systems within the Building	2	To detect and mitigate a fire within the reactor building and laser source/coupler deployment areas. To alarm in case of fire.	Fire and Explosion

ID.	SSCs Description	Category	Performance Requirements	Associated Risk
2	Dust/aerosols collection system	2	In-air cutting: To locally collect and filtrate airborne releases with a high efficiency. To alarm in case of malfunction (filters differential pressure, high activity levels after filters, low flowrate in hoses…). Underwater cutting: To push down back airborne releases (if sprays are used) or to collect airborne activity with filtration systems.	Airborne Releases / Internal contamination
3	Local Contamination Confinement (airlock) with Filtration	2	To confine airborne releases with low level leak. To filtrate the air with high level efficiency. To obtain an adequate air renovation through ventilation. To connect exhaust to building off-gas. To alarm in case of malfunction (filters differential pressure, high activity levels after filters, low flowrate in hoses…).	Airborne Releases / Internal Contamination Hexavalent Chromium (cutting of Stainless Steel)
4	Area Radiation Monitoring (i.e., Ambient gamma dose rate control)	2	To detect deviations from expected radiation levels. To alarm in case of high radiation levels.	External Exposure Airborne Releases / Internal Contamination
5	Building Filtration	4	To filtrate gaseous discharge. To alarm and isolate in case high radioactive releases occur.	External Exposure and Internal Contamination of Public due to normal and accident conditions
6	Water level monitoring	3	To detect and alarm in case of water loss.	External Exposure Water Contamination
7	Electrical cable in the fibre	3	To detect fibre rupture and automatically stop the laser source.	Fire
8	Protection of cavity floor (i.e., plates).	4	To protect the cavity liner from heavy load drop or the residual laser beam.	Loss of shielding / containment / barriers during Handling of Components
9	Auxiliary water filtration systems	4	To recirculate and filtrate cavity water to achieve a determined specific activity.	Water contamination

ID.	SSCs Description	Category	Performance Requirements	Associated Risk
10	Effluents Monitoring (flowrate, activity)	4	To alarm in case of high activity releases and isolate the discharge.	Effluents (gas/liquids)
11	Other RP safety measures: Shielding, Dosimeters, Respiratory Protection…	4	To protect workers from radiation exposure, as necessary, to alarm in case of high external exposure, etc.	External Exposure and Internal Contamination (to be ALARA), i.e., during tasks to be performed locally
12	Closed laser environment or shielding by double bend	N/A	To protect workers from direct laser beam or its reflection.	Loss of control of laser beam or associated residual power.

Potential End Users should review the availability of such SSCs at their facility, and their compliance with functional and performance requirements. Other SSCs may be selected if found to provide similar protection to workers, the public and the environment.

6. EVALUATION OF RESULTS AND SAFETY MEASURES

6.1. COMPARISON OF ANALYSIS RESULTS WITH CRITERIA

The criteria used within this evaluation is detailed in section 1.6. Table 6.1 compares the criteria with the results of the assessment (refer to section 4). As it can be observed, the results indicate the compliance with the criteria during normal conditions if adequate contamination control arrangements are in place.

Table 6.1. Comparison of Safety Criteria and Evaluation Results for Normal Conditions

Criterion	Value	Generic Safety Assessment Output
Worker dose (Max. Individual[12])	20 mSv/y	PWR/RVI: 5.41 mSv/y PWR/RPV: 9.06 mSv/y BWR/RVI: 8.93 mSv/y BWR/RPV: 12.60 mSv/y
Public dose (constraint) (critical individual at 100m)	0.3 mSv/y	PWR/RVI: 8.89E-06 mSv/y PWR/RPV: 1.41E-07 mSv/y BWR/RVI: 6.92E-06 mSv/y BWR/RPV: 7.87E-06 mSv/y

[12] It only considers external exposure. The values of the table should be optimized following ALARA principles. Committed doses are considered negligible as described in section 4.1.1.

The results of the generic safety assessment show safety measures such as contamination containment and collection system (DT cc+cs), following the recommendations of Annex VI, are to be implemented for meeting dose limits.

In case of accident conditions, unmitigated potential consequences of two scenarios are over 20 mSv for the workers and 1mSv for the public, and so, they require adequate number of safety measures to be in place for mitigating the consequences:

- For detecting and mitigating IE.1. Loss of local confinement and/or HEPA filtration during segmentation activities, adequate area radiation monitoring, remote operation, building containment/filtration and other safety measures could be implemented to mitigate the potential consequences.
- For detecting and mitigating IE.2. Fire or explosion (mainly driven by the potential burning of HEPA filters), adequate fire detection and suppression systems should be in place, as well as other measures to reduce the potential for a fire (control of fire loads, adequate laser design, etc.).

These results should be understood as an indication of the level of safety that can be achieved during RPV and RVI segmentation using the laser cutting technology. However, main assumptions and uncertainties described in section 6.2 should be addressed, as to guarantee the so-called "safe envelope" of the generic safety assessment.

6.2. TYPES OF AND TREATMENT OF ASSUMPTIONS AND UNCERTAINTIES

Due to the inherent characteristics of this evaluation, that is, a generic case with generic data, the number of assumptions and uncertainties are high.

Uncertainties associated with data and assumptions made to generate the boundary conditions of this evaluation will not be considerably reduced within this project, as they should be based on plant specific information. However, boundary conditions aim at providing a safe envelope as to demonstrate safety under usual plant conditions and laser cutting configurations. Additionally, notes, remarks and comments are available so Potential End Users may adjust the generic information to their actual conditions and configurations, and thus, eliminating the associated uncertainties.

Major sources of uncertainties with the associated impact on the evaluation are detailed in Table 6.2. The means for reducing the associated uncertainties are identified.

Table 6.2. Major Sources of Uncertainties

Source of Uncertainty	Origin	Major Impact	Uncertainty Reduction Mean
Radioactive Inventory and Segmentation Plan	Generic study	Dose estimations during normal and accident conditions. Water contamination. Safety measures.	Adjustment to End Users conditions
Hydrogen generation	Preliminary data	Risk and safety measures. Wave shock estimations.	Final Laboratory Test Results (WP2)
Laser Beam Residual Power	Preliminary data	Risk and safety measures.	Final Laboratory Test Results (WP2)
Laser cutting performances (cutting speed, kerf)	Preliminary data + Generic Study	Doses during normal and accident conditions. Safety measures.	Updated information in later stages of the project (WP5) Adjustment to End Users conditions
Cutting Configurations (in-air/underwater, cutting location, personnel, airborne control means, etc.)	Generic study	Dose estimations during normal and accident conditions. Water contamination. Other risks. Safety measures.	Updated information in later stages of the project (WP5) Adjustment to End Users conditions
Dose to the public modelling	Generic Study	Doses during normal and accident conditions (gaseous and water discharges). Note: conservativism provides a "safe envelope".	Adjustment to End Users conditions

6.3. RECOMMENDATION OF SAFETY CONTROL MEASURES

Based upon previous decommissioning cutting experiences, Table 6.4 summarizes aspects to be considered in the laser cutting technology implementation. Those aspects have been analysed from a generic perspective, but Potential End Users should ensure that are addressed in their specific case. Two aspects should be considered:

- The laser cutting system itself, which shall be designed considering operational safety, regardless of the components to be cut and the specific plant conditions. For this, safety provisions should be in place, such as:

- Operation of the equipment by at least two persons (operator and supervisor) for implementing double verifications during cutting activities.
- Manual (and not automatic) trigger of the laser beam, requiring a continuous and deliberate action from the operator (if the trigger is stopped, the laser beam will be switched off).
- Availability of emergency stop buttons (manually and automatically triggered). Automatic shutdown is recommended for the parameters listed in Table 6.3.
- Fire control, avoiding the storage of burnable material close to the laser source, coupler and fibre.
- Fibre protections from physical damage such as crushing, squeezing, shocks and tearing.
- Protection from the laser beam. The laser head shall be placed in a closed environment or shielded by a double bend. Because of the power of the laser, even reflected light can potentially be harmful to the personnel exposed.
- Equipment and tools shall be designed in order to facilitate maintenance activities.
- Access restrictions to laser source and cutting areas and adequate training of personnel (i.e., training with mock-ups).

Table 6.3. Relevant Parameters for Monitoring of Laser System

Parameter or Automatic Shutdown Logic	Risk Prevented / Detected	Reference Value
Low air flow rate in ventilation and filtration system, either from local collection system or overall contamination control envelope ventilation arrangements.	Dispersion of contamination. Fire/Explosion (H2 generation).	Considering manufacture recommendations and confinement design requirements. For instance, for achieving an air renewal rate complying with ISO:16647 or with the assumptions of safety evaluations (i.e., air renewal rate of 5 h^{-1} considered in Annex VI).
High differential pressure (ΔP) in HEPA Filters.	Dispersion of contamination. Fire/Explosion (H2 generation).	Filter manufacturer recommendations and/or standard safety practices.
Filtration efficiency	Dispersion of contamination.	Standard safety practices (i.e. 1000 – 3000 filtering efficiency coefficient)
Low differential pressure (ΔP) between cutting area and reactor building (if negative pressure is required).	Dispersion of contamination.	Considering confinement design requirements (i.e., ISO:16647 minimum negative pressure of 20 Pa)
High temperature (i.e., loss of cooling) in laser source, coupler, or laser head.	Fire.	As per manufacture recommendations.
Signal of rupture of fibre (electrical signal)	Fire.	N/A
Programmed stop mechanisms to avoid unintentional cuts or unwanted collateral aggressions. I.e.: • Exceeding stationary time of robotic arm/laser head with laser active. • Exceeding moving time with laser active. • Prohibited movements and/or coordinates of the robotic arm.	Fire. Laser beam and residual power.	As per operational feedback (i.e., demonstrator) and actual segmentation plan.
Release of laser trigger button, requiring continuous and deliberate manual trigger of the laser beam from the operator.	Fire. Laser beam and residual power.	N/A
Compressed air stop when laser or ventilation system is switched off.	Dispersion of contamination. Confinement overpressure.	N/A
Other equipment malfunctions, such as low pressure in air flow (compressed air). Note: this type of parameters may not require automatic shutdown if equipment integrity is not jeopardized.	Equipment Malfunction.	As per manufacture recommendations and operational feedback (i.e., demonstrator).

- The interfaces with the facility, considering plant systems, RPV and RVI characteristics, and associated plant conditions and configurations. For instance, segmentation and handling of RVI components are assumed to be performed underwater, with a minimum level to be guaranteed to provide enough shielding (refer to Annex V for further information). If operators are going to work from the refuelling bridge or any other specific location during relevant times, then additional shielding may be installed.

- For minimizing the risk associated to the residual laser beam, relevant aspects are the correct positioning before cutting and optimizing the cutting speed. This speed should be the fastest as possible for reducing the impact on background structures, but without reducing the robustness of the laser cutting process. Adequate segmentation planning is essential.

Table 6.4. Safety Considerations to be Addressed

Laser Cutting System Standalone Safety Analysis	Interfaces with the Facility
• Fire hazard (laser head, laser generator) • Automation and control of the cutting process, such as fail-safe systems and protection from unwanted collateral laser aggression. • Implementation of periodic checks (i.e., laser source power check using a calorimeter, light-tight test performance of laser closed environment before start of cutting operations). • Maintainability characteristics, for easing installation, maintenance, and removal for reuse. • Human factors and human machine interface, such as ergonomics, software design, and cameras positioning.	• Safety of workers. I.e., Individual dose, collective dose, protective equipment, etc. • Waste management (cutting pattern, drying, radiological characterization, conditioning, storage, handling and removal of radioactive waste, handling equipment...). • Interface with radioactive waste (waste packaging, radiological inventory, activation/contamination quantification). • Interface with the ventilation/filtration systems (temporary enclosure systems, design, dynamic and static confinement criteria). • Interface with the premises (ventilation and utilities such as power and fluids, fire detection and fire-fighting equipment, control rooms). • Interface with the operators (radiation exposure, operability, maintainability, ergonomics...). • Discharges during dismantling (airborne, gaseous, liquids).
• Airborne contamination hazard, if applicable. • Mitigation of water contamination, if applicable. I.e., Filtering systems, ion exchange resins, etc.	

The End User should verify that laser cutting system and associated activities are compatible with technical pre-requisites of the facility, considering all existing interfaces identified (refer to Table 6.4).

Based on the above, and as per Table 5.1, the safety measures of Table 6.5 and safety controls of Table 6.6 are recommended. Additionally, the equipment and systems used shall be designed considering safety, including:

- Fail-safe design of the laser cutting and manipulator systems. This may be demonstrated with a specific HAZOP study of the laser cutting system design.
- Automatic stop of the laser source if gaps identified on a temperature measure.
- Robust design of the laser cutting system, as to avoid repair or maintenance activities in high radiation areas.
- Design considering reduction of installation/uninstallation time.
- Design for minimizing laser cutting system and manipulator contamination and facilitate its decontamination.
- Fail-safe design of handling equipment, which shall be certified and with weight measurement instrumentation.

Table 6.5. Safety Measures Recommended

ID	SSCs	Associated Administrative Safety Control Measures
1	Fire detection and mitigation systems within the Building	Inspection, testing and maintenance Training
2	Dust/aerosols collection system	Maintenance and testing
3	Local Contamination Confinement with Filtration	Inspection, testing and maintenance
4	Area Radiation Monitoring	Inspection, testing and maintenance
5	Building Filtration	Inspection, testing and maintenance
6	Water level monitoring	Inspection, testing and maintenance
7	Electrical cable in the fibre	Testing
8	Protection of cavity floor (i.e. plates).	N/A
9	Auxiliary water filtration systems	Inspection and maintenance
10	Effluents Monitoring (flowrate, activity)	Inspection, testing and maintenance
11	Other RP safety measures: Shielding, Dosimeters, Respiratory Protection…	Inspection, testing and maintenance Training
12	Closed laser environment or shielding by double bend	Inspection, testing and maintenance

Table 6.6. Safety Controls Recommended

Description	Associated Risk/Countermeasure
Emergency and fire plan	Fire and Explosion
Remotely Operated Cutting and Handling	External Exposure and Airborne Releases / Internal Contamination
Control of fire loads close to the laser source, coupler, and head.	Fire
Flexible collection system or cable (pipes…) materials should be fire retardant.	Fire
The path of the optical fibre is studied and labelled and/or physically protected if necessary.	Fire
Laser cutting system including safety measures for avoiding unintentional cuts: stop time, incorporation of prohibited cutting areas in the software, double check of operators…	Fire, Airborne Releases / Internal Contamination, Personnel and Equipment Damage
Planning and double verification during relocation of highly activated components underwater	External Exposure
Human error minimization techniques and training	External Exposure, Internal Contamination, Fire, Drop Loads…
Radiation Protection procedures and controls	External Exposure and Airborne Releases / Internal Contamination
HSE procedures and controls	Personnel and Equipment Damage
Surveillance and monitoring of work premises	External Exposure, Internal Contamination, Fire, etc.
Minimization of waste generation, online removal of waste, optimization of waste location and walking paths…	External Exposure
HEPA filters controls	Internal Contamination

7. GENERIC SAFETY ASSESSMENT SUMMARY

This generic safety assessment was performed for identifying and assessing radiological and non-radiological hazards from normal and accident conditions resulting from laser cutting of the RPV and/or RVI of a PWR or BWR (refer to sections 3 and 4), and based on those hazards, identifying safety measures, systems, and controls following defence-in-depth criteria and as to reduce the risks to ALARA (refer to sections 5 and 6).

To achieve these objectives, boundary conditions were set, defining the cutting conditions and configurations, for instance, the radioactive inventory (refer to section 2). Those boundary conditions pretend to serve as a "safe envelope" that gathers most of the potential conditions and configurations, but adjustments to specific plant conditions are required from Potential End Users.

The methodology followed during this assessment is the one recommended by the IAEA [Ref. 17] for the development of decommissioning safety assessments.

A Risk Matrix (Annex VII) summarizes the risks identified, the potential consequences, and the recommended safety measures and controls, addressing both normal and accidental conditions. For a better understanding, the Risk Matrix includes an estimation of the probability and consequences in a qualitative way. However, the approach remains deterministic. The purpose of the Risk Matrix is to identify possible safety measures and controls, based on three different levels of defence-in-depth: prevention, detection, and mitigation.

The results obtained in this evaluation (refer to table 6.1) should be understood as an indication of the level of safety that can be achieved during RPV and RVI segmentation using the laser cutting technology. However, main assumptions and uncertainties described in section 6.2 should be addressed, as to guarantee the so-called "safe envelope" of the generic safety assessment.

8. ACRONYMS

ALARA	As low as reasonably achievable
BWR	Boiling Water Reactor
CEA	Commissariat a l'Energie Atomique et aux Energies Alternatives
EW	Exempt Waste
HAZOP	Hazard and Operability Analysis
HEPA	High-Efficiency Particulate Air
HLW	High Level Waste
HSE	Health, Safety & Environment
IAEA	International Atomic Energy Agency
ILW	Intermediate Level Waste
LD-SAFE	Laser Dismantling Environmental and Safety Assessment
NPP	Nuclear Power Plant
ODCM	Offsite Doses Calculation Manual
PWR	Pressurized Water Reactor
RCS	Reactor Coolant System
RG	Regulatory Guide
RPV	Reactor Pressure Vessel
RVI	Reactor Vessel Internals
SSCs	Structures, Systems, and Components
VLLW	Very Low Level Waste
VSLW	Very Short-Lived Waste
WP	Work Package

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10. ANNEX

Annex I – HAZOP Study

Annex II – Summary of Non-Radiological Risks

Annex III – Normal Conditions Analysis

Annex IV – Accident Scenarios Analysis

Annex V – Water depth considerations for underwater cutting

Annex VI – Contamination control systems

Annex VII – Risk Matrix

Annex VIII – Recommendations provided by IRSN during the review process

ANNEX I - HAZOP STUDY

The HAZOP method is used for identifying risks during laser cutting activities, both under normal conditions and in case of deviations, in a formal and systematic manner.

In this evaluation, the laser cutting of RPV/RVI is divided into activities (i.e., installation of the laser generation module, installation of the laser head, segmentation of the upper internals, etc.), which will be defined as "nodes" (HAZOP terminology). For each node, a keyword will be applied and assessed (i.e., fire, external dose, drop loads…). The process will be repeated for each keyword, and then, repeated for each node, following the structured process summarized in Figure A-I.1.

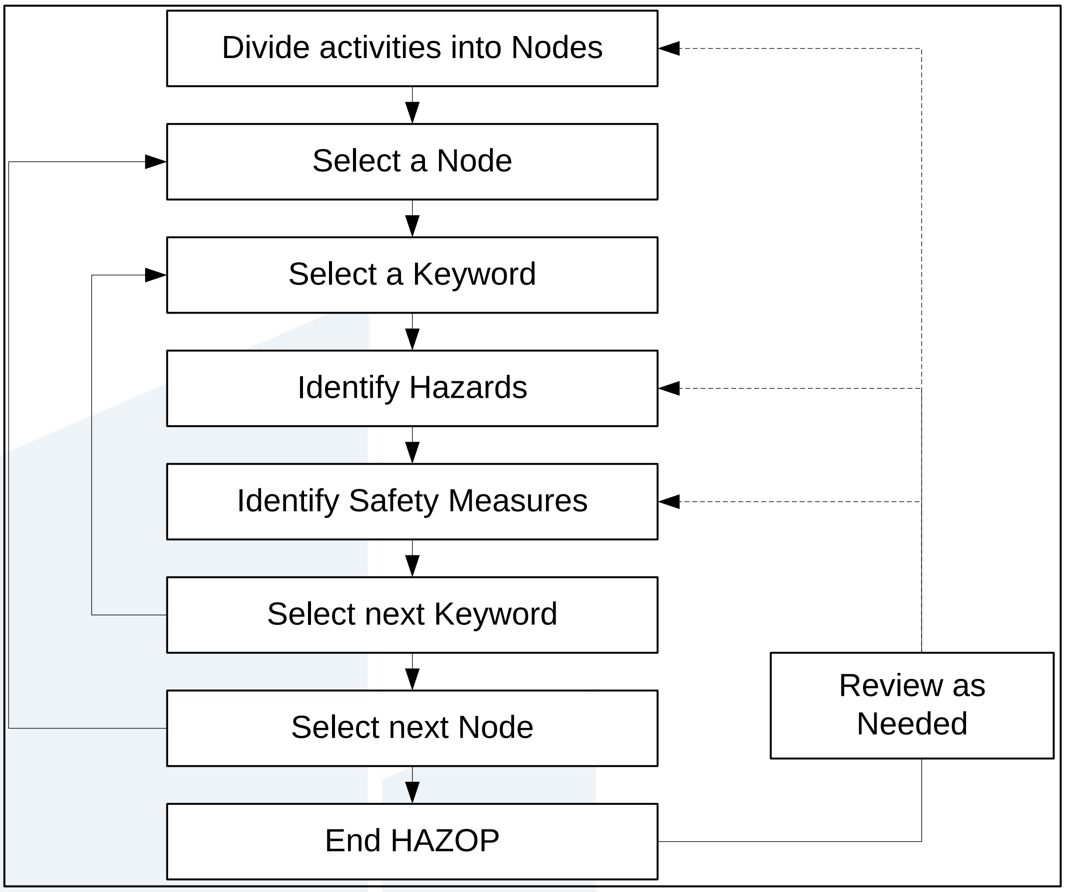

Figure A1.1. HAZOP Methodology Flowchart

For defining the nodes, the following activities and sub-activities will be considered:

1. Preparatory activities:
    1.1. Planning and documentation
    1.2. Mock-up tests and process qualifications
    1.3. Laser cutting system and associated safety measures (i.e. contamination control envelope) installation

2. Segmentation of components using the laser cutting technology and handling of waste packages
    2.1. Segmentation of RVI (underwater)
    2.2. Segmentation of RPV (in-air)
    2.3. Handling of cut pieces
3. Post-segmentation activities
    3.1. Uninstallation of the laser cutting technology
    3.2. Re-conditioning of the area (i.e., clean-up activities)

As indicated above, keywords will be evaluated at each node. These keywords are hazards or initiating events to be considered for the qualitative identification of hazards, standard (and specific) for the nuclear industry. The keywords used during this HAZOP study are the following:

1. External dose
2. Internal dose
3. Loss of shielding/containment/barriers
4. Fire
5. Explosion / overpressure
6. Chemical reactions and toxic and hazardous substances
7. Dropped loads / impacts
8. Maintainability and repair issues
9. Loss of services: power, ventilation, compressed air, water, etc.
10. Control and instrumentation errors/malfunctions
11. Human errors
12. Effluents (gas/liquids) and secondary waste
13. Corrosion, erosion, and other material damage
14. Other conventional hazards

External initiating events are not included within the keywords as they are considered out of the scope of this assessment.

For the identification of safety measures, generic services and practices usually available in nuclear facilities under decommissioning will be considered. If seem appropriate, additional safety measures may be recommended as to reduce the residual risk to ALARA. Both engineered and operational/managerial safety measures will be considered.

Table A1.1. Node: 1.1. Preparatory activities: Planning, and documentation

Keyword	Causes	Consequences	Recommendation of Safety Measures	Comments
1. External exposure	Entry into high radiation areas (RPV/RVI) longer than scheduled for work planning.	Longer execution times resulting in increased exposure risks.	Follow radiation protection program considerations.	
2. Internal exposure	N/A	N/A	N/A	Not considered relevant
3. Loss of shielding / containment / barriers	N/A	N/A	N/A	Not considered relevant
4. Fire	N/A	N/A	N/A	Not considered relevant
5. Explosion / overpressure	N/A	N/A	N/A	Not considered relevant
6. Chemical reactions and toxic and hazardous substances	N/A	N/A	N/A	Not considered relevant
7. Dropped loads / impacts	N/A	N/A	N/A	Not considered relevant
8. Maintainability and repair issues	N/A	N/A	N/A	Not considered relevant
9. Loss of services: power, ventilation, compressed air, water, etc.	N/A	N/A	N/A	Not considered relevant
10. Control and instrumentation errors/malfunctions	N/A	N/A	N/A	Not considered relevant
11. Human errors	N/A	N/A	N/A	Not considered relevant
12. Effluents (gas/liquids) and secondary waste	N/A	N/A	N/A	Not considered relevant
13. Corrosion, erosion, and other material damage	N/A	N/A	N/A	Not considered relevant
14. Other conventional hazards.	Falls, falls at different heights and other associated risk during NPP walkdown activities	Personnel injury	Follow HSE procedures	

Table A1.2. Node: 1.2. Preparatory activities: Mock-up tests and process qualifications

Keyword	Causes	Consequences	Recommendation of Safety Measures	Comments
1. External exposure	N/A	N/A	N/A	Not considered credible
2. Internal exposure	N/A	N/A	N/A	Not considered credible
3. Loss of shielding / containment / barriers	N/A	N/A	N/A	Not considered credible
4. Fire	If the laser source, coupler and head are used in Mock-up tests, they would become potential fire sources. For in-air: the beam and residual beam together with inflammable materials (flexible collection system, flexible cables…). Laser source or coupler overheating, resulting in a risk of fire departure. Damaging optical fiber, leading to the creation of a "hot spot" resulting in a risk of fire departure. Potential flammable hydraulic fluids in the robotic arm.	Material and/or personal damage	1. Emergency and fire plan, with fire detection and mitigation systems. 2. Control of fire loads close to the laser source, coupler, and head. 3. Flexible collection system or cable (pipes…) materials should be fire retardant. 4. Automatic stop of the source if gaps identified on a temperature measure. 5. The path of the optical fiber is studied and labeled and/or physically protected if necessary. 6. Electrical cable in the fiber that will detect fiber rupture and automatically stop the laser source.	
5. Explosion / overpressure	Air flow is used for laser cutting.	Material and/or personal damage	1. Design including as necessary pressure safety valves, pressure instrumentation, etc..	WP2 preliminary studies indicate that cutting of stainless steel will result in H2 concentrations in the range of several hundreds of ppm.

Keyword	Causes	Consequences	Recommendation of Safety Measures	Comments
6. Chemical reactions and toxic and hazardous substances	Hexavalent Chromium generation during cutting of stainless steel	Toxicity to personnel.	1. Cut under confinement 2. Local filtration	
7. Dropped loads / impacts	Failures of different origin that produce the fall of heavy loads (i.e., cut pieces, loss of structural integrity due to unintended damage) during mock-up test.	Material and/or personal damage.	1. Follow HSE procedures	
8. Maintainability and repair issues	N/A	N/A	N/A	Not considered relevant
9. Loss of services: power, ventilation, compressed air, water, etc.	N/A	N/A	N/A	Not considered relevant
10. Control and instrumentation errors/malfunctions	Inadequate equipment operation due to errors in design or fail of instrumentation/equipment. I.e., Inadvertent laser beam operation.	Personnel injury from drop loads, fire, cuts, etc.	1. Application of HAZOP study to laser equipment with design considerations for fail-safe modes. 2. Follow HSE procedures.	
11. Human errors	Inadequate equipment operation from human error	Personnel injury from drop loads, fire, cuts, etc.	1. Application of techniques for minimization of human errors (i.e., double verification by two operators). 2. Training. 3. Follow HSE procedures.	
12. Effluents (gas/liquids) and secondary waste	N/A	N/A	N/A	Not considered credible
13. Corrosion, erosion, and other material damage	N/A	N/A	N/A	Not considered relevant
14. Other conventional hazards	Falls, falls at different heights and other associated risk during tests. Laser unintentional cuts	Personnel injury and equipment damage	1. Follow HSE procedures 2. Laser cutting system including safety measures for avoiding unintended cuts: stop time, prohibited cutting areas in the software, operators double check...	

Table A1.3. Node: 1.3. Preparatory activities: Laser cutting system and associated safety measures (i.e., contamination control envelope) installation

Keyword	Causes	Consequences	Recommendation of Safety Measures	Comments
1. External exposure	RPV/RVI and other radioactive components are relevant sources of radiation in the installation area. Inadvertent entry into high radiation zones. Water shielding loss.	External dose	1. Follow radiation protection program and procedures (ALARA, remote handling, shielding, etc.). 2. Radiation monitoring. 3. Water level monitoring. 4. Design considering reduction of installation time.	
2. Internal exposure	Inhalation of airborne releases in case drilling is necessary in concrete of the reactor building Contamination dispersion in case of accidents (i.e., drop loads in contaminated floor).	Internal dose from inhalation	1. Follow radiation protection program and procedures (ALARA, remote handling, shielding, etc.). 2. Radiation monitoring 3. Building off-gas monitoring and filtration	
3. Loss of shielding / containment / barriers	Water shielding loss	External dose	1. Follow radiation protection program and procedures (ALARA, remote handling, shielding, etc.). 2. Radiation monitoring. 3. Water level monitoring.	
4. Fire	If laser cutting system installation involve hot cutting techniques or welding	In case of accident: - Material and/or personal damage - Dispersion of radioactive material in the containment area	1. Emergency and fire plan, with fire detection and mitigation systems. 2. Control of fire loads close to fire sources. 3. Radiation monitoring 4. Building exhaust filtration	

Keyword	Causes	Consequences	Recommendation of Safety Measures	Comments
5. Explosion / overpressure	N/A	N/A	N/A	Not considered within the scope of tasks.
6. Chemical reactions and toxic and hazardous substances	N/A	N/A	N/A	Not considered within the scope of tasks.
7. Dropped loads / impacts	Potential drop of loads (i.e., heavy components of the laser cutting system, manipulator, etc.)	Structural damage, worker injury or fatality. Internal dose from airborne activity releases (i.e., inhalation due to contamination dispersion in case of accidents as drop loads in contaminated floors)	1. Follow HSE procedures. 2. Radiation Monitoring. 3. Building off-gas filtering.	
8. Maintainability and repair issues	N/A	N/A	N/A	Not considered relevant
9. Loss of services: power, ventilation, compressed air, water, etc.	Failures of different origin that produce the loss of services (i.e., power, ventilation) during plant modifications activities, resulting in equipment malfunction.	- In case of accident, drop of large pieces that may produce material and/or personal damage. - Internal dose: Airborne activity releases (i.e., Inhalation due to contamination dispersion in case of heavy loads drop in contaminated floor).	1. Fail-safe design of equipment 2. Follow HSE procedures (i.e. distance from lifted load so no personnel is injured in case of drop).	
10. Control and instrumentation errors/malfunctions	Inadequate equipment operation due to errors in design or fail of instrumentation/equipment	- In case of accident, drop of large pieces that may produce material and/or personal damage. - Internal dose from airborne	1. Fail-safe design of equipment 2. Follow HSE procedures (i.e., distance from lifted load so no personnel are injured in case of drop).	

Keyword	Causes	Consequences	Recommendation of Safety Measures	Comments
		activity releases (i.e., inhalation due to contamination dispersion in case of heavy loads drop in contaminated floor).		
11. Human errors	Lack of training	Dispersion of contamination due to drop of large pieces that may provoke material and/or personal damage during laser cutting system installation.	1. Application of techniques for minimization of human errors. 2. Training. 3. Follow HSE procedures (i.e., distance from lifted load so no personnel are injured in case of drop).	
12. Effluents (gas/liquids) and secondary waste	N/A	N/A	N/A	Not considered relevant
13. Corrosion, erosion, and other material damage	N/A	N/A	N/A	Not considered relevant
14. Other conventional hazards	Falls, falls at different heights, cuts, hits, trapping, electrical risks, and other associated risk during installation activities	Personnel injury	1. Follow HSE procedures	

Table A1.4. Node: 2.1. Segmentation of components using the laser cutting technology: Segmentation of RVI (underwater)

Keyword	Causes	Consequences	Recommendation of Safety Measures	Comments
1. External exposure	RVI and other radioactive components are relevant sources of radiation in the operating area. Inadvertent entry into high radiation zones. Water shielding loss due to water level reduction or excessive elevation of activated components.	External dose	1. Radiation protection program and procedures (ALARA, remote handling, shielding, area evacuation, etc.). 2. Area radiation monitoring. 3. Water level monitoring, and movement planning to ensure minimum water shielding. Control of movement speed and elevation.	
2. Internal exposure	Aerosols dispersion during in-air or underwater cutting activities. Contamination dispersion in case of accidents (i.e., drop loads, loss of local filtration…). Loss of collecting capability due to collector malfunction or filters saturation.	Internal dose during normal cutting activities and for accident situations	1. Follow radiation protection program and procedures (ALARA, clothing, etc.). 2. Radiation monitoring 3. Local confinement with filtration 4. Dust/aerosols collection system 5. Building off-gas monitoring and filtration 6. Alarm indication in case of abnormal indication of collection system (filters differential pressure, high activity levels, low flow rate in hoses, etc.).	Confinement and filtration systems to be evaluated (i.e., single or combined use).
3. Loss of shielding / containment / barriers	Loss of local confinement (i.e., due to rupture from hits, etc.) Loss of water shielding	External dose from loss of shielding. Internal dose from uncontrolled release of radionuclides due to rupture of confinement	1. Follow radiation protection program and procedures (ALARA, clothing, etc.). 2. Radiation monitoring 3. Dust/aerosols collection system 4. Building off-gas filtration. 5. Water level monitoring. 6. Alarm indication in case of abnormal	

Keyword	Causes	Consequences	Recommendation of Safety Measures	Comments
			indication of collection system (filters differential pressure, high activity levels, low flow rate in hoses, etc.).	
4. Fire	Laser source, coupler and head are potential sources of fire. Laser source or coupler overheating, resulting in a risk of fire departure. Damaging optical fiber, leading to the creation of a "hot spot" resulting in a risk of fire departure.	Material and/or personal damage Internal dose in case of dispersion of radioactive material if the fire reaches local HEPA filters.	1. Emergency and fire plan, with fire detection and mitigation systems. 2. Control of fire loads close to the laser source, coupler and head. 3. Radiation monitoring 4. Building off-gas filtration. 5. Automatic stop of the source if gaps identified on a temperature measure. 6. The path of the optical fiber is studied and labeled and/or physically protected if necessary. 7. Electrical cable in the fiber that will detect fiber rupture and automatically stop the laser source	Consequences and safety measures to be further evaluated based on accident analysis of a fire of HEPA filters. WP2 studies indicate that cutting of stainless steel will result in H2 concentrations in the range of several hundreds of ppm (to be confirmed in the demonstrator). Local built-up of H2 is not considered credible due to air renewal flows. The loss of ventilation should lead to automatic stop of the laser cutting, supported with alarms for potential manual stop.
5. Explosion / overpressure	Hydrogen generation for underwater cutting.	Material and/or personal damage Internal dose in case of dispersion of radioactive material if the explosion affects local HEPA filters.	1. Emergency and fire plan, with fire detection and mitigation systems. 2. Radiation monitoring 3. Building off-gas filtration. 4. Design including as necessary pressure safety valves, pressure instrumentation, etc.	WP2 studies indicate that cutting of stainless steel will result in H2 concentrations in the range of several hundreds of ppm (to be confirmed in the demonstrator). Local built-up of H2 is not considered credible due to air renewal flows. The loss of ventilation should lead to

Keyword	Causes	Consequences	Recommendation of Safety Measures	Comments
				automatic stop of the laser cutting, supported with alarms for potential manual stop. Pressure increase inside the reactor containment due to laser air supply is not considered realistic.
6. Chemical reactions and toxic and hazardous substances	Hexavalent Chromium generation during cutting of stainless steel	Toxicity to personnel	1. Cut under confinement 2. Local filtration	
7. Dropped loads / impacts	N/A	N/A	N/A	Drop of cut pieces evaluated in node 2.3.
8. Maintainability and repair issues	Laser cutting system break and maintenance requirements	External dose for performing repair/maintenance activities	1. Robust design of laser cutting system. 2. Repair/maintenance planning outside high radiation areas (separated from RVI/RPV).	
9. Loss of services: power, ventilation, compressed air, water, etc.	Failures of different origin that produce the loss of power or ventilation during laser cutting.	Internal dose from loss of filtration means. Increase of cutting time, with associated increase of cost and doses.	1. Radiation monitoring 2. Local confinement with filtration 3 Dust/aerosols collection system 4. Building off-gas filtration	
10. Control and instrumentation errors/malfunctions	Inadequate equipment operation due to errors in design or fail of instrumentation/equipment. I.e. Inadvertent laser beam operation.	Material and/or personal damage from inadvertent cutting Internal dose from inadvertent cutting of non-planned components or due to rupture of local confinement	1. Application of HAZOP study to laser equipment with design considerations for fail-safe modes. 2. Radiation monitoring 3. Local confinement with filtration 4. Dust/aerosols collection system 5. Building off-gas filtration	

Keyword	Causes	Consequences	Recommendation of Safety Measures	Comments
11. Human errors	Inadequate equipment operation from human error. I.e. Inadvertent laser beam operation, inadvertent entry into high radiation zones.	Material and/or personal damage from inadvertent cutting Internal dose from inadvertent cutting of non-planned components or due to rupture of local confinement	1. Application of techniques for minimization of human errors. 2. Training. 3. Radiation monitoring 4. Local confinement with filtration 5. Dust/aerosols collection system 6. Building off-gas filtration	
12. Effluents (gas/liquids) and secondary waste	Gaseous releases during cutting activities (both in-air and underwater). Liquid releases during underwater cutting.	Doses to the public and to workers due to gaseous effluents. Doses to the public due to water effluents.	1. Radiation monitoring (as per ODCM) 2. Local confinement with filtration 3. Dust/aerosols collection system 4. Building filtration 5. Water cleanup system	
13. Corrosion, erosion, and other material damage	Inadvertent laser beam operation and residual beam power.	Material and/or personal damage from inadvertent cutting Internal dose from inadvertent cutting of non-planned components or due to rupture of local confinement	1. Application of techniques for minimization of human errors (i.e., double verification by two operators). 2. Radiation monitoring 3. Local confinement with filtration 4. Dust/aerosols collection system 5. Building filtration	
14. Other conventional hazards	Laser unintentional cuts: - Laser shot in stationary position implying damage on parts located behind the target. Laser shot on prohibited/ weak area implying damage on parts, structure and equipment.	Personnel injury and equipment damage	1. Follow HSE procedures 2. Laser cutting system including safety measures for avoiding unintentional cuts: stop time, incorporation of prohibited cutting areas in the software, double check of operators...	

Table A1.5. Node: 2.2. Segmentation of components using the laser cutting technology: Segmentation of RPV (in-air)

Keyword	Causes	Consequences	Recommendation of Safety Measures	Comments
1. External exposure	RPV and other radioactive components are relevant sources of radiation in the operating area. Inadvertent entry into high radiation zones. Water shielding loss.	External dose	1. Follow radiation protection program and procedures (ALARA, remote handling, shielding such as water level, etc.). 2. Radiation monitoring.	
2. Internal exposure	Aerosols dispersion during in-air or underwater cutting activities. Contamination dispersion in case of accidents (i.e., drop loads, loss of local filtration...).	Internal dose during normal cutting activities and for accident situations	1. Follow radiation protection program and procedures (ALARA, clothing, etc.). 2. Radiation monitoring 3. Local confinement with filtration 4. Dust/aerosols collection system 5. Building off-gas monitoring and filtration 6. Alarm indication in case of abnormal indication of collection system (filters differential pressure, high activity levels, low flow rate in hoses, etc.).	
3. Loss of shielding / containment / barriers	Loss of local confinement (i.e., due to rupture from hits, residual laser beam power, etc.) Loss of water shielding	External dose from loss of shielding. Internal dose from uncontrolled release of radionuclides due to rupture of confinement	1. Follow radiation protection program and procedures (ALARA, clothing, etc.). 2. Radiation monitoring 3. Dust/aerosols collection system 4. Building off-gas monitoring and filtration. 5. Water level monitoring.	

Keyword	Causes	Consequences	Recommendation of Safety Measures	Comments
			6. Alarm indication in case of abnormal indication of collection system (filters differential pressure, high activity levels, low flow rate in hoses, etc.).	
4. Fire	Laser source, coupler and head are potential sources of fire. The beam and residual beam together with inflammable materials (flexible collection system, flexible cables...). Laser source or coupler overheating, resulting in a risk of fire departure. Damaging optical fiber, leading to the creation of a "hot spot" resulting in a risk of fire departure. Potential flammable hydraulic fluids in the robotic arm.	Material and/or personal damage Internal dose in case of dispersion of radioactive material if the fire reaches local HEPA filters.	1. Emergency and fire plan, with fire detection and mitigation systems. 2. Control of fire loads close to the laser source, coupler and head. 3. Flexible collection system or cable (pipes...) materials should be fire retardant. 4. Radiation monitoring 5. Building off-gas filtration. 6. Automatic stop of the source if gaps identified on a temperature measure. 7. The path of the optical fiber is studied and labeled and/or physically protected if necessary. 8. Electrical cable in the fiber that will detect fiber rupture and automatically stop the laser source.	Consequences and safety measures to be further evaluated based on accident analysis of a fire of HEPA filters
5. Explosion / overpressure	N/A	N/A	N/A	Not considered relevant
6. Chemical reactions and toxic and hazardous substances	N/A	N/A	N/A	Not considered relevant, since there is only a small layer of stainless steel in the RPV.
7. Dropped loads / impacts	N/A	N/A	N/A	Drop of cut pieces evaluated in node 2.3.
8. Maintainability and repair issues	Laser cutting system break and	External dose for performing	1. Robust design of laser cutting	

Keyword	Causes	Consequences	Recommendation of Safety Measures	Comments
	maintenance requirements	repair/maintenance activities	system. 2. Repair/maintenance planning outside high radiation areas (separated from RVI/RPV).	
9. Loss of services: power, ventilation, compressed air, water, etc.	Failures of different origin that produce the loss of power or ventilation during laser cutting.	Internal dose from loss of filtration means. Increase of cutting time, with associated increase of cost and doses.	1. Radiation monitoring 2. Local confinement with filtration 3 Dust/aerosols collection system 4. Building off-gas filtration	
10. Control and instrumentation errors/malfunctions	Inadequate equipment operation due to errors in design or fail of instrumentation/equipment. I.e. Inadvertent laser beam operation.	Material and/or personal damage from inadvertent cutting Internal dose from inadvertent cutting of non-planned components or due to rupture of local confinement	1. Application of HAZOP study to laser equipment with design considerations for fail-safe modes. 2. Radiation monitoring 3. Local confinement with filtration 4. Dust/aerosols collection system 5. Building off-gas filtration	
11. Human errors	Inadequate equipment operation from human error. I.e. Inadvertent laser beam operation, inadvertent entry into high radiation zones.	Material and/or personal damage from inadvertent cutting Internal dose from inadvertent cutting of non-planned components or due to rupture of local confinement	1. Application of techniques for minimization of human errors. 2. Training. 3. Radiation monitoring 4. Local confinement with filtration 5. Dust/aerosols collection system 6. Building off-gas filtration	
12. Effluents (gas/liquids) and secondary waste	Gaseous releases during cutting activities (both in-air and underwater). Liquid releases during underwater cutting.	Doses to the public and to workers due to gaseous effluents. Doses to the public due to water effluents.	1. Radiation monitoring (as per ODCM) 2. Local confinement with filtration 3. Dust/aerosols collection system 4. Building filtration 5. Water cleanup system	Water cleanup system is considered necessary as water level may be maintained right below the cutting operations, and dust and particles may drop

Keyword	Causes	Consequences	Recommendation of Safety Measures	Comments
				to the water.
13. Corrosion, erosion, and other material damage	Inadvertent laser beam operation and residual beam power.	Material and/or personal damage from inadvertent cutting Internal dose from inadvertent cutting of non-planned components or due to rupture of local confinement	1. Application of techniques for minimization of human errors (i.e. double verification by two operators). 2. Radiation monitoring 3. Local confinement with filtration 4. Dust/aerosols collection system 5. Building filtration	
14. Other conventional hazards	Laser unintentional cuts: - Laser shot in stationary position implying damage on parts located behind the target. - Laser shot on prohibited/ weak area implying damage on parts, structure, and equipment.	Personnel injury and equipment damage	1. Follow HSE procedures 2. Laser cutting system including safety measures for avoiding unintentional cuts: stop time, incorporation of prohibited cutting areas in the software, double check of operators...	

Table A1.6. Node: 2.3. Segmentation of components using the laser cutting technology: Handling of cut pieces

Keyword	Causes	Consequences	Recommendation of Safety Measures	Comments
1. External exposure	RPV/RVI and other radioactive components are relevant sources of radiation in the operating area. Inadvertent entry into high radiation zones. Water shielding loss.	External dose	1. Follow radiation protection program and procedures (ALARA, remote handling, shielding, etc.). 2. Radiation monitoring. 3. Water level monitoring, and movement planning to ensure minimum water shielding. Control of movement	

Keyword	Causes	Consequences	Recommendation of Safety Measures	Comments
			speed and elevation.	
2. Internal exposure	Accidental drop of cut pieces	Internal dose from inhalation of airborne releases from cut pieces	1. Radiation monitoring 2. Building monitoring and filtration	
3. Loss of shielding / containment / barriers	Water shielding loss. Rupture of cavity liner due to load drop.	External dose	1. Follow radiation protection program and procedures (ALARA, remote handling, shielding, area evacuation, etc.). 2. Radiation monitoring. 3. Water level monitoring, and movement planning to ensure minimum water shielding. Control of movement speed and elevation. 4. Protection of cavity floor (i.e., plates).	
4. Fire	N/A	N/A	N/A	Not considered relevant
5. Explosion / overpressure	N/A	N/A	N/A	Not considered relevant
6. Chemical reactions and toxic and hazardous substances	N/A	N/A	N/A	Not considered relevant
7. Dropped loads / impacts	Handling of cut pieces	Structural damage, worker injury or fatality. Internal dose from airborne activity releases (i.e., inhalation due to contamination dispersion in case of accidental drop of cut pieces)	1. Fail-safe design of equipment, which shall be certified and with weight measuring device. 2. Radiation monitoring 3. Building off-gas filtration	
8. Maintainability and repair issues	Handling system break and maintenance requirements	External dose for performing repair/maintenance activities	1. Robust design of handling system. 2. Repair/maintenance planning outside	

Keyword	Causes	Consequences	Recommendation of Safety Measures	Comments
			high radiation areas.	
9. Loss of services: power, ventilation, compressed air, water, etc.	Potential drop of cut pieces due to loss of power.	Structural damage, worker injury or fatality. Internal dose from airborne activity releases (i.e. inhalation due to contamination dispersion in case of accidental drop of cut pieces)	1. Fail-safe design of equipment 2. Follow HSE procedures. 3. Radiation Monitoring. 4. Building off-gas filtering.	
10. Control and instrumentation errors/malfunctions	Inadequate equipment operation due to errors in design or fail of instrumentation/equipment	- In case of accident, drop of cut pieces that may produce material and/or personal damage. - Internal dose from airborne activity releases (i.e. inhalation due to contamination dispersion in case of cut pieces drop).	1. Fail-safe design of equipment 2. Follow HSE procedures. 3. Radiation Monitoring. 4. Building off-gas filtering.	
11. Human errors	Inadequate equipment operation from human error.	Dispersion of contamination due to drop of cut pieces that may provoke material and/or personal damage and internal dose	1. Application of techniques for minimization of human errors. 2. Training. 3. Radiation monitoring 4. Building off-gas filtration	
12. Effluents (gas/liquids) and secondary waste	N/A	N/A	N/A	Not considered relevant
13. Corrosion, erosion and other material damage	N/A	N/A	N/A	Not considered relevant
14. Other conventional hazards	N/A	N/A	N/A	Not considered relevant

Table A1.7. Node: 3.1. Post-segmentation activities: Uninstallation of the laser cutting technology

Keyword	Causes	Consequences	Recommendation of Safety Measures	Comments
1. External exposure	Radioactive components within the reactor building are relevant sources of radiation in the uninstallation area.	External dose	1. Follow radiation protection program and procedures (ALARA, remote handling, shielding, etc.). 2. Radiation monitoring. 3. Design considering reduction of uninstallation time.	
2. Internal exposure	Malfunction or error in operation of cleaning equipment or handling of contaminated parts of the laser system.	Internal dose from dispersion of contamination, including hot particles	1. Follow radiation protection program and procedures. 2. Radiation monitoring.	
3. Loss of shielding / containment / barriers	Malfunction or error in operation of cleaning equipment or handling of contaminated parts of the laser system.	Dispersion of contamination and doses to workers.	1. Follow radiation protection program and procedures. 2. Radiation monitoring.	
4. Fire	N/A	N/A	N/A	Not considered relevant
5. Explosion / overpressure	N/A	N/A	N/A	Not considered within the scope of tasks.
6. Chemical reactions and toxic and hazardous substances	N/A	N/A	N/A	Decontamination of the system is not considered within the scope of tasks.
7. Dropped loads / impacts	Potential drop of loads (i.e. heavy components of the laser cutting system, manipulator, etc.)	Structural damage, worker injury or fatality. Internal dose from airborne activity releases (i.e. inhalation	1. Follow HSE procedures. 2. Radiation Monitoring. 3. Building off-gas filtering.	

Keyword	Causes	Consequences	Recommendation of Safety Measures	Comments
		due to contamination dispersion in case of accidents as drop loads in contaminated floors)		
8. Maintainability and repair issues	N/A	N/A	N/A	Not considered relevant
9. Loss of services: power, ventilation, compressed air, water, etc.	Failures of different origin that produce the loss of services (i.e., power, ventilation) during plant modifications activities, resulting in equipment malfunction.	In case of accident, drop of large pieces that may produce material and/or personal damage. Internal dose: Airborne activity releases (i.e., Inhalation due to contamination dispersion in case of heavy loads drop in contaminated floor).	1. Fail-safe design of equipment 2. Follow HSE procedures	
10. Control and instrumentation errors/malfunctions	Inadequate equipment operation due to errors in design or fail of instrumentation/equipment	In case of accident, drop of large pieces that may produce material and/or personal damage. Internal dose from airborne activity releases (i.e., inhalation due to contamination dispersion in case of loads drop in contaminated floor).	1. Fail-safe design of equipment 2. Follow HSE procedures	
11. Human errors	Lack of training	Dispersion of contamination due to drop of large pieces that may provoke material and/or personal damage during laser	1. Application of techniques for minimization of human errors. 2. Training. 3. Follow HSE procedures.	

Keyword	Causes	Consequences	Recommendation of Safety Measures	Comments
		cutting system uninstallation.		
12. Effluents (gas/liquids) and secondary waste	Effluent releases from decontamination of laser cutting system	Doses to the public and to workers due to effluents.	1. Design for minimizing laser cutting system and manipulator contamination and facilitate its decontamination.	
13. Corrosion, erosion, and other material damage	N/A	N/A	N/A	Not considered relevant
14. Other conventional hazards	Falls, falls at different heights, cuts, hits, trapping, and other associated risk during uninstallation activities	Personnel injury	1. Follow HSE procedures	

Table A1.8. Node: 3.2. Post-segmentation activities: Re-conditioning of the area (i.e., clean-up activities)

Keyword	Causes	Consequences	Recommendation of Safety Measures	Comments
1. External exposure	Proximity to high radiation areas Handling of filters from cleanup system	External dose	1. Follow radiation protection program and procedures (ALARA, remote handling, shielding, etc.).	
2. Internal exposure	Malfunction or error in operation of cleaning equipment.	Internal dose from dispersion of contamination, including hot particles	1. Follow radiation protection program and procedures. 2. Radiation monitoring.	
3. Loss of shielding / containment / barriers	N/A	N/A	N/A	Not considered relevant
4. Fire	N/A	N/A	N/A	Not considered relevant
5. Explosion / overpressure	N/A	N/A	N/A	Not considered relevant
6. Chemical reactions and toxic and hazardous substances	N/A	N/A	N/A	To be adjusted based on actual decontamination methods.
7. Dropped loads / impacts	N/A	N/A	N/A	Not considered relevant
8. Maintainability and repair issues	N/A	N/A	N/A	Not considered relevant

Keyword	Causes	Consequences	Recommendation of Safety Measures	Comments
9. Loss of services: power, ventilation, compressed air, water, etc.	N/A	N/A	N/A	Not considered relevant
10. Control and instrumentation errors/malfunctions	Inadequate cleanup system operation from malfunctions	Dispersion of contamination, resulting in doses and secondary waste	1. Follow radiation protection program and procedures.	
11. Human errors	Inadequate equipment operation from human error.	Dispersion of contamination, resulting in doses and secondary waste	1. Application of techniques for minimization of human errors. 2. Training.	
12. Effluents (gas/liquids) and secondary waste	Effluent releases from cleanup process	Doses to the public and to workers due to effluents.	1. Effluents monitoring (based on ODCM)	
13. Corrosion, erosion, and other material damage	N/A	N/A	N/A	Not considered relevant
14. Other conventional hazards	N/A	N/A	N/A	Not considered relevant

ANNEX II - SUMMARY OF NON-RADIOLOGICAL RISKS

Table A2.1. Summary of Non-Radiological Risks and Recommendation of Safety Measures

Non-Radiological Hazards		*Recommendation of Safety Measures*
Fire	Laser cutting, as a thermal cutting technique, involves a risk of fire for which safety measures should be in place (laser source, coupler, laser beam and associated residual power, flammable hydraulic fluids, hydrogen generation).	1. Emergency and fire plan, with fire detection and mitigation systems. 2. Control of fire loads close to the laser source, coupler, and head. 3. Flexible collection system materials should be fire retardant. 4. Automatic stop of the source if gaps identified on a temperature measure. 5. The path of the optical fibre is studied and labelled and/or physically protected if necessary. 6. Electrical cable in the fibre that will detect fibre rupture and automatically stop the laser source.
Explosion / overpressure	Air flow used for laser cutting. Hydrogen generation considered negligible (see section 4.1.3.1).	1. Design including as necessary pressure safety valves, pressure instrumentation, etc.
Lead, Asbestos, and other toxic materials	Lead shielding may be used in the proximities of the components to be cut, and it may be impacted by the residual laser beam. Other toxic materials may be present.	1. Planning of cutting activities, with enough distance to lead shielding as to avoid residual beam power impact.
Other hazardous substances	Ozone, carbon oxides, nickel carbonyl, nitrogen oxide and toluene may be produced during cutting operations. Hexavalent chromium may be generated during cutting of stainless steel.	1. Dust/Aerosols Collection System (in-air) 2. Contamination control envelope with filtration means.
Electrical hazards	400 V (3 phases) is assumed to be required.	As per usual/plant specific HSE recommendations.

Non-Radiological Hazards		Recommendation of Safety Measures
Loss of control of laser beam and associated residual power	A powerful laser beam is used for laser cutting, which may result in personnel and equipment damage, including components around the cutting point. Loss of structural integrity of damaged components.	1. Prohibited access to cutting area during laser shot, with access control measures, confinement of cutting area, and remote operation. 2. Laser cutting system safe design, with features such as: - Laser beam non-effective unless triggered by the operator. Automatic stop if the operator stops moving for too long. - Specification of laser shot authorized areas within the software. The laser does not operate in prohibited areas. - Definition of maximum time that the laser beam can be stationary. Automatic stop of the laser if the time is passed. 3. Double check of operations. 4. Periodic check of the laser source power. 5. Exhaustive analysis of segmentation plan, identifying distances to other components.
Drop of heavy loads	Heavy loads are to be handled (i.e., cut pieces, laser system and manipulator components, etc.) which may result in personnel and equipment damage.	As per usual/plant specific HSE recommendations.
Other industrial hazards	Working at heights, high noise areas, use of dangerous equipment (i.e., powered tools), pinch points and sharp objects, kinetic energy, compressed air (used for the laser head), etc.	As per usual/plant specific HSE recommendations.

ANNEX III - NORMAL CONDITIONS ANALYSIS

Doses to workers and to the public under normal conditions were analysed. Modelling information and associated results are detailed below.

A3.1 Doses to workers

A3.1.1. Doses to Workers from External exposure

Effective dose (E), in mSv, from external exposure will be calculated per the following formulae:

$$E = DR \cdot t \qquad \text{Eq. A3.1.}$$

Where:

- DR, in mSv/h is the dose rate where the worker is performing the work
- t is the time, in hours, required for performing the work

The Collective Effective dose, E-p, in mSv, will be calculated based on the number of workers required for each activity, and the Effective dose received by all of them. Maximum individual dose and total collective dose are also calculated assuming the RPV and RVI segmentation activities are performed in the same year and by the same working personnel.

For the calculations, the following was assumed:

- Working crew composition as referred in section 2.5.2, with two shifts of 8 hours each.
- 4 weeks for preparatory and post-segmentation activities (2 weeks each), as per Table 1.1. Ineffective time results in a 57.4% of time increase (section 5.2), thus, it has been considered that effective time (in radiation-controlled areas) is of around 63.5%.
- Operating time for segmenting activities is shown in Tables 2.12 (for a PWR) and Table 2.13 (for a BWR).
- Time distribution in the different working areas for each working group is assumed to be as provided in Table A3.1.
- Dose rates for each activity are based on the time distribution and dose rates of each location:
    - Segmenting area:
        - Dose rate in segmenting areas is considered to be 0.05 mSv/h, as per the average value from NUREG/CR-0130 [Ref. 48].

- Dose rate when moving the RVI to the Refuelling Cavity or Dryer and Separator Storage Pool is considered to be 0.1 mSv/h, based on the average value from NUREG/CR-0130 [Ref. 48].

  This dose rate is applied to 25% of the time devoted to the preparatory activities.

In the segmenting area, after segmenting activities are finished, radiation fields are considered to decrease in a factor of 10, due to the removal of the highly activated components.

- Operating Control Room is considered to be in a low radiation area (0.005 mSv/h or less).
- Supporting Activities Area is considered to be in a low radiation area with a dose rate 10 times lower than that of the segmenting area. This area concept is used for supervision activities as well as repair/maintenance activities in areas with lower radiation fields.

Table A3.1. Time Distribution in Different Working Areas per Working Group

Worker	Activity	Segmenting Area	Operating Control Room	Supporting Activities Area
Supervisor	Preparatory	0.35	0.05	0.6
	Segmentation	0.05	0.25	0.25
	Post-segmentation	0.5	0	0.5
Operator	Preparatory	0.25	0.25	0.25
	Segmentation	0.05	0.9	0.05
	Post-segmentation	0.25	0.25	0.25
Technician	Preparatory	0.75	0.05	0.2
	Segmentation	0.05	0.9	0.05
	Post-segmentation	0.75	0.05	0.2
RP Technician	Preparatory	0.75	0.05	0.2
	Segmentation	0.05	0.9	0.05
	Post-segmentation	0.75	0.05	0.2

The evaluation is summarized in next table:

Table A3.2. Estimation of External Doses to the workers, in mSv, for planned conditions

Worker	Activity	PWR								BWR							
		RVI				RPV				RVI				RPV [(1)]			
		Time (h)	DR (mSv/h)	E (mSv)	E-p (mSv-p)	Time (h)	DR (mSv/h)	E (mSv)	E-p (mSv-p)	Time (h)	DR (mSv/h)	E (mSv)	E-p (mSv-p)	Time (h)	DR (mSv/h)	E (mSv)	E-p (mSv-p)
Supervisor	Preparatory	51	0.025	1.28	2.55	51	0.021	1.05	2.11	51	0.025	1.28	2.55	51	0.021	1.05	2.11
	Segmentation	374	0.005	1.87	3.74	943	0.005	4.72	9.43	860	0.005	4.30	8.60	1432	0.005	7.16	14.32
	Post.segm.	51	0.005	0.25	0.51	51	0.005	0.25	0.51	51	0.005	0.25	0.51	51	0.005	0.25	0.51
	Total	N/A	N/A	3.40	6.80	N/A	N/A	6.02	12.05	N/A	N/A	5.83	11.66	N/A	N/A	8.47	16.94
Operators	Preparatory	51	0.018	0.92	5.53	51	0.015	0.76	4.57	51	0.018	0.92	5.53	51	0.015	0.76	4.57
	Segmentation	374	0.007	2.71	16.27	943	0.007	6.84	41.02	860	0.007	6.23	37.39	1432	0.007	10.38	62.29
	Post.segm.	51	0.004	0.19	1.14	51	0.004	0.19	1.14	51	0.004	0.19	1.14	51	0.004	0.19	1.14
	Total	N/A	N/A	3.82	22.94	N/A	N/A	7.79	46.74	N/A	N/A	7.34	44.07	N/A	N/A	11.33	68.00
Technicians	Preparatory	51	0.048	2.45	34.24	51	0.039	1.97	27.57	51	0.048	2.45	34.24	51	0.039	1.97	27.57
	Segmentation	374	0.007	2.71	37.96	943	0.007	6.84	95.72	860	0.007	6.23	87.25	1432	0.007	10.38	145.33
	Post.segm.	51	0.005	0.25	3.56	51	0.005	0.25	3.56	51	0.005	0.25	3.56	51	0.005	0.25	3.56
	Total	N/A	N/A	5.41	75.77	N/A	N/A	9.06	126.85	N/A	N/A	8.93	125.06	N/A	N/A	12.60	176.46

Worker	Activity	PWR								BWR							
		RVI				RPV				RVI				RPV (1)			
		Time (h)	DR (mSv/h)	E (mSv)	E-p (mSv-p)	Time (h)	DR (mSv/h)	E (mSv)	E-p (mSv-p)	Time (h)	DR (mSv/h)	E (mSv)	E-p (mSv-p)	Time (h)	DR (mSv/h)	E (mSv)	E-p (mSv-p)
RP Technician	Preparatory	51	0.048	2.45	9.78	51	0.039	1.97	7.88	51	0.048	2.45	9.78	51	0.039	1.97	7.88
	Segmentation	374	0.007	2.71	10.85	943	0.007	6.84	27.35	860	0.007	6.23	12.46	1432	0.007	10.38	20.76
	Post.segm.	51	0.005	0.25	1.02	51	0.005	0.25	1.02	51	0.005	0.25	0.51	51	0.005	0.25	0.51
	Total	N/A	N/A	5.41	21.65	N/A	N/A	9.06	36.24	N/A	N/A	8.93	22.76	N/A	N/A	12.60	29.15
TOTAL	Preparatory	N/A	N/A	N/A	52.11	N/A	N/A	N/A	42.13	N/A	N/A	N/A	52.11	N/A	N/A	N/A	42.13
	Segmentation	N/A	N/A	N/A	68.82	N/A	N/A	N/A	173.52	N/A	N/A	N/A	145.71	N/A	N/A	N/A	242.70
	Post.segm.	N/A	N/A	N/A	6.23	N/A	N/A	N/A	6.23	N/A	N/A	N/A	5.72	N/A	N/A	N/A	5.72
	Total	N/A	N/A	N/A	127.16	N/A	N/A	N/A	221.88	N/A	N/A	N/A	203.54	N/A	N/A	N/A	290.55
Maximum Individual Dose RPV or RVI		9.06								12.6							
Collective Dose RPV + RVI		349								498							

A3.1.2. Doses to Workers from Airborne Releases with No Safety Controls

Cutting operations are considered to be performed remotely and with safety controls in place. However, for a deep analysis of the segmentation conditions, an evaluation of the potential doses if no safety controls were in place will be performed considering airborne releases. Calculated doses will be both from external exposure (airborne cloud-shine) and from inhalation (committed dose).

The Effective Dose E, in mSv, from external exposure to the airborne cloud-shine will be calculated as follows:

$$E = \sum_i A_{av.i} \cdot \frac{1}{Vf} \cdot fc \cdot CFE_i \cdot Tc \cdot 3600 \cdot 10^3 \qquad \text{Eq. A3.2.}$$

Where:

- Aav_i, in Bq, is the average activity release for each radionuclide. For obtaining this value, total activity released, Ai, based on the airborne release rate (refer to section 4.3.1.1) will be divided by the Cutting Time, Tc. This assumes that the air within the Reactor Building is continuously renovated (five times per hour, following the approach in Annex VI).
  - For obtaining Cm (specific activity (Bq/g) for each radionuclide (i) and component (j)), Core Mid-Plane activities (Bq) from Table 2.5 are used, dividing by the total mass of material for RVI or RPV [Ref. 48, 49].
  - The weights considered, as per NUREG/CR-0130 for PWR [Ref. 48] and NUREG-CR-0672 for BWR (RVI and RPV) [Ref. 49], are the following:
    - PWR - RPV: 3.08E+05 Kg
    - PWR - RVI: 1.81E+05 Kg
    - BWR - RPV: 6.58E+05 Kg
    - BWR - RVI: 2.86E+05 Kg
- Vf, in m^3, is the free volume of the Containment Building where aerosols will be dispersed. This value varies representatively for different types of reactors, as it can be observed in RASCAL 4.3.3 database [Ref. 56].
  - For a PWR, with a rated power from 2750 to 3250 MW(t), which is representative to the reference reactor within this study, free containment volumes in RASCAL database range from 50,000 to 80,000 m^3. The average value will be used in the calculations, and that is approximately 60,000m^3.
  - For a BWR, with a rated power from 2750 to 3250 MW(t), which is representative to the reference reactor within this study, free containment volumes in RASCAL database range

from 7,000 to 35,000 m^3, which is highly dependent on type of containment (Mark I, Mark II, Mark III). The average value will be used in the calculations, and that is approximately 12,000 m^3.

- For conservative purposes, a factor (fc) will be considered in order to account for higher activity concentrations in areas of the plant. A factor of 5 will be used (reducing the dilution effect).
- CFEi is the effective dose coefficient for each radionuclide, in (Sv·m^3) / (Bq·s) [Ref. 24]
- Tc is the cutting time, in hours, from Tables 2.12 (PWR) and 2.13 (BWR).
- The factor $3600 \cdot 10^3$ is used for adjusting units (s·mSv/h·Sv).

The inhalation Committed Effective Dose E(50) for workers, in mSv, is calculated as follows:

$$E(50) = \sum_i A_{av.i} \cdot 1/Vf \cdot fc \cdot BR \cdot CFE(50)_i \cdot Tc \cdot 10^3 \qquad \text{Eq. A3.3.}$$

Where:

- Aav$_i$, in Bq, is the average activity release for each radionuclide. For obtaining this value, total activity released, Ai, based on the airborne release rate (refer to section 4.3.1.1) will be divided by the Cutting Time, Tc. This assumes that the air within the Reactor Building is continuously renovated (five times per hour, following the approach in Annex VI). Same assumptions as for Eq. A3.2 are made.
- Vf, in m^3, is the free volume of the Containment Building where aerosols will be dispersed. The same assumptions as in Eq. A3.2 are made.
- For conservative purposes, a factor (fc) will be considered in order to account for higher activity concentrations in areas of the plant. A factor of 5 will be used for PWR (to reducing the higher dilution effect) and a factor of 5 for a BWR.
- BR is the breathing rate of the worker of 1.2 m^3/h [Ref. 22, 23].
- CFE(50)i is the inhalation dose coefficient for each radionuclide (i), in Sv/Bq. [Ref. 27]. Values are selected for AMAD of 0.3 µm for underwater cutting and for 0.1 µm for in-air cutting [Ref. 43]. Type S is selected since is more representative of the type of particles (i.e., cobalt oxide).
- Tc is the cutting time, in hours.
- The factor 10^3 is used for adjusting units (mSv/Sv).

Total Dose (DT) will be calculated by adding E and E(50). Based on the results from the worst-case scenario (no safety measures, systems, and controls are in place), reduction factors will be applied per section 4.3.1.2, in order to obtain DTcc (with contamination confinement), DTcs (with Collection system) and DT cc+cs (with both safety measures). The results are summarized in Tables A3.3 (RVI of a PWR) A3.4 (RPV of a PWR), A3.5 (RVI of a BWR) and A3.6 (RPV of a BWR).

NOTE: These calculations assume that workers are present in the working area during all cutting hours. Safety controls should be in place, such as remote operation, access control, and area radiation monitoring in order to keep doses to workers ALARA.

Table A3.3. Potential Doses to Workers from Airborne Releases (RVI, PWR), in mSv, with reduced Safety Controls

Nuclide	Cm (Bq/g)	Cs (Bq/cm^2)	Aav (Bq)	CFE	CFE(50)w	E	**E(50)**	DT	DTcc	DTcs	DTcc+cs
Nb-95	5.91E-06	5.72E-09	3.96E-06	3.74E-14	1.70E-09	1.35E-14	2.04E-13	2.17E-13	2.17E-16	4.35E-14	4.35E-17
Fe-59	4.09E-02	3.99E-05	2.74E-02	5.97E-14	3.20E-09	1.49E-10	2.66E-09	2.80E-09	2.80E-12	5.61E-10	5.61E-13
Co-58	2.10E+02	2.03E-01	1.40E+02	4.76E-14	3.20E-09	6.07E-07	1.36E-05	1.42E-05	1.42E-08	2.84E-06	2.84E-09
Zr-95	4.06E-05	4.26E-08	2.72E-05	3.60E-14	6.10E-09	8.89E-14	5.02E-12	5.11E-12	5.11E-15	1.02E-12	1.02E-15
Zn-65	9.06E+02	8.77E-01	6.07E+02	2.90E-14	2.00E-09	1.60E-06	3.68E-05	3.84E-05	3.84E-08	7.67E-06	7.67E-09
Mn-54	1.08E+06	1.06E+03	7.25E+05	4.09E-14	7.10E-09	2.69E-03	1.56E-01	1.59E-01	1.59E-04	3.17E-02	3.17E-05
Fe-55	1.78E+08	1.73E+05	1.19E+08	0.00E+00	4.10E-10	0.00E+00	1.48E+00	1.48E+00	1.48E-03	2.96E-01	2.96E-04
Co-60	1.98E+08	1.92E+05	1.33E+08	1.26E-13	8.10E-08	1.52E+00	3.26E+02	3.28E+02	3.28E-01	6.55E+01	6.55E-02
Ni-63	4.00E+07	3.87E+04	2.68E+07	0.00E+00	4.30E-09	0.00E+00	3.49E+00	3.49E+00	3.49E-03	6.98E-01	6.98E-04
Mo-93	1.27E+02	1.27E-01	8.47E+01	2.52E-17	2.90E-10	1.94E-10	7.45E-07	7.45E-07	7.45E-10	1.49E-07	1.49E-10
C-14	5.08E+04	4.93E+01	3.40E+04	2.24E-19	1.60E-08	6.93E-10	1.65E-02	1.65E-02	1.65E-05	3.30E-03	3.30E-06
Nb-94	1.62E+03	1.57E+00	1.09E+03	7.70E-14	2.50E-07	7.62E-06	8.24E-03	8.25E-03	8.25E-06	1.65E-03	1.65E-06
Ni-59	2.70E+05	2.62E+02	1.81E+05	0.00E+00	2.10E-09	0.00E+00	1.15E-02	1.15E-02	1.15E-05	2.31E-03	2.31E-06
Ru-103	0	1.97E+02	8.63E+00	2.25E-14	2.20E-09	1.77E-08	5.75E-07	5.93E-07	5.93E-10	1.19E-07	1.19E-10
Ru-106	0	4.34E-07	1.90E-08	0.00E+00	9.60E-08	0.00E+00	5.54E-14	5.54E-14	5.54E-17	1.11E-14	1.11E-17
Cs-134	0	5.37E+03	2.36E+02	7.57E-14	3.80E-08	1.62E-06	2.71E-04	2.73E-04	2.73E-07	5.46E-05	5.46E-08
Cs-137	0	2.87E+04	1.26E+03	7.74E-18	1.30E-07	8.86E-10	4.96E-03	4.96E-03	4.96E-06	9.92E-04	9.92E-07
Ce-141	0	4.06E-09	1.78E-10	3.43E-15	1.20E-09	5.55E-20	6.48E-18	6.53E-18	6.53E-21	1.31E-18	1.31E-21
Ce-144	0	3.31E+02	1.45E+01	8.53E-16	3.90E-08	1.13E-09	1.72E-05	1.72E-05	1.72E-08	3.43E-06	3.43E-09
		RATE	2.80E+08		TOTAL	1.52E+00	3.31E+02	3.33E+02	3.33E-01	6.66E+01	6.66E-02

Table A3.4. Potential Doses to Workers from Airborne Releases (RPV, PWR), in mSv, with reduced Safety Controls

Nuclide	Cm (Bq/g)	Cs (Bq/cm^2)	Aav (Bq)	CFE	CFE(50)w	E	**E(50)**	DT	DTcc	DTcs	DTcc+cs
Nb-95	4.34E-11	5.72E-09	1.90E-10	3.74E-14	2.50E-09	3.73E-18	8.31E-17	8.68E-17	8.68E-20	1.74E-17	1.74E-20
Fe-59	1.77E-04	3.99E-05	4.36E-04	5.97E-14	4.40E-09	1.37E-11	3.36E-10	3.49E-10	3.49E-13	6.99E-11	6.99E-14
Co-58	9.86E-02	2.03E-01	2.45E-01	4.76E-14	4.50E-09	6.12E-09	1.93E-07	1.99E-07	1.99E-10	3.98E-08	3.98E-11
Zr-95	2.04E-06	4.26E-08	5.00E-06	3.60E-14	8.60E-09	9.45E-14	7.52E-12	7.62E-12	7.62E-15	1.52E-12	1.52E-15
Zn-65	2.56E-03	8.77E-01	1.91E-02	2.90E-14	2.50E-09	2.90E-10	8.33E-09	8.62E-09	8.62E-12	1.72E-09	1.72E-12
Mn-54	5.86E+03	1.06E+03	1.44E+04	4.09E-14	9.90E-09	3.09E-04	2.50E-02	2.53E-02	2.53E-05	5.05E-03	5.05E-06
Fe-55	7.13E+05	1.73E+05	1.75E+06	0.00E+00	5.60E-10	0.00E+00	1.72E-01	1.72E-01	1.72E-04	3.43E-02	3.43E-05
Co-60	1.42E+05	1.92E+05	3.51E+05	1.26E-13	1.10E-07	2.32E-02	6.75E+00	6.77E+00	6.77E-03	1.35E+00	1.35E-03
Ni-63	1.56E+04	3.87E+04	3.88E+04	0.00E+00	6.00E-09	0.00E+00	4.08E-02	4.08E-02	4.08E-05	8.15E-03	8.15E-06
Mo-93	3.06E+00	1.27E-01	7.51E+00	2.52E-17	4.00E-10	9.93E-11	5.25E-07	5.25E-07	5.25E-10	1.05E-07	1.05E-10
C-14	5.22E+01	4.93E+01	1.29E+02	2.24E-19	2.30E-08	1.52E-11	5.19E-04	5.19E-04	5.19E-07	1.04E-04	1.04E-07
Nb-94	1.87E-01	1.57E+00	4.83E-01	7.70E-14	3.50E-07	1.95E-08	2.96E-05	2.96E-05	2.96E-08	5.92E-06	5.92E-09
Ni-59	1.34E+02	2.62E+02	3.32E+02	0.00E+00	2.90E-09	0.00E+00	1.69E-04	1.69E-04	1.69E-07	3.37E-05	3.37E-08
Ru-103	0	1.97E+02	2.87E+00	2.25E-14	3.10E-09	3.39E-08	1.56E-06	1.59E-06	1.59E-09	3.18E-07	3.18E-10
Ru-106	0	4.34E-07	6.33E-09	0.00E+00	1.30E-07	0.00E+00	1.44E-13	1.44E-13	1.44E-16	2.88E-14	2.88E-17
Cs-134	0	5.37E+03	7.83E+01	7.57E-14	5.30E-08	3.11E-06	7.26E-04	7.29E-04	7.29E-07	1.46E-04	1.46E-07
Cs-137	0	2.87E+04	4.18E+02	7.74E-18	1.90E-07	1.70E-09	1.39E-02	1.39E-02	1.39E-05	2.78E-03	2.78E-06
Ce-141	0	4.06E-09	5.92E-11	3.43E-15	2.60E-09	1.07E-19	2.69E-17	2.70E-17	2.70E-20	5.41E-18	5.41E-21
Ce-144	0	3.31E+02	4.83E+00	8.53E-16	8.40E-08	2.16E-09	7.10E-05	7.10E-05	7.10E-08	1.42E-05	1.42E-08
		RATE	2.16E+06		TOTAL	2.35E-02	7.00E+00	7.02E+00	7.02E-03	1.40E+00	1.40E-03

Table A3.5. Potential Doses to Workers from Airborne Releases (RVI, BWR), in mSv, with reduced Safety Controls

Nuclide	Cm (Bq/g)	Cs (Bq/cm²)	Aav (Bq)	CFE	CFE(50)w	E	E(50)	DT	DTcc	DTcs	DTcc+cs
H-3	1.89E-01	0.00E+00	1.27E-01	3.31E-19	7.20E-10	2.63E-14	1.91E-08	1.91E-08	1.91E-11	3.82E-09	3.82E-12
Be-10	1.30E-03	0.00E+00	8.73E-04	1.12E-17	1.20E-07	6.13E-15	2.19E-08	2.19E-08	2.19E-11	4.38E-09	4.38E-12
C-14	5.20E+04	0.00E+00	3.48E+04	2.24E-19	1.60E-08	4.89E-09	1.17E-01	1.17E-01	1.17E-04	2.33E-02	2.33E-05
P-32	5.38E-23	0.00E+00	3.60E-23	9.90E-17	3.20E-09	2.24E-33	2.41E-29	2.41E-29	2.41E-32	4.82E-30	4.82E-33
P-33	1.78E-10	0.00E+00	1.19E-10	8.23E-19	8.00E-10	6.17E-23	2.00E-17	2.00E-17	2.00E-20	4.00E-18	4.00E-21
S-35	1.12E+00	0.00E+00	7.48E-01	2.43E-19	1.10E-09	1.14E-13	1.72E-07	1.72E-07	1.72E-10	3.44E-08	3.44E-11
Cl-36	1.33E-01	0.00E+00	8.92E-02	2.23E-17	1.40E-07	1.25E-12	2.61E-06	2.61E-06	2.61E-09	5.23E-07	5.23E-10
Cr-51	9.91E-06	3.68E-10	6.64E-06	1.51E-15	5.70E-11	6.29E-15	7.91E-14	8.54E-14	8.54E-17	1.71E-14	1.71E-17
Mn-54	2.20E+05	2.72E+04	1.48E+05	4.09E-14	7.10E-09	3.80E-03	2.20E-01	2.23E-01	2.23E-04	4.47E-02	4.47E-05
Fe-55	1.86E+08	0.00E+00	1.25E+08	0.00E+00	4.10E-10	0.00E+00	1.07E+01	1.07E+01	1.07E-02	2.14E+00	2.14E-03
Fe-59	3.70E-02	9.09E-05	2.48E-02	5.97E-14	3.20E-09	9.29E-10	1.66E-08	1.75E-08	1.75E-11	3.51E-09	3.51E-12
Co-58	4.68E+01	5.57E-02	3.13E+01	4.76E-14	3.20E-09	9.36E-07	2.10E-05	2.19E-05	2.19E-08	4.38E-06	4.38E-09
Co-60	1.05E+08	3.95E+05	7.04E+07	1.26E-13	8.10E-08	5.56E+00	1.19E+03	1.20E+03	1.20E+00	2.40E+02	2.40E-01
Ni-59	3.15E+05	0.00E+00	2.11E+05	0.00E+00	2.10E-09	0.00E+00	9.27E-02	9.27E-02	9.27E-05	1.85E-02	1.85E-05
Ni-63	4.23E+07	0.00E+00	2.83E+07	0.00E+00	4.30E-09	0.00E+00	2.55E+01	2.55E+01	2.55E-02	5.10E+00	5.10E-03
Zn-65	4.31E+02	2.19E+02	2.92E+02	2.90E-14	2.00E-09	5.32E-06	1.22E-04	1.27E-04	1.27E-07	2.55E-05	2.55E-08
Zr-93	4.04E-03	0.00E+00	2.70E-03	0.00E+00	1.00E-08	0.00E+00	5.66E-09	5.66E-09	5.66E-12	1.13E-09	1.13E-12
Zr-95	8.44E-06	6.44E-03	1.11E-04	3.60E-14	6.10E-09	2.50E-12	1.41E-10	1.44E-10	1.44E-13	2.88E-11	2.88E-14
Nb-93m	5.76E+01	0.00E+00	3.85E+01	4.44E-18	5.10E-09	1.07E-10	4.11E-05	4.11E-05	4.11E-08	8.22E-06	8.22E-09
Nb-94	7.43E+02	0.00E+00	4.98E+02	7.70E-14	2.50E-07	2.40E-05	2.60E-02	2.60E-02	2.60E-05	5.21E-03	5.21E-06
Nb-95	6.33E-07	5.67E-08	4.25E-07	3.74E-14	1.70E-09	9.97E-15	1.51E-13	1.61E-13	1.61E-16	3.22E-14	3.22E-17
Mo-93	1.61E+02	0.00E+00	1.08E+02	2.52E-17	2.90E-10	1.71E-09	6.56E-06	6.56E-06	6.56E-09	1.31E-06	1.31E-09
Tc-99	0.00E+00	0.00E+00	0.00E+00	1.62E-18	4.00E-08	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00

Nuclide	Cm (Bq/g)	Cs (Bq/cm²)	Aav (Bq)	CFE	CFE(50)w	E	E(50)	DT	DTcc	DTcs	DTcc+cs
Ag-108m	3.58E+01	0.00E+00	2.40E+01	7.80E-14	2.20E-07	1.17E-06	1.10E-03	1.10E-03	1.10E-06	2.21E-04	2.21E-07
Ag-108	0.00E+00	0.00E+00	0.00E+00	9.28E-16	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Ag-109m	0.00E+00	0.00E+00	0.00E+00	1.92E-16	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Cd-109	2.47E+02	0.00E+00	1.66E+02	2.94E-16	4.30E-09	3.05E-08	1.49E-04	1.49E-04	1.49E-07	2.98E-05	2.98E-08
Ag-110m	1.15E+02	0.00E+00	7.73E+01	1.36E-13	2.30E-08	6.60E-06	3.72E-04	3.79E-04	3.79E-07	7.57E-05	7.57E-08
Ag-110	0.00E+00	0.00E+00	0.00E+00	1.78E-15	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Sm-151	9.55E+04	0.00E+00	6.39E+04	3.61E-20	3.30E-09	1.45E-09	4.41E-02	4.41E-02	4.41E-05	8.82E-03	8.82E-06
Eu-152	8.59E+00	0.00E+00	5.75E+00	5.65E-14	4.80E-08	2.04E-07	5.77E-05	5.79E-05	5.79E-08	1.16E-05	1.16E-08
Eu-154	2.36E+01	0.00E+00	1.58E+01	6.14E-14	4.90E-08	6.08E-07	1.62E-04	1.62E-04	1.62E-07	3.25E-05	3.25E-08
Tb-160	7.25E-03	0.00E+00	4.85E-03	5.54E-14	5.40E-09	1.69E-10	5.48E-09	5.65E-09	5.65E-12	1.13E-09	1.13E-12
Ho-166m	4.67E-01	0.00E+00	3.13E-01	8.45E-14	1.60E-07	1.66E-08	1.05E-05	1.05E-05	1.05E-08	2.10E-06	2.10E-09
Ru-103	0.00E+00	2.86E+02	4.68E+00	2.25E-14	2.20E-09	6.61E-08	2.15E-06	2.22E-06	2.22E-09	4.44E-07	4.44E-10
Ru-106	0.00E+00	6.32E-07	1.03E-08	0.00E+00	9.60E-08	0.00E+00	2.07E-13	2.07E-13	2.07E-16	4.15E-14	4.15E-17
Cs-134	0.00E+00	7.82E+03	1.28E+02	7.57E-14	3.80E-08	6.07E-06	1.02E-03	1.02E-03	1.02E-06	2.04E-04	2.04E-07
Cs-137	0.00E+00	4.18E+04	6.83E+02	7.74E-18	1.30E-07	3.32E-09	1.86E-02	1.86E-02	1.86E-05	3.71E-03	3.71E-06
Ce-141	0.00E+00	5.91E-09	9.66E-11	3.43E-15	1.20E-09	2.08E-19	2.42E-17	2.44E-17	2.44E-20	4.89E-18	4.89E-21
Ce-144	0.00E+00	4.82E+02	7.88E+00	8.53E-16	3.90E-08	4.22E-09	6.43E-05	6.43E-05	6.43E-08	1.29E-05	1.29E-08
		RATE	2.24E+08		TOTAL	5.57E+00	1.23E+03	1.23E+03	1.23E+00	2.47E+02	2.47E-01

Table A3.6. Potential Doses to Workers from Airborne Releases (RPV, BWR), in mSv, with reduced Safety Controls

Nuclide	Cm (Bq/g)	Cs (Bq/cm^2)	Aav (Bq)	CFE	CFE(50)w	E	E(50)	DT	DTcc	DTcs	DTcc+cs
H-3	9.19E-03	0.00E+00	2.26E-02	3.31E-19	1.00E-09	2.99E-14	3.01E-08	3.01E-08	3.01E-11	6.01E-09	6.01E-12
Be-10	6.33E-05	0.00E+00	1.55E-04	1.12E-17	1.70E-07	6.96E-15	3.52E-08	3.52E-08	3.52E-11	7.04E-09	7.04E-12
C-14	2.53E+03	0.00E+00	6.22E+03	2.24E-19	2.30E-08	5.57E-09	1.91E-01	1.91E-01	1.91E-04	3.81E-02	3.81E-05
P-32	3.38E-24	0.00E+00	8.31E-24	9.90E-17	4.40E-09	3.29E-33	4.87E-29	4.87E-29	4.87E-32	9.74E-30	9.74E-33
P-33	8.67E-12	0.00E+00	2.13E-11	8.23E-19	1.20E-09	7.00E-23	3.40E-17	3.40E-17	3.40E-20	6.80E-18	6.80E-21
S-35	5.49E-02	0.00E+00	1.35E-01	2.43E-19	1.60E-09	1.31E-13	2.87E-07	2.87E-07	2.87E-10	5.74E-08	5.74E-11
Cl-36	6.48E-03	0.00E+00	1.59E-02	2.23E-17	1.90E-07	1.42E-12	4.02E-06	4.02E-06	4.02E-09	8.05E-07	8.05E-10
Cr-51	4.82E-07	3.68E-10	1.18E-06	1.51E-15	7.90E-11	7.13E-15	1.24E-13	1.32E-13	1.32E-16	2.63E-14	2.63E-17
Mn-54	1.12E+04	2.72E+04	2.79E+04	4.09E-14	9.90E-09	4.56E-03	3.68E-01	3.73E-01	3.73E-04	7.46E-02	7.46E-05
Fe-55	9.16E+06	0.00E+00	2.25E+07	0.00E+00	5.60E-10	0.00E+00	1.68E+01	1.68E+01	1.68E-02	3.35E+00	3.35E-03
Fe-59	1.82E-03	9.09E-05	4.47E-03	5.97E-14	4.40E-09	1.07E-09	2.62E-08	2.73E-08	2.73E-11	5.46E-09	5.46E-12
Co-58	2.28E+00	5.57E-02	5.60E+00	4.76E-14	4.50E-09	1.06E-06	3.35E-05	3.46E-05	3.46E-08	6.92E-06	6.92E-09
Co-60	5.11E+06	3.95E+05	1.25E+07	1.26E-13	1.10E-07	6.32E+00	1.84E+03	1.85E+03	1.85E+00	3.69E+02	3.69E-01
Ni-59	1.53E+04	0.00E+00	3.76E+04	0.00E+00	2.90E-09	0.00E+00	1.45E-01	1.45E-01	1.45E-04	2.91E-02	2.91E-05
Ni-63	2.06E+06	0.00E+00	5.05E+06	0.00E+00	6.00E-09	0.00E+00	4.04E+01	4.04E+01	4.04E-02	8.07E+00	8.07E-03
Zn-65	2.09E+01	2.19E+02	5.53E+01	2.90E-14	2.50E-09	6.41E-06	1.84E-04	1.90E-04	1.90E-07	3.81E-05	3.81E-08
Zr-93	1.96E-04	0.00E+00	4.82E-04	0.00E+00	1.40E-08	0.00E+00	8.98E-09	8.98E-09	8.98E-12	1.80E-09	1.80E-12
Zr-95	5.78E-07	6.44E-03	1.15E-04	3.60E-14	8.60E-09	1.66E-11	1.32E-09	1.34E-09	1.34E-12	2.67E-10	2.67E-13
Nb-93m	3.08E+00	0.00E+00	7.57E+00	4.44E-18	7.20E-09	1.34E-10	7.26E-05	7.26E-05	7.26E-08	1.45E-05	1.45E-08
Nb-94	3.61E+01	0.00E+00	8.87E+01	7.70E-14	3.50E-07	2.73E-05	4.13E-02	4.14E-02	4.14E-05	8.27E-03	8.27E-06
Nb-95	3.08E-08	5.67E-08	7.65E-08	3.74E-14	2.50E-09	1.14E-14	2.55E-13	2.66E-13	2.66E-16	5.33E-14	5.33E-17
Mo-93	8.65E+00	0.00E+00	2.12E+01	2.52E-17	4.00E-10	2.14E-09	1.13E-05	1.13E-05	1.13E-08	2.26E-06	2.26E-09

Nuclide	Cm (Bq/g)	Cs (Bq/cm^2)	Aav (Bq)	CFE	CFE(50)w	E	E(50)	DT	DTcc	DTcs	DTcc+cs
Tc-99	0.00E+00	0.00E+00	0.00E+00	1.62E-18	5.50E-08	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Ag-108m	1.74E+00	0.00E+00	4.27E+00	7.80E-14	3.10E-07	1.33E-06	1.76E-03	1.76E-03	1.76E-06	3.53E-04	3.53E-07
Ag-108	0.00E+00	0.00E+00	0.00E+00	9.28E-16	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Ag-109m	0.00E+00	0.00E+00	0.00E+00	1.92E-16	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Cd-109	1.20E+01	0.00E+00	2.95E+01	2.94E-16	6.00E-09	3.46E-08	2.36E-04	2.36E-04	2.36E-07	4.71E-05	4.71E-08
Ag-110m	5.61E+00	0.00E+00	1.38E+01	1.36E-13	3.20E-08	7.49E-06	5.87E-04	5.95E-04	5.95E-07	1.19E-04	1.19E-07
Ag-110	0.00E+00	0.00E+00	0.00E+00	1.78E-15	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Sm-151	4.97E-01	0.00E+00	1.22E+00	3.61E-20	4.70E-09	1.76E-13	7.63E-06	7.63E-06	7.63E-09	1.53E-06	1.53E-09
Eu-152	2.25E-02	0.00E+00	5.52E-02	5.65E-14	6.70E-08	1.25E-08	4.92E-06	4.94E-06	4.94E-09	9.87E-07	9.87E-10
Eu-154	5.67E+01	0.00E+00	1.39E+02	6.14E-14	6.90E-08	3.41E-05	1.28E-02	1.28E-02	1.28E-05	2.56E-03	2.56E-06
Tb-160	1.09E-07	0.00E+00	2.68E-07	5.54E-14	7.60E-09	5.94E-14	2.71E-12	2.77E-12	2.77E-15	5.55E-13	5.55E-16
Ho-166m	1.88E-02	0.00E+00	4.62E-02	8.45E-14	1.60E-07	1.56E-08	9.86E-06	9.87E-06	9.87E-09	1.97E-06	1.97E-09
Ru-103	0.00E+00	2.86E+02	5.07E+00	2.25E-14	3.10E-09	4.56E-07	2.09E-05	2.14E-05	2.14E-08	4.28E-06	4.28E-09
Ru-106	0.00E+00	6.32E-07	1.12E-08	0.00E+00	1.30E-07	0.00E+00	1.94E-12	1.94E-12	1.94E-15	3.87E-13	3.87E-16
Cs-134	0.00E+00	7.82E+03	1.38E+02	7.57E-14	5.30E-08	4.18E-05	9.76E-03	9.80E-03	9.80E-06	1.96E-03	1.96E-06
Cs-137	0.00E+00	4.18E+04	7.39E+02	7.74E-18	1.90E-07	2.29E-08	1.87E-01	1.87E-01	1.87E-04	3.74E-02	3.74E-05
Ce-141	0.00E+00	5.91E-09	1.05E-10	3.43E-15	2.60E-09	1.43E-18	3.62E-16	3.63E-16	3.63E-19	7.27E-17	7.27E-20
Ce-144	0.00E+00	4.82E+02	8.53E+00	8.53E-16	8.40E-08	2.91E-08	9.55E-04	9.55E-04	9.55E-07	1.91E-04	1.91E-07
		RATE	4.02E+07		TOTAL	6.32E+00	1.90E+03	1.90E+03	1.90E+00	3.81E+02	3.81E-01

A3.2. Doses to public

Doses to public should be evaluated considering all possible releases, both liquid and gaseous, and associated dose pathways (i.e. cloud shine, ground shine, ingestion, inhalation…), as per Offsite Doses Calculation Manual (ODCM). This requires very detailed information about the plant and its surroundings, and of the population habits. As this is not available, an evaluation will be performed based on the considered two most relevant pathways with conservative conditions: cloud-shine dose and inhalation dose from gaseous discharges. Potential End Users may perform a more detailed analysis based on specific plant conditions and as per their Offsite Doses Calculation Manual (ODCM).

For estimating doses, the following process will be followed for each accident scenario:

- Airborne releases will be released through the off-gas considering building filtration.
- The activity will be dispersed up to the location of the group of the public considering meteorological conditions and associated dispersion factors. Calculation distances are 100 for infants and adults, plus 250, 500 and 1,000 meters for the found to be the critical individual.
- Doses will be calculated using dose coefficients of each group of the public, and thus, identifying the critical individual.

Effective Dose (E), in mSv, from external exposure (cloud-shine dose) will be calculated as follows:

$$E = \sum_i A_i \cdot X/Q \cdot CFE_i \cdot 10^3 \qquad \text{Eq. A3.4.}$$

Where:

- Ai is the activity released for each radionuclide, in Bq. Airborne releases will be obtained per section 4.3.1.1. Different releases will be estimated based on the availability of collection and filtration means, as per section 4.3.1.2. Same assumptions as for Eq. A3.2 are made.
- X/Q is the dispersion factor, in s/m^3. Refer to section 4.3.3.
- CFEi is the effective dose coefficient for each radionuclide, in (Sv·m^3) / (Bq·s) [Ref. 24]
- The factor 10^3 is used for adjusting units (mSv/Sv).

The inhalation Committed Effective Dose E(ζ), in mSv, will be calculated as follows:

$$E(\zeta) = \sum_i A_i \cdot BR \cdot X/Q \cdot CFE(50)_i \cdot 10^3 \qquad \text{Eq. A3.5.}$$

Where:

- Ai is the activity released for each radionuclide, in Bq. Airborne releases will be obtained per section 4.3.1.1. Different releases will be estimated based on the availability of collection and filtration means, as per section 4.3.1.2. Same assumptions as for Eq. A3.2 are made.

- BR is the breathing rate of the critical person, 3.5E-04 m^3/s [Ref. 32].
- X/Q is the dispersion factor, in s/m^3. Refer to section 4.3.3.
- CFE(ζ)i is the inhalation dose coefficient for each radionuclide, in Sv/Bq, for the individual (1-2 year child or adult) [Ref. 24, 27]. The highest value from the table is selected.
- The factor 10^3 is used for adjusting units (mSv/Sv).

The results are summarized in Tables A3.7 (RVI of a PWR) A3.8 (RPV of a PWR), A3.9 (RVI of a BWR) and A3.10 (RPV of a BWR).

Table A3.7. Public Doses from normal activities (RVI, PWR), in mSv, considering the implementation of different safety controls

							Infant 1-2y at 100m						
Nuclide	Cm (Bq/g)	Cs (Bq/cm²)	Ai (Bq)	CFE	CFE(70)$_{1\text{-}2}$	CFE(50)a	E	E(70)	DT	DTb	DTcc	DTcs	DTcc+cs
Nb-95	5.91E-06	5.72E-09	6.00E-03	3.74E-14	5.90E-09	1.80E-09	1.79E-15	9.86E-14	1.00E-13	3.01E-17	3.91E-20	6.03E-18	1.81E-20
Fe-59	4.09E-02	3.99E-05	4.15E+01	5.97E-14	1.30E-08	4.00E-09	1.97E-11	1.50E-09	1.52E-09	4.57E-13	5.94E-16	9.15E-14	2.74E-16
Co-58	2.10E+02	2.03E-01	2.13E+05	4.76E-14	7.50E-09	2.10E-09	8.06E-08	4.44E-06	4.52E-06	1.36E-09	1.76E-12	2.72E-10	8.14E-13
Zr-95	4.06E-05	4.26E-08	4.12E-02	3.60E-14	1.90E-08	5.90E-09	1.18E-14	2.18E-12	2.19E-12	6.57E-16	8.55E-19	1.32E-16	3.94E-19
Zn-65	9.06E+02	8.77E-01	9.19E+05	2.90E-14	6.70E-09	2.00E-09	2.12E-07	1.72E-05	1.74E-05	5.21E-09	6.77E-12	1.04E-09	3.13E-12
Mn-54	1.08E+06	1.06E+03	1.10E+09	4.09E-14	6.20E-09	1.50E-09	3.57E-04	1.90E-02	1.93E-02	5.80E-06	7.54E-09	1.16E-06	3.48E-09
Fe-55	1.78E+08	1.73E+05	1.81E+11	0.00E+00	8.50E-10	1.80E-10	0.00E+00	4.28E-01	4.28E-01	1.28E-04	1.67E-07	2.57E-05	7.70E-08
Co-60	1.98E+08	1.92E+05	2.01E+11	1.26E-13	8.60E-08	3.10E-08	2.02E-01	4.82E+01	4.84E+01	1.45E-02	1.89E-05	2.91E-03	8.72E-06
Ni-63	4.00E+07	3.87E+04	4.06E+10	0.00E+00	4.30E-09	1.30E-09	0.00E+00	4.86E-01	4.86E-01	1.46E-04	1.90E-07	2.92E-05	8.75E-08
Mo-93	1.27E+02	1.27E-01	1.28E+05	2.52E-17	5.80E-09	2.30E-09	2.58E-11	2.07E-06	2.07E-06	6.22E-10	8.09E-13	1.25E-10	3.73E-13
C-14	5.08E+04	4.93E+01	5.16E+07	2.24E-19	1.70E-08	5.80E-09	9.19E-11	2.44E-03	2.44E-03	7.32E-07	9.52E-10	1.47E-07	4.39E-10
Nb-94	1.62E+03	1.57E+00	1.65E+06	7.70E-14	1.20E-07	4.90E-08	1.01E-06	5.51E-04	5.52E-04	1.66E-07	2.15E-10	3.32E-08	9.94E-11
Ni-59	2.70E+05	2.62E+02	2.74E+08	0.00E+00	1.50E-09	4.40E-10	0.00E+00	1.15E-03	1.15E-03	3.44E-07	4.47E-10	6.89E-08	2.06E-10
Ru-103	0	1.97E+02	1.31E+04	2.25E-14	1.00E-08	3.00E-09	2.34E-09	3.64E-07	3.67E-07	1.10E-10	1.43E-13	2.20E-11	6.60E-14
Ru-106	0	4.34E-07	2.88E-05	0.00E+00	2.30E-07	6.60E-08	0.00E+00	1.85E-14	1.85E-14	5.55E-18	7.21E-21	1.11E-18	3.33E-21
Cs-134	0	5.37E+03	3.57E+05	7.57E-14	6.30E-08	2.00E-08	2.15E-07	6.26E-05	6.29E-05	1.89E-08	2.45E-11	3.77E-09	1.13E-11
Cs-137	0	2.87E+04	1.91E+06	7.74E-18	1.00E-07	3.90E-08	1.18E-10	5.31E-04	5.31E-04	1.59E-07	2.07E-10	3.19E-08	9.57E-11
Ce-141	0	4.06E-09	2.70E-07	3.43E-15	1.20E-08	3.80E-09	7.37E-21	9.02E-18	9.03E-18	2.71E-21	3.52E-24	5.42E-22	1.62E-24
Ce-144	0	3.31E+02	2.20E+04	8.53E-16	1.80E-07	5.30E-08	1.49E-10	1.10E-05	1.10E-05	3.31E-09	4.31E-12	6.63E-10	1.99E-12
						TOTAL	2.02E-01	4.92E+01	4.94E+01	1.48E-02	1.93E-05	2.97E-03	8.89E-06

	Adult at 100m							Infant 1-2y at 250m						
Nuclide	E	E(50)	DT	Dtb	DTcc	DTcs	DTcc+cs	E	E(70)	DT	DTb	DTcc	DTcs	DTcc+cs
Nb-95	1.79E-15	3.01E-14	3.19E-14	9.56E-18	1.24E-20	1.91E-18	5.73E-21	3.57E-16	1.97E-14	2.00E-14	6.01E-18	7.82E-21	1.20E-18	3.61E-21
Fe-59	1.97E-11	4.62E-10	4.82E-10	1.45E-13	1.88E-16	2.90E-14	8.68E-17	3.94E-12	3.00E-10	3.04E-10	9.13E-14	1.19E-16	1.83E-14	5.48E-17
Co-58	8.06E-08	1.24E-06	1.32E-06	3.97E-10	5.17E-13	7.96E-11	2.38E-13	1.61E-08	8.87E-07	9.04E-07	2.71E-10	3.52E-13	5.43E-11	1.63E-13
Zr-95	1.18E-14	6.77E-13	6.89E-13	2.07E-16	2.69E-19	4.14E-17	1.24E-19	2.36E-15	4.35E-13	4.38E-13	1.31E-16	1.71E-19	2.63E-17	7.88E-20
Zn-65	2.12E-07	5.12E-06	5.33E-06	1.60E-09	2.08E-12	3.20E-10	9.60E-13	4.24E-08	3.43E-06	3.47E-06	1.04E-09	1.35E-12	2.08E-10	6.24E-13
Mn-54	3.57E-04	4.59E-03	4.95E-03	1.48E-06	1.93E-09	2.97E-07	8.90E-10	7.14E-05	3.79E-03	3.86E-03	1.16E-06	1.51E-09	2.32E-07	6.95E-10
Fe-55	0.00E+00	9.05E-02	9.05E-02	2.72E-05	3.53E-08	5.44E-06	1.63E-08	0.00E+00	8.54E-02	8.54E-02	2.56E-05	3.33E-08	5.13E-06	1.54E-08
Co-60	2.02E-01	1.74E+01	1.76E+01	5.28E-03	6.86E-06	1.06E-03	3.17E-06	4.03E-02	9.64E+00	9.68E+00	2.90E-03	3.77E-06	5.81E-04	1.74E-06
Ni-63	0.00E+00	1.47E-01	1.47E-01	4.41E-05	5.73E-08	8.82E-06	2.64E-08	0.00E+00	9.71E-02	9.71E-02	2.91E-05	3.79E-08	5.83E-06	1.75E-08
Mo-93	2.58E-11	8.23E-07	8.23E-07	2.47E-10	3.21E-13	4.94E-11	1.48E-13	5.14E-12	4.14E-07	4.14E-07	1.24E-10	1.62E-13	2.49E-11	7.46E-14
C-14	9.19E-11	8.33E-04	8.33E-04	2.50E-07	3.25E-10	5.00E-08	1.50E-10	1.84E-11	4.88E-04	4.88E-04	1.46E-07	1.90E-10	2.93E-08	8.78E-11
Nb-94	1.01E-06	2.25E-04	2.26E-04	6.78E-08	8.82E-11	1.36E-08	4.07E-11	2.02E-07	1.10E-04	1.10E-04	3.31E-08	4.30E-11	6.62E-09	1.99E-11
Ni-59	0.00E+00	3.36E-04	3.36E-04	1.01E-07	1.31E-10	2.02E-08	6.05E-11	0.00E+00	2.29E-04	2.29E-04	6.87E-08	8.93E-11	1.38E-08	4.12E-11
Ru-103	2.34E-09	1.09E-07	1.12E-07	3.35E-11	4.35E-14	6.70E-12	2.01E-14	4.68E-10	7.28E-08	7.32E-08	2.20E-11	2.86E-14	4.40E-12	1.32E-14
Ru-106	0.00E+00	5.30E-15	5.30E-15	1.59E-18	2.07E-21	3.19E-19	9.55E-22	0.00E+00	3.69E-15	3.69E-15	1.11E-18	1.44E-21	2.22E-19	6.65E-22
Cs-134	2.15E-07	1.99E-05	2.01E-05	6.03E-09	7.84E-12	1.21E-09	3.62E-12	4.30E-08	1.25E-05	1.26E-05	3.77E-09	4.90E-12	7.54E-10	2.26E-12
Cs-137	1.18E-10	2.07E-04	2.07E-04	6.22E-08	8.08E-11	1.24E-08	3.73E-11	2.35E-11	1.06E-04	1.06E-04	3.18E-08	4.14E-11	6.38E-09	1.91E-11
Ce-141	7.37E-21	2.86E-18	2.86E-18	8.59E-22	1.12E-24	1.72E-22	5.15E-25	1.47E-21	1.80E-18	1.80E-18	5.41E-22	7.03E-25	1.08E-22	3.25E-25
Ce-144	1.49E-10	3.25E-06	3.25E-06	9.75E-10	1.27E-12	1.95E-10	5.85E-13	2.99E-11	2.21E-06	2.21E-06	6.62E-10	8.60E-13	1.32E-10	3.97E-13
TOTAL	2.02E-01	1.76E+01	1.78E+01	5.35E-03	6.96E-06	1.07E-03	3.21E-06	4.04E-02	9.82E+00	9.86E+00	2.96E-03	3.85E-06	5.92E-04	1.78E-06

	Infant 1-2y at 500m							Infant 1-2y at 1000m						
Nuclide	E	E(70)	DT	DTb	DTcc	DTcs	DTcc+cs	E	E(70)	DT	DTb	DTcc	DTcs	DTcc+cs
Nb-95	1.05E-16	5.80E-15	5.90E-15	1.77E-18	2.30E-21	3.54E-19	1.06E-21	3.66E-17	2.02E-15	2.06E-15	6.17E-19	8.02E-22	1.23E-19	3.70E-22
Fe-59	1.16E-12	8.84E-11	8.95E-11	2.69E-14	3.49E-17	5.38E-15	1.61E-17	4.04E-13	3.08E-11	3.12E-11	9.36E-15	1.22E-17	1.87E-15	5.61E-18
Co-58	4.74E-09	2.61E-07	2.66E-07	7.98E-11	1.04E-13	1.60E-11	4.79E-14	1.65E-09	9.10E-08	9.26E-08	2.78E-11	3.61E-14	5.56E-12	1.67E-14
Zr-95	6.94E-16	1.28E-13	1.29E-13	3.87E-17	5.02E-20	7.74E-18	2.32E-20	2.42E-16	4.46E-14	4.49E-14	1.35E-17	1.75E-20	2.70E-18	8.08E-21
Zn-65	1.25E-08	1.01E-06	1.02E-06	3.06E-10	3.98E-13	6.13E-11	1.84E-13	4.34E-09	3.51E-07	3.56E-07	1.07E-10	1.39E-13	2.14E-11	6.40E-14
Mn-54	2.10E-05	1.11E-03	1.14E-03	3.41E-07	4.43E-10	6.82E-08	2.04E-10	7.32E-06	3.88E-04	3.96E-04	1.19E-07	1.54E-10	2.38E-08	7.12E-11
Fe-55	0.00E+00	2.51E-02	2.51E-02	7.54E-06	9.80E-09	1.51E-06	4.52E-09	0.00E+00	8.75E-03	8.75E-03	2.63E-06	3.41E-09	5.26E-07	1.58E-09
Co-60	1.19E-02	2.84E+00	2.85E+00	8.55E-04	1.11E-06	1.71E-04	5.13E-07	4.14E-03	9.88E-01	9.92E-01	2.98E-04	3.87E-07	5.96E-05	1.79E-07
Ni-63	0.00E+00	2.86E-02	2.86E-02	8.57E-06	1.11E-08	1.72E-06	5.14E-09	0.00E+00	9.95E-03	9.95E-03	2.99E-06	3.88E-09	5.98E-07	1.79E-09
Mo-93	1.51E-12	1.22E-07	1.22E-07	3.66E-11	4.76E-14	7.33E-12	2.20E-14	5.27E-13	4.25E-08	4.25E-08	1.27E-11	1.66E-14	2.55E-12	7.65E-15
C-14	5.40E-12	1.44E-04	1.44E-04	4.31E-08	5.60E-11	8.62E-09	2.58E-11	1.88E-12	5.00E-05	5.00E-05	1.50E-08	1.95E-11	3.00E-09	9.00E-12
Nb-94	5.94E-08	3.24E-05	3.25E-05	9.74E-09	1.27E-11	1.95E-09	5.84E-12	2.07E-08	1.13E-05	1.13E-05	3.39E-09	4.41E-12	6.79E-10	2.04E-12
Ni-59	0.00E+00	6.74E-05	6.74E-05	2.02E-08	2.63E-11	4.05E-09	1.21E-11	0.00E+00	2.35E-05	2.35E-05	7.04E-09	9.16E-12	1.41E-09	4.23E-12
Ru-103	1.38E-10	2.14E-08	2.16E-08	6.47E-12	8.41E-15	1.29E-12	3.88E-15	4.80E-11	7.46E-09	7.51E-09	2.25E-12	2.93E-15	4.51E-13	1.35E-15
Ru-106	0.00E+00	1.09E-15	1.09E-15	3.26E-19	4.24E-22	6.53E-20	1.96E-22	0.00E+00	3.79E-16	3.79E-16	1.14E-19	1.48E-22	2.27E-20	6.81E-23
Cs-134	1.26E-08	3.68E-06	3.70E-06	1.11E-09	1.44E-12	2.22E-10	6.65E-13	4.40E-09	1.28E-06	1.29E-06	3.86E-10	5.02E-13	7.73E-11	2.32E-13
Cs-137	6.91E-12	3.12E-05	3.12E-05	9.37E-09	1.22E-11	1.88E-09	5.62E-12	2.41E-12	1.09E-05	1.09E-05	3.26E-09	4.24E-12	6.54E-10	1.96E-12
Ce-141	4.33E-22	5.30E-19	5.31E-19	1.59E-22	2.07E-25	3.19E-23	9.55E-26	1.51E-22	1.85E-19	1.85E-19	5.55E-23	7.21E-26	1.11E-23	3.33E-26
Ce-144	8.79E-12	6.49E-07	6.49E-07	1.95E-10	2.53E-13	3.90E-11	1.17E-13	3.06E-12	2.26E-07	2.26E-07	6.78E-11	8.82E-14	1.36E-11	4.07E-14
TOTAL	1.19E-02	2.89E+00	2.90E+00	8.71E-04	1.13E-06	1.74E-04	5.23E-07	4.14E-03	1.01E+00	1.01E+00	3.03E-04	3.94E-07	6.07E-05	1.82E-07

Table A3.8. Public Doses from normal activities (RPV, PWR), in mSv, considering the implementation of different safety controls

							Infant 1-2y at 100m						
Nuclide	Cm (Bq/g)	Cs (Bq/cm^2)	Ai (Bq)	CFE	CFE(70)	CFE(50)	E	E(70)	DT	DTb	DTcc	DTcs	DTcc+cs
Nb-95	4.34E-11	5.72E-09	1.66E-06	3.74E-14	5.90E-09	1.80E-09	4.95E-19	2.73E-17	2.78E-17	8.35E-21	1.08E-23	1.67E-21	5.01E-24
Fe-59	1.77E-04	3.99E-05	3.82E+00	5.97E-14	1.30E-08	4.00E-09	1.81E-12	1.38E-10	1.40E-10	4.20E-14	5.46E-17	8.41E-15	2.52E-17
Co-58	9.86E-02	2.03E-01	2.14E+03	4.76E-14	7.50E-09	2.10E-09	8.12E-10	4.48E-08	4.56E-08	1.37E-11	1.78E-14	2.74E-12	8.20E-15
Zr-95	2.04E-06	4.26E-08	4.37E-02	3.60E-14	1.90E-08	5.90E-09	1.25E-14	2.31E-12	2.33E-12	6.98E-16	9.08E-19	1.40E-16	4.19E-19
Zn-65	2.56E-03	8.77E-01	1.67E+02	2.90E-14	6.70E-09	2.00E-09	3.85E-11	3.11E-09	3.15E-09	9.45E-13	1.23E-15	1.89E-13	5.67E-16
Mn-54	5.86E+03	1.06E+03	1.26E+08	4.09E-14	6.20E-09	1.50E-09	4.10E-05	2.18E-03	2.22E-03	6.66E-07	8.65E-10	1.33E-07	3.99E-10
Fe-55	7.13E+05	1.73E+05	1.53E+10	0.00E+00	8.50E-10	1.80E-10	0.00E+00	3.63E-02	3.63E-02	1.09E-05	1.42E-08	2.18E-06	6.53E-09
Co-60	1.42E+05	1.92E+05	3.07E+09	1.26E-13	8.60E-08	3.10E-08	3.08E-03	7.35E-01	7.38E-01	2.21E-04	2.88E-07	4.43E-05	1.33E-07
Ni-63	1.56E+04	3.87E+04	3.40E+08	0.00E+00	4.30E-09	1.30E-09	0.00E+00	4.07E-03	4.07E-03	1.22E-06	1.59E-09	2.44E-07	7.33E-10
Mo-93	3.06E+00	1.27E-01	6.57E+04	2.52E-17	5.80E-09	2.30E-09	1.32E-11	1.06E-06	1.06E-06	3.18E-10	4.14E-13	6.37E-11	1.91E-13
C-14	5.22E+01	4.93E+01	1.13E+06	2.24E-19	1.70E-08	5.80E-09	2.01E-12	5.34E-05	5.34E-05	1.60E-08	2.08E-11	3.21E-09	9.62E-12
Nb-94	1.87E-01	1.57E+00	4.22E+03	7.70E-14	1.20E-07	4.90E-08	2.59E-09	1.41E-06	1.41E-06	4.24E-10	5.52E-13	8.50E-11	2.55E-13
Ni-59	1.34E+02	2.62E+02	2.91E+06	0.00E+00	1.50E-09	4.40E-10	0.00E+00	1.22E-05	1.22E-05	3.65E-09	4.74E-12	7.30E-10	2.19E-12
Ru-103	0	1.97E+02	2.51E+04	2.25E-14	1.00E-08	3.00E-09	4.49E-09	6.99E-07	7.03E-07	2.11E-10	2.74E-13	4.22E-11	1.27E-13
Ru-106	0	4.34E-07	5.54E-05	0.00E+00	2.30E-07	6.60E-08	0.00E+00	3.55E-14	3.55E-14	1.06E-17	1.38E-20	2.13E-18	6.38E-21
Cs-134	0	5.37E+03	6.85E+05	7.57E-14	6.30E-08	2.00E-08	4.13E-07	1.20E-04	1.21E-04	3.62E-08	4.70E-11	7.24E-09	2.17E-11
Cs-137	0	2.87E+04	3.66E+06	7.74E-18	1.00E-07	3.90E-08	2.25E-10	1.02E-03	1.02E-03	3.06E-07	3.98E-10	6.12E-08	1.84E-10
Ce-141	0	4.06E-09	5.18E-07	3.43E-15	1.20E-08	3.80E-09	1.41E-20	1.73E-17	1.73E-17	5.20E-21	6.76E-24	1.04E-21	3.12E-24
Ce-144	0	3.31E+02	4.22E+04	8.53E-16	1.80E-07	5.30E-08	2.87E-10	2.12E-05	2.12E-05	6.36E-09	8.26E-12	1.27E-09	3.81E-12
						TOTAL	3.12E-03	7.79E-01	7.82E-01	2.34E-04	3.05E-07	4.69E-05	1.41E-07

	Adult at 100m							Infant 1-2y at 250m						
Nuclide	E	E(75)	DT	DTb	DTcc	DTcs	DTcc+cs	E	E(70)	DT	DTb	DTcc	DTcs	DTcc+cs
Nb-95	4.95E-19	8.34E-18	8.83E-18	2.65E-21	3.44E-24	5.30E-22	1.59E-24	9.88E-20	5.46E-18	5.56E-18	1.67E-21	2.17E-24	3.34E-22	1.00E-24
Fe-59	1.81E-12	4.25E-11	4.43E-11	1.33E-14	1.73E-17	2.66E-15	7.98E-18	3.62E-13	2.76E-11	2.80E-11	8.39E-15	1.09E-17	1.68E-15	5.03E-18
Co-58	8.12E-10	1.25E-08	1.33E-08	4.00E-12	5.21E-15	8.02E-13	2.40E-15	1.62E-10	8.94E-09	9.10E-09	2.73E-12	3.55E-15	5.47E-13	1.64E-15
Zr-95	1.25E-14	7.19E-13	7.31E-13	2.19E-16	2.85E-19	4.39E-17	1.32E-19	2.50E-15	4.62E-13	4.65E-13	1.39E-16	1.81E-19	2.79E-17	8.37E-20
Zn-65	3.85E-11	9.29E-10	9.67E-10	2.90E-13	3.77E-16	5.81E-14	1.74E-16	7.68E-12	6.21E-10	6.29E-10	1.89E-13	2.45E-16	3.78E-14	1.13E-16
Mn-54	4.10E-05	5.27E-04	5.68E-04	1.70E-07	2.21E-10	3.41E-08	1.02E-10	8.20E-06	4.35E-04	4.43E-04	1.33E-07	1.73E-10	2.66E-08	7.98E-11
Fe-55	0.00E+00	7.69E-03	7.69E-03	2.31E-06	3.00E-09	4.62E-07	1.38E-09	0.00E+00	7.25E-03	7.25E-03	2.18E-06	2.83E-09	4.36E-07	1.31E-09
Co-60	3.08E-03	2.65E-01	2.68E-01	8.04E-05	1.04E-07	1.61E-05	4.82E-08	6.14E-04	1.47E-01	1.47E-01	4.42E-05	5.75E-08	8.85E-06	2.65E-08
Ni-63	0.00E+00	1.23E-03	1.23E-03	3.69E-07	4.80E-10	7.39E-08	2.21E-10	0.00E+00	8.13E-04	8.13E-04	2.44E-07	3.17E-10	4.88E-08	1.46E-10
Mo-93	1.32E-11	4.21E-07	4.21E-07	1.26E-10	1.64E-13	2.53E-11	7.57E-14	2.63E-12	2.12E-07	2.12E-07	6.36E-11	8.27E-14	1.27E-11	3.82E-14
C-14	2.01E-12	1.82E-05	1.82E-05	5.47E-09	7.11E-12	1.09E-09	3.28E-12	4.02E-13	1.07E-05	1.07E-05	3.20E-09	4.16E-12	6.41E-10	1.92E-12
Nb-94	2.59E-09	5.77E-07	5.79E-07	1.74E-10	2.26E-13	3.48E-11	1.04E-13	5.17E-10	2.82E-07	2.83E-07	8.48E-11	1.10E-13	1.70E-11	5.09E-14
Ni-59	0.00E+00	3.57E-06	3.57E-06	1.07E-09	1.39E-12	2.14E-10	6.42E-13	0.00E+00	2.43E-06	2.43E-06	7.28E-10	9.47E-13	1.46E-10	4.37E-13
Ru-103	4.49E-09	2.10E-07	2.14E-07	6.43E-11	8.35E-14	1.29E-11	3.86E-14	8.97E-10	1.40E-07	1.41E-07	4.22E-11	5.48E-14	8.44E-12	2.53E-14
Ru-106	0.00E+00	1.02E-14	1.02E-14	3.05E-18	3.97E-21	6.11E-19	1.83E-21	0.00E+00	7.08E-15	7.08E-15	2.13E-18	2.76E-21	4.26E-19	1.28E-21
Cs-134	4.13E-07	3.82E-05	3.86E-05	1.16E-08	1.50E-11	2.32E-09	6.94E-12	8.24E-08	2.40E-05	2.41E-05	7.23E-09	9.40E-12	1.45E-09	4.34E-12
Cs-137	2.25E-10	3.98E-04	3.98E-04	1.19E-07	1.55E-10	2.39E-08	7.16E-11	4.50E-11	2.04E-04	2.04E-04	6.11E-08	7.94E-11	1.22E-08	3.67E-11
Ce-141	1.41E-20	5.48E-18	5.49E-18	1.65E-21	2.14E-24	3.30E-22	9.89E-25	2.82E-21	3.46E-18	3.46E-18	1.04E-21	1.35E-24	2.08E-22	6.23E-25
Ce-144	2.87E-10	6.24E-06	6.24E-06	1.87E-09	2.43E-12	3.75E-10	1.12E-12	5.73E-11	4.23E-06	4.23E-06	1.27E-09	1.65E-12	2.54E-10	7.62E-13
TOTAL	3.12E-03	2.75E-01	2.78E-01	8.34E-05	1.08E-07	1.67E-05	5.00E-08	6.23E-04	1.56E-01	1.56E-01	4.68E-05	6.09E-08	9.38E-06	2.81E-08

	Infant 1-2y at 500m							Infant 1-2y at 1000m						
Nuclide	E	E(70)	DT	DTb	DTcc	DTcs	DTcc+cs	E	E(70)	DT	DTb	DTcc	DTcs	DTcc+cs
Nb-95	2.91E-20	1.61E-18	1.64E-18	4.91E-22	6.38E-25	9.82E-23	2.94E-25	1.01E-20	5.60E-19	5.70E-19	1.71E-22	2.22E-25	3.42E-23	1.03E-25
Fe-59	1.07E-13	8.12E-12	8.23E-12	2.47E-15	3.21E-18	4.94E-16	1.48E-18	3.71E-14	2.83E-12	2.87E-12	8.60E-16	1.12E-18	1.72E-16	5.16E-19
Co-58	4.77E-11	2.63E-09	2.68E-09	8.04E-13	1.05E-15	1.61E-13	4.82E-16	1.66E-11	9.17E-10	9.33E-10	2.80E-13	3.64E-16	5.61E-14	1.68E-16
Zr-95	7.37E-16	1.36E-13	1.37E-13	4.11E-17	5.34E-20	8.22E-18	2.46E-20	2.57E-16	4.74E-14	4.77E-14	1.43E-17	1.86E-20	2.86E-18	8.58E-21
Zn-65	2.26E-12	1.83E-10	1.85E-10	5.55E-14	7.22E-17	1.11E-14	3.33E-17	7.88E-13	6.37E-11	6.45E-11	1.93E-14	2.52E-17	3.87E-15	1.16E-17
Mn-54	2.41E-06	1.28E-04	1.30E-04	3.91E-08	5.09E-11	7.83E-09	2.35E-11	8.40E-07	4.46E-05	4.54E-05	1.36E-08	1.77E-11	2.73E-09	8.18E-12
Fe-55	0.00E+00	2.13E-03	2.13E-03	6.40E-07	8.32E-10	1.28E-07	3.84E-10	0.00E+00	7.43E-04	7.43E-04	2.23E-07	2.90E-10	4.46E-08	1.34E-10
Co-60	1.81E-04	4.32E-02	4.34E-02	1.30E-05	1.69E-08	2.61E-06	7.81E-09	6.30E-05	1.50E-02	1.51E-02	4.53E-06	5.89E-09	9.07E-07	2.72E-09
Ni-63	0.00E+00	2.39E-04	2.39E-04	7.18E-08	9.33E-11	1.44E-08	4.31E-11	0.00E+00	8.33E-05	8.33E-05	2.50E-08	3.25E-11	5.01E-09	1.50E-11
Mo-93	7.74E-13	6.24E-08	6.24E-08	1.87E-11	2.43E-14	3.75E-12	1.12E-14	2.70E-13	2.17E-08	2.17E-08	6.52E-12	8.47E-15	1.30E-12	3.91E-15
C-14	1.18E-13	3.14E-06	3.14E-06	9.42E-10	1.23E-12	1.89E-10	5.65E-13	4.12E-14	1.09E-06	1.09E-06	3.28E-10	4.27E-13	6.57E-11	1.97E-13
Nb-94	1.52E-10	8.30E-08	8.32E-08	2.50E-11	3.24E-14	5.00E-12	1.50E-14	5.30E-11	2.89E-08	2.90E-08	8.69E-12	1.13E-14	1.74E-12	5.21E-15
Ni-59	0.00E+00	7.15E-07	7.15E-07	2.14E-10	2.79E-13	4.29E-11	1.29E-13	0.00E+00	2.49E-07	2.49E-07	7.47E-11	9.71E-14	1.49E-11	4.48E-14
Ru-103	2.64E-10	4.11E-08	4.14E-08	1.24E-11	1.61E-14	2.48E-12	7.44E-15	9.20E-11	1.43E-08	1.44E-08	4.32E-12	5.62E-15	8.65E-13	2.59E-15
Ru-106	0.00E+00	2.09E-15	2.09E-15	6.26E-19	8.13E-22	1.25E-19	3.75E-22	0.00E+00	7.26E-16	7.26E-16	2.18E-19	2.83E-22	4.36E-20	1.31E-22
Cs-134	2.43E-08	7.07E-06	7.09E-06	2.13E-09	2.77E-12	4.26E-10	1.28E-12	8.45E-09	2.46E-06	2.47E-06	7.41E-10	9.63E-13	1.48E-10	4.45E-13
Cs-137	1.33E-11	6.00E-05	6.00E-05	1.80E-08	2.34E-11	3.60E-09	1.08E-11	4.62E-12	2.09E-05	2.09E-05	6.26E-09	8.14E-12	1.25E-09	3.76E-12
Ce-141	8.31E-22	1.02E-18	1.02E-18	3.06E-22	3.97E-25	6.12E-23	1.83E-25	2.89E-22	3.54E-19	3.55E-19	1.06E-22	1.38E-25	2.13E-23	6.38E-26
Ce-144	1.69E-11	1.25E-06	1.25E-06	3.74E-10	4.86E-13	7.48E-11	2.24E-13	5.87E-12	4.34E-07	4.34E-07	1.30E-10	1.69E-13	2.61E-11	7.81E-14
TOTAL	1.83E-04	4.58E-02	4.60E-02	1.38E-05	1.79E-08	2.76E-06	8.27E-09	6.38E-05	1.59E-02	1.60E-02	4.80E-06	6.24E-09	9.61E-07	2.88E-09

Table A3.9. Public Doses from normal activities (RVI, BWR), in mSv, considering the implementation of different safety controls

							Infant 1-2y at 100m						
Nuclide	Cm (Bq/g)	Cs (Bq/cm^2)	Ai (Bq)	CFE	CFE(70)	CFE(50)	E	E(70)	DT	DTb	DTcc	DTcs	DTcc+cs
H-3	1.89E-01	0.00E+00	2.65E+02	3.31E-19	1.00E-09	2.60E-10	6.98E-16	7.38E-10	7.38E-10	2.21E-13	2.88E-16	4.43E-14	1.33E-16
Be-10	1.30E-03	0.00E+00	1.82E+00	1.12E-17	9.10E-08	3.50E-08	1.63E-16	4.63E-10	4.63E-10	1.39E-13	1.80E-16	2.78E-14	8.33E-17
C-14	5.20E+04	0.00E+00	7.28E+07	2.24E-19	1.70E-08	5.80E-09	1.30E-10	3.45E-03	3.45E-03	1.03E-06	1.35E-09	2.07E-07	6.21E-10
P-32	5.38E-23	0.00E+00	7.53E-20	9.90E-17	1.50E-08	3.40E-09	5.93E-35	3.15E-30	3.15E-30	9.44E-34	1.23E-36	1.89E-34	5.67E-37
P-33	1.78E-10	0.00E+00	2.50E-07	8.23E-19	4.60E-09	1.50E-09	1.64E-24	3.20E-18	3.20E-18	9.61E-22	1.25E-24	1.92E-22	5.76E-25
S-35	1.12E+00	0.00E+00	1.56E+03	2.43E-19	6.00E-09	1.90E-09	3.02E-15	2.61E-08	2.61E-08	7.84E-12	1.02E-14	1.57E-12	4.71E-15
Cl-36	1.33E-01	0.00E+00	1.87E+02	2.23E-17	2.60E-08	7.30E-09	3.31E-14	1.35E-08	1.35E-08	4.06E-12	5.27E-15	8.12E-13	2.43E-15
Cr-51	9.91E-06	3.68E-10	1.39E-02	1.51E-15	2.10E-10	3.70E-11	1.67E-16	8.12E-15	8.29E-15	2.49E-18	3.23E-21	4.98E-19	1.49E-21
Mn-54	2.20E+05	2.72E+04	3.09E+08	4.09E-14	6.20E-09	1.50E-09	1.01E-04	5.34E-03	5.45E-03	1.63E-06	2.12E-09	3.27E-07	9.80E-10
Fe-55	1.86E+08	0.00E+00	2.61E+11	0.00E+00	3.20E-09	7.70E-10	0.00E+00	2.32E+00	2.32E+00	6.97E-04	9.06E-07	1.40E-04	4.18E-07
Fe-59	3.70E-02	9.09E-05	5.19E+01	5.97E-14	1.30E-08	4.00E-09	2.47E-11	1.88E-09	1.90E-09	5.71E-13	7.42E-16	1.14E-13	3.43E-16
Co-58	4.68E+01	5.57E-02	6.55E+04	4.76E-14	7.50E-09	2.10E-09	2.48E-08	1.37E-06	1.39E-06	4.18E-10	5.44E-13	8.37E-11	2.51E-13
Co-60	1.05E+08	3.95E+05	1.47E+11	1.26E-13	8.60E-08	3.10E-08	1.48E-01	3.53E+01	3.54E+01	1.06E-02	1.38E-05	2.13E-03	6.37E-06
Ni-59	3.15E+05	0.00E+00	4.41E+08	0.00E+00	1.50E-09	4.40E-10	0.00E+00	1.84E-03	1.84E-03	5.53E-07	7.19E-10	1.11E-07	3.32E-10
Ni-63	4.23E+07	0.00E+00	5.93E+10	0.00E+00	4.30E-09	1.30E-09	0.00E+00	7.10E-01	7.10E-01	2.13E-04	2.77E-07	4.26E-05	1.28E-07
Zn-65	4.31E+02	2.19E+02	6.11E+05	2.90E-14	6.70E-09	2.00E-09	1.41E-07	1.14E-05	1.15E-05	3.46E-09	4.50E-12	6.93E-10	2.08E-12
Zr-93	4.04E-03	0.00E+00	5.66E+00	0.00E+00	6.40E-09	2.50E-08	0.00E+00	1.01E-10	1.01E-10	3.03E-14	3.93E-17	6.06E-15	1.82E-17
Zr-95	8.44E-06	6.44E-03	2.32E-01	3.60E-14	1.90E-08	5.90E-09	6.64E-14	1.23E-11	1.23E-11	3.70E-15	4.81E-18	7.41E-16	2.22E-18
Nb-93m	5.76E+01	0.00E+00	8.06E+04	4.44E-18	6.50E-09	1.80E-09	2.85E-12	1.46E-06	1.46E-06	4.38E-10	5.69E-13	8.77E-11	2.63E-13
Nb-94	7.43E+02	0.00E+00	1.04E+06	7.70E-14	1.20E-07	4.90E-08	6.38E-07	3.48E-04	3.49E-04	1.05E-07	1.36E-10	2.09E-08	6.27E-11
Nb-95	6.33E-07	5.67E-08	8.89E-04	3.74E-14	5.90E-09	1.80E-09	2.65E-16	1.46E-14	1.49E-14	4.46E-18	5.80E-21	8.93E-19	2.68E-21
Mo-93	1.61E+02	0.00E+00	2.26E+05	2.52E-17	5.80E-09	2.30E-09	4.53E-11	3.65E-06	3.65E-06	1.10E-09	1.42E-12	2.19E-10	6.58E-13
Tc-99	0.00E+00	0.00E+00	0.00E+00	1.62E-18	3.70E-08	1.30E-08	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Ag-108m	3.58E+01	0.00E+00	5.01E+04	7.80E-14	8.70E-08	3.70E-08	3.11E-08	1.21E-05	1.22E-05	3.65E-09	4.75E-12	7.31E-10	2.19E-12
Ag-108	0.00E+00	0.00E+00	0.00E+00	9.28E-16	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Ag-109m	0.00E+00	0.00E+00	0.00E+00	1.92E-16	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00

							Infant 1-2y at 100m						
Nuclide	Cm (Bq/g)	Cs (Bq/cm^2)	Ai (Bq)	CFE	CFE(70)	CFE(50)	E	E(70)	DT	DTb	DTcc	DTcs	DTcc+cs
Cd-109	2.47E+02	0.00E+00	3.46E+05	2.94E-16	3.70E-08	8.10E-09	8.10E-10	3.57E-05	3.57E-05	1.07E-08	1.39E-11	2.14E-09	6.42E-12
Ag-110m	1.15E+02	0.00E+00	1.62E+05	1.36E-13	4.10E-08	1.20E-08	1.75E-07	1.85E-05	1.86E-05	5.59E-09	7.27E-12	1.12E-09	3.36E-12
Ag-110	0.00E+00	0.00E+00	0.00E+00	1.78E-15	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Sm-151	9.55E+04	0.00E+00	1.34E+08	3.61E-20	1.00E-08	4.00E-09	3.84E-11	3.72E-03	3.72E-03	1.12E-06	1.45E-09	2.24E-07	6.70E-10
Eu-152	8.59E+00	0.00E+00	1.20E+04	5.65E-14	1.00E-07	4.20E-08	5.41E-09	3.35E-06	3.36E-06	1.01E-09	1.31E-12	2.02E-10	6.04E-13
Eu-154	2.36E+01	0.00E+00	3.30E+04	6.14E-14	1.50E-07	5.30E-08	1.61E-08	1.38E-05	1.38E-05	4.14E-09	5.39E-12	8.30E-10	2.49E-12
Tb-160	7.25E-03	0.00E+00	1.02E+01	5.54E-14	2.50E-08	7.00E-09	4.48E-12	7.07E-10	7.12E-10	2.14E-13	2.78E-16	4.27E-14	1.28E-16
Ho-166m	4.67E-01	0.00E+00	6.54E+02	8.45E-14	2.50E-07	1.20E-07	4.40E-10	4.56E-07	4.56E-07	1.37E-10	1.78E-13	2.74E-11	8.21E-14
Ru-103	0.00E+00	2.86E+02	9.79E+03	2.25E-14	1.00E-08	3.00E-09	1.75E-09	2.73E-07	2.74E-07	8.23E-11	1.07E-13	1.65E-11	4.94E-14
Ru-106	0.00E+00	6.32E-07	2.16E-05	0.00E+00	2.30E-07	6.60E-08	0.00E+00	1.38E-14	1.38E-14	4.15E-18	5.40E-21	8.31E-19	2.49E-21
Cs-134	0.00E+00	7.82E+03	2.67E+05	7.57E-14	6.30E-08	2.00E-08	1.61E-07	4.69E-05	4.70E-05	1.41E-08	1.83E-11	2.83E-09	8.47E-12
Cs-137	0.00E+00	4.18E+04	1.43E+06	7.74E-18	1.00E-07	3.90E-08	8.80E-11	3.98E-04	3.98E-04	1.19E-07	1.55E-10	2.39E-08	7.16E-11
Ce-141	0.00E+00	5.91E-09	2.02E-07	3.43E-15	1.20E-08	3.80E-09	5.51E-21	6.75E-18	6.76E-18	2.03E-21	2.64E-24	4.06E-22	1.22E-24
Ce-144	0.00E+00	4.82E+02	1.65E+04	8.53E-16	1.80E-07	5.30E-08	1.12E-10	8.26E-06	8.26E-06	2.48E-09	3.22E-12	4.96E-10	1.49E-12
						TOTAL	1.48E-01	3.83E+01	3.85E+01	1.15E-02	1.50E-05	2.31E-03	6.92E-06

	Adult at 100m							Infant 1-2y at 250m						
Nuclide	E	E(50)	DT	DTb	DTcc	DTcs	DTcc+cs	E	E(70)	DT	DTb	DTcc	DTcs	DTcc+cs
H-3	6.98E-16	1.92E-10	1.92E-10	5.76E-14	7.49E-17	1.15E-14	3.46E-17	1.39E-16	1.47E-10	1.47E-10	4.42E-14	5.75E-17	8.86E-15	2.65E-17
Be-10	1.63E-16	1.78E-10	1.78E-10	5.34E-14	6.94E-17	1.07E-14	3.20E-17	3.25E-17	9.24E-11	9.24E-11	2.77E-14	3.60E-17	5.55E-15	1.66E-17
C-14	1.30E-10	1.18E-03	1.18E-03	3.53E-07	4.59E-10	7.07E-08	2.12E-10	2.59E-11	6.89E-04	6.89E-04	2.07E-07	2.69E-10	4.14E-08	1.24E-10
P-32	5.93E-35	7.13E-31	7.13E-31	2.14E-34	2.78E-37	4.28E-35	1.28E-37	1.19E-35	6.29E-31	6.29E-31	1.89E-34	2.45E-37	3.78E-35	1.13E-37
P-33	1.64E-24	1.04E-18	1.04E-18	3.13E-22	4.07E-25	6.27E-23	1.88E-25	3.27E-25	6.40E-19	6.40E-19	1.92E-22	2.49E-25	3.84E-23	1.15E-25
S-35	3.02E-15	8.28E-09	8.28E-09	2.48E-12	3.23E-15	4.97E-13	1.49E-15	6.04E-16	5.22E-09	5.22E-09	1.57E-12	2.04E-15	3.14E-13	9.40E-16
Cl-36	3.31E-14	3.80E-09	3.80E-09	1.14E-12	1.48E-15	2.28E-13	6.83E-16	6.62E-15	2.70E-09	2.70E-09	8.10E-13	1.05E-15	1.62E-13	4.86E-16
Cr-51	1.67E-16	1.43E-15	1.60E-15	4.79E-19	6.23E-22	9.60E-20	2.88E-22	3.33E-17	1.62E-15	1.66E-15	4.97E-19	6.46E-22	9.94E-20	2.98E-22
Mn-54	1.01E-04	1.29E-03	1.39E-03	4.18E-07	5.44E-10	8.37E-08	2.51E-10	2.01E-05	1.07E-03	1.09E-03	3.26E-07	4.24E-10	6.53E-08	1.96E-10
Fe-55	0.00E+00	5.59E-01	5.59E-01	1.68E-04	2.18E-07	3.36E-05	1.01E-07	0.00E+00	4.64E-01	4.64E-01	1.39E-04	1.81E-07	2.79E-05	8.35E-08
Fe-59	2.47E-11	5.78E-10	6.03E-10	1.81E-13	2.35E-16	3.62E-14	1.09E-16	4.92E-12	3.75E-10	3.80E-10	1.14E-13	1.48E-16	2.28E-14	6.84E-17
Co-58	2.48E-08	3.83E-07	4.08E-07	1.22E-10	1.59E-13	2.45E-11	7.35E-14	4.96E-09	2.73E-07	2.78E-07	8.35E-11	1.09E-13	1.67E-11	5.01E-14
Co-60	1.48E-01	1.27E+01	1.29E+01	3.86E-03	5.01E-06	7.72E-04	2.31E-06	2.95E-02	7.04E+00	7.07E+00	2.12E-03	2.76E-06	4.25E-04	1.27E-06
Ni-59	0.00E+00	5.41E-04	5.41E-04	1.62E-07	2.11E-10	3.25E-08	9.74E-11	0.00E+00	3.68E-04	3.68E-04	1.11E-07	1.44E-10	2.21E-08	6.63E-11
Ni-63	0.00E+00	2.15E-01	2.15E-01	6.44E-05	8.37E-08	1.29E-05	3.86E-08	0.00E+00	1.42E-01	1.42E-01	4.25E-05	5.53E-08	8.52E-06	2.55E-08
Zn-65	1.41E-07	3.40E-06	3.55E-06	1.06E-09	1.38E-12	2.13E-10	6.38E-13	2.82E-08	2.28E-06	2.31E-06	6.92E-10	8.99E-13	1.39E-10	4.15E-13
Zr-93	0.00E+00	3.94E-10	3.94E-10	1.18E-13	1.54E-16	2.37E-14	7.09E-17	0.00E+00	2.01E-11	2.01E-11	6.04E-15	7.86E-18	1.21E-15	3.63E-18
Zr-95	6.64E-14	3.81E-12	3.88E-12	1.16E-15	1.51E-18	2.33E-16	6.98E-19	1.33E-14	2.45E-12	2.46E-12	7.39E-16	9.61E-19	1.48E-16	4.43E-19
Nb-93m	2.85E-12	4.04E-07	4.04E-07	1.21E-10	1.58E-13	2.43E-11	7.28E-14	5.69E-13	2.92E-07	2.92E-07	8.75E-11	1.14E-13	1.75E-11	5.25E-14
Nb-94	6.38E-07	1.42E-04	1.43E-04	4.28E-08	5.57E-11	8.57E-09	2.57E-11	1.27E-07	6.95E-05	6.96E-05	2.09E-08	2.72E-11	4.18E-09	1.25E-11
Nb-95	2.65E-16	4.46E-15	4.72E-15	1.42E-18	1.84E-21	2.84E-19	8.50E-22	5.28E-17	2.92E-15	2.97E-15	8.91E-19	1.16E-21	1.78E-19	5.35E-22
Mo-93	4.53E-11	1.45E-06	1.45E-06	4.35E-10	5.65E-13	8.70E-11	2.61E-13	9.06E-12	7.30E-07	7.30E-07	2.19E-10	2.85E-13	4.38E-11	1.31E-13
Tc-99	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Ag-108m	3.11E-08	5.17E-06	5.20E-06	1.56E-09	2.03E-12	3.12E-10	9.35E-13	6.21E-09	2.43E-06	2.43E-06	7.30E-10	9.49E-13	1.46E-10	4.38E-13
Ag-108	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Ag-	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00

	Adult at 100m							Infant 1-2y at 250m						
Nuclide	E	E(50)	DT	DTb	DTcc	DTcs	DTcc+cs	E	E(70)	DT	DTb	DTcc	DTcs	DTcc+cs
109m														
Cd-109	8.10E-10	7.81E-06	7.81E-06	2.34E-09	3.05E-12	4.69E-10	1.41E-12	1.62E-10	7.13E-06	7.13E-06	2.14E-09	2.78E-12	4.28E-10	1.28E-12
Ag-110m	1.75E-07	5.41E-06	5.58E-06	1.67E-09	2.18E-12	3.35E-10	1.00E-12	3.50E-08	3.69E-06	3.72E-06	1.12E-09	1.45E-12	2.24E-10	6.70E-13
Ag-110	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Sm-151	3.84E-11	1.49E-03	1.49E-03	4.47E-07	5.81E-10	8.95E-08	2.68E-10	7.67E-12	7.44E-04	7.44E-04	2.23E-07	2.90E-10	4.47E-08	1.34E-10
Eu-152	5.41E-09	1.41E-06	1.41E-06	4.24E-10	5.51E-13	8.49E-11	2.54E-13	1.08E-09	6.69E-07	6.70E-07	2.01E-10	2.61E-13	4.03E-11	1.21E-13
Eu-154	1.61E-08	4.87E-06	4.89E-06	1.47E-09	1.91E-12	2.94E-10	8.80E-13	3.22E-09	2.76E-06	2.76E-06	8.28E-10	1.08E-12	1.66E-10	4.97E-13
Tb-160	4.48E-12	1.98E-10	2.03E-10	6.08E-14	7.90E-17	1.22E-14	3.65E-17	8.94E-13	1.41E-10	1.42E-10	4.26E-14	5.54E-17	8.54E-15	2.56E-17
Ho-166m	4.40E-10	2.19E-07	2.19E-07	6.58E-11	8.55E-14	1.32E-11	3.95E-14	8.79E-11	9.10E-08	9.11E-08	2.73E-11	3.55E-14	5.47E-12	1.64E-14
Ru-103	1.75E-09	8.18E-08	8.36E-08	2.51E-11	3.26E-14	5.02E-12	1.50E-14	3.50E-10	5.45E-08	5.48E-08	1.64E-11	2.14E-14	3.29E-12	9.87E-15
Ru-106	0.00E+00	3.97E-15	3.97E-15	1.19E-18	1.55E-21	2.38E-19	7.15E-22	0.00E+00	2.76E-15	2.76E-15	8.29E-19	1.08E-21	1.66E-19	4.98E-22
Cs-134	1.61E-07	1.49E-05	1.50E-05	4.51E-09	5.87E-12	9.04E-10	2.71E-12	3.22E-08	9.37E-06	9.40E-06	2.82E-09	3.67E-12	5.64E-10	1.69E-12
Cs-137	8.80E-11	1.55E-04	1.55E-04	4.65E-08	6.05E-11	9.32E-09	2.79E-11	1.76E-11	7.95E-05	7.95E-05	2.38E-08	3.10E-11	4.77E-09	1.43E-11
Ce-141	5.51E-21	2.14E-18	2.14E-18	6.43E-22	8.36E-25	1.29E-22	3.86E-25	1.10E-21	1.35E-18	1.35E-18	4.05E-22	5.26E-25	8.11E-23	2.43E-25
Ce-144	1.12E-10	2.43E-06	2.43E-06	7.30E-10	9.49E-13	1.46E-10	4.38E-13	2.24E-11	1.65E-06	1.65E-06	4.95E-10	6.44E-13	9.92E-11	2.97E-13
TOTAL	1.48E-01	1.35E+01	1.36E+01	4.09E-03	5.32E-06	8.19E-04	2.45E-06	2.95E-02	7.65E+00	7.68E+00	2.30E-03	3.00E-06	4.61E-04	1.38E-06

	Infant 1-2y at 500m							Infant 1-2y at 1000m						
Nuclide	E	E(70)	DT	DTb	DTcc	DTcs	DTcc+cs	E	E(70)	DT	DTb	DTcc	DTcs	DTcc+cs
H-3	4.11E-17	4.34E-11	4.34E-11	1.30E-14	1.69E-17	2.61E-15	7.81E-18	1.43E-17	1.51E-11	1.51E-11	4.54E-15	5.90E-18	9.08E-16	2.72E-18
Be-10	9.57E-18	2.72E-11	2.72E-11	8.16E-15	1.06E-17	1.63E-15	4.90E-18	3.33E-18	9.47E-12	9.47E-12	2.84E-15	3.70E-18	5.69E-16	1.71E-18
C-14	7.63E-12	2.03E-04	2.03E-04	6.08E-08	7.91E-11	1.22E-08	3.65E-11	2.66E-12	7.06E-05	7.06E-05	2.12E-08	2.75E-11	4.24E-09	1.27E-11
P-32	3.49E-36	1.85E-31	1.85E-31	5.55E-35	7.22E-38	1.11E-35	3.33E-38	1.22E-36	6.44E-32	6.44E-32	1.93E-35	2.51E-38	3.87E-36	1.16E-38
P-33	9.62E-26	1.88E-19	1.88E-19	5.65E-23	7.34E-26	1.13E-23	3.39E-26	3.35E-26	6.56E-20	6.56E-20	1.97E-23	2.56E-26	3.94E-24	1.18E-26
S-35	1.78E-16	1.54E-09	1.54E-09	4.61E-13	5.99E-16	9.23E-14	2.77E-16	6.19E-17	5.35E-10	5.35E-10	1.61E-13	2.09E-16	3.21E-14	9.63E-17
Cl-36	1.95E-15	7.95E-10	7.95E-10	2.38E-13	3.10E-16	4.77E-14	1.43E-16	6.78E-16	2.77E-10	2.77E-10	8.31E-14	1.08E-16	1.66E-14	4.98E-17
Cr-51	9.81E-18	4.77E-16	4.87E-16	1.46E-19	1.90E-22	2.93E-20	8.77E-23	3.42E-18	1.66E-16	1.70E-16	5.09E-20	6.62E-23	1.02E-20	3.05E-23
Mn-54	5.92E-06	3.14E-04	3.20E-04	9.60E-08	1.25E-10	1.92E-08	5.76E-11	2.06E-06	1.09E-04	1.12E-04	3.35E-08	4.35E-11	6.70E-09	2.01E-11
Fe-55	0.00E+00	1.37E-01	1.37E-01	4.10E-05	5.33E-08	8.20E-06	2.46E-08	0.00E+00	4.76E-02	4.76E-02	1.43E-05	1.86E-08	2.86E-06	8.56E-09
Fe-59	1.45E-12	1.10E-10	1.12E-10	3.36E-14	4.37E-17	6.72E-15	2.01E-17	5.05E-13	3.85E-11	3.90E-11	1.17E-14	1.52E-17	2.34E-15	7.02E-18
Co-58	1.46E-09	8.05E-08	8.20E-08	2.46E-11	3.20E-14	4.92E-12	1.48E-14	5.08E-10	2.80E-08	2.85E-08	8.56E-12	1.11E-14	1.71E-12	5.14E-15
Co-60	8.68E-03	2.07E+00	2.08E+00	6.25E-04	8.12E-07	1.25E-04	3.75E-07	3.02E-03	7.22E-01	7.25E-01	2.18E-04	2.83E-07	4.35E-05	1.31E-07
Ni-59	0.00E+00	1.08E-04	1.08E-04	3.25E-08	4.23E-11	6.51E-09	1.95E-11	0.00E+00	3.78E-05	3.78E-05	1.13E-08	1.47E-11	2.27E-09	6.80E-12
Ni-63	0.00E+00	4.17E-02	4.17E-02	1.25E-05	1.63E-08	2.51E-06	7.51E-09	0.00E+00	1.45E-02	1.45E-02	4.36E-06	5.67E-09	8.73E-07	2.62E-09
Zn-65	8.29E-09	6.70E-07	6.79E-07	2.04E-10	2.65E-13	4.08E-11	1.22E-13	2.89E-09	2.34E-07	2.36E-07	7.09E-11	9.22E-14	1.42E-11	4.26E-14
Zr-93	0.00E+00	5.93E-12	5.93E-12	1.78E-15	2.31E-18	3.56E-16	1.07E-18	0.00E+00	2.06E-12	2.06E-12	6.19E-16	8.05E-19	1.24E-16	3.72E-19
Zr-95	3.90E-15	7.21E-13	7.25E-13	2.18E-16	2.83E-19	4.35E-17	1.31E-19	1.36E-15	2.51E-13	2.53E-13	7.58E-17	9.85E-20	1.52E-17	4.55E-20
Nb-93m	1.67E-13	8.58E-08	8.58E-08	2.57E-11	3.35E-14	5.15E-12	1.54E-14	5.83E-14	2.99E-08	2.99E-08	8.97E-12	1.17E-14	1.80E-12	5.38E-15
Nb-94	3.75E-08	2.05E-05	2.05E-05	6.15E-09	7.99E-12	1.23E-09	3.69E-12	1.31E-08	7.12E-06	7.14E-06	2.14E-09	2.78E-12	4.29E-10	1.28E-12
Nb-95	1.56E-17	8.59E-16	8.74E-16	2.62E-19	3.41E-22	5.25E-20	1.57E-22	5.42E-18	2.99E-16	3.05E-16	9.14E-20	1.19E-22	1.83E-20	5.48E-23
Mo-93	2.67E-12	2.15E-07	2.15E-07	6.44E-11	8.38E-14	1.29E-11	3.87E-14	9.29E-13	7.48E-08	7.48E-08	2.24E-11	2.92E-14	4.49E-12	1.35E-14
Tc-99	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Ag-108m	1.83E-09	7.14E-07	7.16E-07	2.15E-10	2.79E-13	4.30E-11	1.29E-13	6.37E-10	2.49E-07	2.49E-07	7.48E-11	9.72E-14	1.50E-11	4.49E-14
Ag-108	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Ag-	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00

	Infant 1-2y at 500m							Infant 1-2y at 1000m						
Nuclide	E	E(70)	DT	DTb	DTcc	DTcs	DTcc+cs	E	E(70)	DT	DTb	DTcc	DTcs	DTcc+cs
109m														
Cd-109	4.76E-11	2.10E-06	2.10E-06	6.29E-10	8.18E-13	1.26E-10	3.78E-13	1.66E-11	7.31E-07	7.31E-07	2.19E-10	2.85E-13	4.39E-11	1.32E-13
Ag-110m	1.03E-08	1.09E-06	1.10E-06	3.29E-10	4.28E-13	6.59E-11	1.97E-13	3.59E-09	3.78E-07	3.82E-07	1.15E-10	1.49E-13	2.29E-11	6.87E-14
Ag-110	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Sm-151	2.26E-12	2.19E-04	2.19E-04	6.57E-08	8.54E-11	1.32E-08	3.94E-11	7.87E-13	7.63E-05	7.63E-05	2.29E-08	2.97E-11	4.58E-09	1.37E-11
Eu-152	3.18E-10	1.97E-07	1.97E-07	5.92E-11	7.70E-14	1.19E-11	3.55E-14	1.11E-10	6.86E-08	6.87E-08	2.06E-11	2.68E-14	4.13E-12	1.24E-14
Eu-154	9.49E-10	8.11E-07	8.12E-07	2.44E-10	3.17E-13	4.88E-11	1.46E-13	3.30E-10	2.82E-07	2.83E-07	8.48E-11	1.10E-13	1.70E-11	5.09E-14
Tb-160	2.63E-13	4.16E-11	4.18E-11	1.26E-14	1.63E-17	2.51E-15	7.53E-18	9.17E-14	1.45E-11	1.46E-11	4.37E-15	5.68E-18	8.75E-16	2.62E-18
Ho-166m	2.59E-11	2.68E-08	2.68E-08	8.05E-12	1.05E-14	1.61E-12	4.83E-15	9.01E-12	9.33E-09	9.34E-09	2.80E-12	3.64E-15	5.61E-13	1.68E-15
Ru-103	1.03E-10	1.60E-08	1.61E-08	4.84E-12	6.29E-15	9.69E-13	2.90E-15	3.59E-11	5.58E-09	5.62E-09	1.69E-12	2.19E-15	3.38E-13	1.01E-15
Ru-106	0.00E+00	8.14E-16	8.14E-16	2.44E-19	3.17E-22	4.89E-20	1.46E-22	0.00E+00	2.83E-16	2.83E-16	8.50E-20	1.11E-22	1.70E-20	5.10E-23
Cs-134	9.46E-09	2.76E-06	2.77E-06	8.30E-10	1.08E-12	1.66E-10	4.98E-13	3.30E-09	9.60E-07	9.63E-07	2.89E-10	3.76E-13	5.79E-11	1.73E-13
Cs-137	5.17E-12	2.34E-05	2.34E-05	7.02E-09	9.12E-12	1.40E-09	4.21E-12	1.80E-12	8.15E-06	8.15E-06	2.44E-09	3.18E-12	4.89E-10	1.47E-12
Ce-141	3.24E-22	3.97E-19	3.97E-19	1.19E-22	1.55E-25	2.39E-23	7.15E-26	1.13E-22	1.38E-19	1.38E-19	4.15E-23	5.40E-26	8.31E-24	2.49E-26
Ce-144	6.58E-12	4.86E-07	4.86E-07	1.46E-10	1.90E-13	2.92E-11	8.75E-14	2.29E-12	1.69E-07	1.69E-07	5.08E-11	6.60E-14	1.02E-11	3.05E-14
TOTAL	8.68E-03	2.25E+00	2.26E+00	6.78E-04	8.82E-07	1.36E-04	4.07E-07	3.02E-03	7.84E-01	7.87E-01	2.36E-04	3.07E-07	4.73E-05	1.42E-07

Table A3.10. Public Doses from normal activities (RPV, BWR), in mSv, considering the implementation of different safety controls

							Infant 1-2y at 100m						
Nuclide	Cm (Bq/g)	Cs (Bq/cm^2)	Ai (Bq)	CFE	CFE(70)	CFE(50)	E	E(70)	DT	DTb	DTcc	DTcs	DTcc+cs
H-3	9.19E-03	0.00E+00	3.01E+02	3.31E-19	1.00E-09	2.60E-10	7.92E-16	8.38E-10	8.38E-10	2.51E-13	3.27E-16	5.03E-14	1.51E-16
Be-10	6.33E-05	0.00E+00	2.07E+00	1.12E-17	9.10E-08	3.50E-08	1.85E-16	5.25E-10	5.25E-10	1.57E-13	2.05E-16	3.15E-14	9.45E-17
C-14	2.53E+03	0.00E+00	8.28E+07	2.24E-19	1.70E-08	5.80E-09	1.48E-10	3.92E-03	3.92E-03	1.18E-06	1.53E-09	2.36E-07	7.06E-10
P-32	3.38E-24	0.00E+00	1.11E-19	9.90E-17	1.50E-08	3.40E-09	8.72E-35	4.63E-30	4.63E-30	1.39E-33	1.80E-36	2.78E-34	8.33E-37
P-33	8.67E-12	0.00E+00	2.84E-07	8.23E-19	4.60E-09	1.50E-09	1.86E-24	3.63E-18	3.63E-18	1.09E-21	1.42E-24	2.18E-22	6.54E-25
S-35	5.49E-02	0.00E+00	1.79E+03	2.43E-19	6.00E-09	1.90E-09	3.47E-15	3.00E-08	3.00E-08	9.00E-12	1.17E-14	1.80E-12	5.40E-15
Cl-36	6.48E-03	0.00E+00	2.12E+02	2.23E-17	2.60E-08	7.30E-09	3.76E-14	1.53E-08	1.53E-08	4.60E-12	5.98E-15	9.21E-13	2.76E-15
Cr-51	4.82E-07	3.68E-10	1.58E-02	1.51E-15	2.10E-10	3.70E-11	1.89E-16	9.21E-15	9.40E-15	2.82E-18	3.67E-21	5.65E-19	1.69E-21
Mn-54	1.12E+04	2.72E+04	3.72E+08	4.09E-14	6.20E-09	1.50E-09	1.21E-04	6.43E-03	6.55E-03	1.96E-06	2.55E-09	3.93E-07	1.18E-09
Fe-55	9.16E+06	0.00E+00	2.99E+11	0.00E+00	3.20E-09	7.70E-10	0.00E+00	2.67E+00	2.67E+00	8.01E-04	1.04E-06	1.60E-04	4.81E-07
Fe-59	1.82E-03	9.09E-05	5.96E+01	5.97E-14	1.30E-08	4.00E-09	2.83E-11	2.16E-09	2.19E-09	6.56E-13	8.53E-16	1.31E-13	3.94E-16
Co-58	2.28E+00	5.57E-02	7.46E+04	4.76E-14	7.50E-09	2.10E-09	2.82E-08	1.56E-06	1.59E-06	4.76E-10	6.19E-13	9.53E-11	2.85E-13
Co-60	5.11E+06	3.95E+05	1.67E+11	1.26E-13	8.60E-08	3.10E-08	1.68E-01	4.01E+01	4.02E+01	1.21E-02	1.57E-05	2.42E-03	7.24E-06
Ni-59	1.53E+04	0.00E+00	5.01E+08	0.00E+00	1.50E-09	4.40E-10	0.00E+00	2.09E-03	2.09E-03	6.28E-07	8.17E-10	1.26E-07	3.77E-10
Ni-63	2.06E+06	0.00E+00	6.73E+10	0.00E+00	4.30E-09	1.30E-09	0.00E+00	8.06E-01	8.06E-01	2.42E-04	3.14E-07	4.84E-05	1.45E-07
Zn-65	2.09E+01	2.19E+02	7.36E+05	2.90E-14	6.70E-09	2.00E-09	1.70E-07	1.37E-05	1.39E-05	4.17E-09	5.43E-12	8.36E-10	2.50E-12
Zr-93	1.96E-04	0.00E+00	6.42E+00	0.00E+00	6.40E-09	2.50E-08	0.00E+00	1.14E-10	1.14E-10	3.43E-14	4.46E-17	6.87E-15	2.06E-17
Zr-95	5.78E-07	6.44E-03	1.54E+00	3.60E-14	1.90E-08	5.90E-09	4.40E-13	8.13E-11	8.17E-11	2.45E-14	3.19E-17	4.91E-15	1.47E-17
Nb-93m	3.08E+00	0.00E+00	1.01E+05	4.44E-18	6.50E-09	1.80E-09	3.57E-12	1.83E-06	1.83E-06	5.48E-10	7.12E-13	1.10E-10	3.29E-13
Nb-94	3.61E+01	0.00E+00	1.18E+06	7.70E-14	1.20E-07	4.90E-08	7.24E-07	3.95E-04	3.96E-04	1.19E-07	1.54E-10	2.38E-08	7.12E-11
Nb-95	3.08E-08	5.67E-08	1.02E-03	3.74E-14	5.90E-09	1.80E-09	3.04E-16	1.68E-14	1.71E-14	5.12E-18	6.65E-21	1.02E-18	3.07E-21
Mo-93	8.65E+00	0.00E+00	2.83E+05	2.52E-17	5.80E-09	2.30E-09	5.67E-11	4.57E-06	4.57E-06	1.37E-09	1.78E-12	2.75E-10	8.23E-13
Tc-99	0.00E+00	0.00E+00	0.00E+00	1.62E-18	3.70E-08	1.30E-08	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Ag-108m	1.74E+00	0.00E+00	5.69E+04	7.80E-14	8.70E-08	3.70E-08	3.53E-08	1.38E-05	1.38E-05	4.14E-09	5.39E-12	8.30E-10	2.49E-12
Ag-108	0.00E+00	0.00E+00	0.00E+00	9.28E-16	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00

							Infant 1-2y at 100m						
Nuclide	Cm (Bq/g)	Cs (Bq/cm^2)	Ai (Bq)	CFE	CFE(70)	CFE(50)	E	E(70)	DT	DTb	DTcc	DTcs	DTcc+cs
Ag-109m	0.00E+00	0.00E+00	0.00E+00	1.92E-16	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Cd-109	1.20E+01	0.00E+00	3.93E+05	2.94E-16	3.70E-08	8.10E-09	9.19E-10	4.05E-05	4.05E-05	1.21E-08	1.58E-11	2.43E-09	7.29E-12
Ag-110m	5.61E+00	0.00E+00	1.84E+05	1.36E-13	4.10E-08	1.20E-08	1.99E-07	2.10E-05	2.12E-05	6.35E-09	8.25E-12	1.27E-09	3.81E-12
Ag-110	0.00E+00	0.00E+00	0.00E+00	1.78E-15	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Sm-151	4.97E-01	0.00E+00	1.62E+04	3.61E-20	1.00E-08	4.00E-09	4.67E-15	4.53E-07	4.53E-07	1.36E-10	1.76E-13	2.72E-11	8.15E-14
Eu-152	2.25E-02	0.00E+00	7.35E+02	5.65E-14	1.00E-07	4.20E-08	3.30E-10	2.05E-07	2.05E-07	6.15E-11	8.00E-14	1.23E-11	3.69E-14
Eu-154	5.67E+01	0.00E+00	1.85E+06	6.14E-14	1.50E-07	5.30E-08	9.06E-07	7.74E-04	7.75E-04	2.33E-07	3.02E-10	4.66E-08	1.40E-10
Tb-160	1.09E-07	0.00E+00	3.57E-03	5.54E-14	2.50E-08	7.00E-09	1.58E-15	2.49E-13	2.50E-13	7.51E-17	9.76E-20	1.50E-17	4.51E-20
Ho-166m	1.88E-02	0.00E+00	6.16E+02	8.45E-14	2.50E-07	1.20E-07	4.14E-10	4.29E-07	4.29E-07	1.29E-10	1.68E-13	2.58E-11	7.73E-14
Ru-103	0.00E+00	2.86E+02	6.75E+04	2.25E-14	1.00E-08	3.00E-09	1.21E-08	1.88E-06	1.89E-06	5.68E-10	7.38E-13	1.14E-10	3.41E-13
Ru-106	0.00E+00	6.32E-07	1.49E-04	0.00E+00	2.30E-07	6.60E-08	0.00E+00	9.54E-14	9.54E-14	2.86E-17	3.72E-20	5.73E-18	1.72E-20
Cs-134	0.00E+00	7.82E+03	1.84E+06	7.57E-14	6.30E-08	2.00E-08	1.11E-06	3.23E-04	3.24E-04	9.73E-08	1.27E-10	1.95E-08	5.84E-11
Cs-137	0.00E+00	4.18E+04	9.85E+06	7.74E-18	1.00E-07	3.90E-08	6.07E-10	2.74E-03	2.74E-03	8.23E-07	1.07E-09	1.65E-07	4.94E-10
Ce-141	0.00E+00	5.91E-09	1.39E-06	3.43E-15	1.20E-08	3.80E-09	3.80E-20	4.66E-17	4.66E-17	1.40E-20	1.82E-23	2.80E-21	8.39E-24
Ce-144	0.00E+00	4.82E+02	1.14E+05	8.53E-16	1.80E-07	5.30E-08	7.72E-10	5.70E-05	5.70E-05	1.71E-08	2.22E-11	3.42E-09	1.03E-11
						TOTAL	1.68E-01	4.35E+01	4.37E+01	1.31E-02	1.70E-05	2.63E-03	7.87E-06

	Adult at 100m							Infant 1-2y at 250m						
Nuclide	E	E(50)	DT	DTb	DTcc	DTcs	DTcc+cs	E	E(70)	DT	DTb	DTcc	DTcs	DTcc+cs
H-3	7.92E-16	2.18E-10	2.18E-10	6.53E-14	8.49E-17	1.31E-14	3.92E-17	1.58E-16	1.67E-10	1.67E-10	5.02E-14	6.53E-17	1.01E-14	3.01E-17
Be-10	1.85E-16	2.02E-10	2.02E-10	6.06E-14	7.87E-17	1.21E-14	3.63E-17	3.69E-17	1.05E-10	1.05E-10	3.15E-14	4.09E-17	6.30E-15	1.89E-17
C-14	1.48E-10	1.34E-03	1.34E-03	4.02E-07	5.22E-10	8.04E-08	2.41E-10	2.95E-11	7.84E-04	7.84E-04	2.35E-07	3.06E-10	4.71E-08	1.41E-10
P-32	8.72E-35	1.05E-30	1.05E-30	3.15E-34	4.09E-37	6.30E-35	1.89E-37	1.74E-35	9.24E-31	9.24E-31	2.77E-34	3.60E-37	5.55E-35	1.66E-37
P-33	1.86E-24	1.18E-18	1.18E-18	3.55E-22	4.62E-25	7.12E-23	2.13E-25	3.71E-25	7.26E-19	7.26E-19	2.18E-22	2.83E-25	4.36E-23	1.31E-25
S-35	3.47E-15	9.50E-09	9.50E-09	2.85E-12	3.70E-15	5.70E-13	1.71E-15	6.93E-16	5.99E-09	5.99E-09	1.80E-12	2.34E-15	3.60E-13	1.08E-15
Cl-36	3.76E-14	4.31E-09	4.31E-09	1.29E-12	1.68E-15	2.59E-13	7.75E-16	7.51E-15	3.06E-09	3.06E-09	9.19E-13	1.20E-15	1.84E-13	5.52E-16
Cr-51	1.89E-16	1.62E-15	1.81E-15	5.44E-19	7.07E-22	1.09E-19	3.26E-22	3.78E-17	1.84E-15	1.88E-15	5.64E-19	7.33E-22	1.13E-19	3.38E-22
Mn-54	1.21E-04	1.55E-03	1.68E-03	5.03E-07	6.54E-10	1.01E-07	3.02E-10	2.42E-05	1.28E-03	1.31E-03	3.92E-07	5.10E-10	7.85E-08	2.35E-10
Fe-55	0.00E+00	6.42E-01	6.42E-01	1.93E-04	2.51E-07	3.86E-05	1.16E-07	0.00E+00	5.33E-01	5.33E-01	1.60E-04	2.08E-07	3.20E-05	9.60E-08
Fe-59	2.83E-11	6.64E-10	6.93E-10	2.08E-13	2.70E-16	4.16E-14	1.25E-16	5.66E-12	4.31E-10	4.37E-10	1.31E-13	1.70E-16	2.62E-14	7.86E-17
Co-58	2.82E-08	4.36E-07	4.64E-07	1.39E-10	1.81E-13	2.79E-11	8.36E-14	5.64E-09	3.11E-07	3.17E-07	9.50E-11	1.24E-13	1.90E-11	5.70E-14
Co-60	1.68E-01	1.44E+01	1.46E+01	4.38E-03	5.70E-06	8.77E-04	2.63E-06	3.35E-02	8.00E+00	8.03E+00	2.41E-03	3.13E-06	4.83E-04	1.45E-06
Ni-59	0.00E+00	6.14E-04	6.14E-04	1.84E-07	2.40E-10	3.69E-08	1.11E-10	0.00E+00	4.18E-04	4.18E-04	1.26E-07	1.63E-10	2.51E-08	7.53E-11
Ni-63	0.00E+00	2.44E-01	2.44E-01	7.31E-05	9.50E-08	1.46E-05	4.39E-08	0.00E+00	1.61E-01	1.61E-01	4.83E-05	6.28E-08	9.67E-06	2.90E-08
Zn-65	1.70E-07	4.10E-06	4.27E-06	1.28E-09	1.67E-12	2.57E-10	7.69E-13	3.39E-08	2.75E-06	2.78E-06	8.34E-10	1.08E-12	1.67E-10	5.00E-13
Zr-93	0.00E+00	4.47E-10	4.47E-10	1.34E-13	1.74E-16	2.68E-14	8.04E-17	0.00E+00	2.29E-11	2.29E-11	6.86E-15	8.91E-18	1.37E-15	4.11E-18
Zr-95	4.40E-13	2.52E-11	2.57E-11	7.70E-15	1.00E-17	1.54E-15	4.62E-18	8.79E-14	1.62E-11	1.63E-11	4.90E-15	6.37E-18	9.80E-16	2.94E-18
Nb-93m	3.57E-12	5.06E-07	5.06E-07	1.52E-10	1.97E-13	3.04E-11	9.11E-14	7.12E-13	3.65E-07	3.65E-07	1.09E-10	1.42E-13	2.19E-11	6.57E-14
Nb-94	7.24E-07	1.61E-04	1.62E-04	4.86E-08	6.32E-11	9.73E-09	2.91E-11	1.45E-07	7.89E-05	7.90E-05	2.37E-08	3.08E-11	4.75E-09	1.42E-11
Nb-95	3.04E-16	5.11E-15	5.42E-15	1.62E-18	2.11E-21	3.25E-19	9.75E-22	6.06E-17	3.35E-15	3.41E-15	1.02E-18	1.33E-21	2.05E-19	6.13E-22
Mo-93	5.67E-11	1.81E-06	1.81E-06	5.44E-10	7.07E-13	1.09E-10	3.26E-13	1.13E-11	9.13E-07	9.13E-07	2.74E-10	3.56E-13	5.48E-11	1.64E-13
Tc-99	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Ag-108m	3.53E-08	5.86E-06	5.90E-06	1.77E-09	2.30E-12	3.54E-10	1.06E-12	7.05E-09	2.75E-06	2.76E-06	8.28E-10	1.08E-12	1.66E-10	4.97E-13
Ag-108	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Ag-109m	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Cd-109	9.19E-10	8.86E-06	8.87E-06	2.66E-09	3.46E-12	5.32E-10	1.60E-12	1.84E-10	8.09E-06	8.09E-06	2.43E-09	3.15E-12	4.86E-10	1.46E-12

	Adult at 100m							Infant 1-2y at 250m						
Nuclide	E	E(50)	DT	DTb	DTcc	DTcs	DTcc+cs	E	E(70)	DT	DTb	DTcc	DTcs	DTcc+cs
Ag-110m	1.99E-07	6.13E-06	6.33E-06	1.90E-09	2.47E-12	3.80E-10	1.14E-12	3.97E-08	4.19E-06	4.23E-06	1.27E-09	1.65E-12	2.54E-10	7.61E-13
Ag-110	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Sm-151	4.67E-15	1.81E-07	1.81E-07	5.43E-11	7.06E-14	1.09E-11	3.26E-14	9.32E-16	9.04E-08	9.04E-08	2.71E-11	3.53E-14	5.43E-12	1.63E-14
Eu-152	3.30E-10	8.60E-08	8.63E-08	2.59E-11	3.37E-14	5.18E-12	1.55E-14	6.60E-11	4.09E-08	4.10E-08	1.23E-11	1.60E-14	2.46E-12	7.37E-15
Eu-154	9.06E-07	2.74E-04	2.74E-04	8.23E-08	1.07E-10	1.65E-08	4.94E-11	1.81E-07	1.55E-04	1.55E-04	4.65E-08	6.04E-11	9.30E-09	2.79E-11
Tb-160	1.58E-15	6.97E-14	7.12E-14	2.14E-17	2.78E-20	4.28E-18	1.28E-20	3.15E-16	4.97E-14	5.00E-14	1.50E-17	1.95E-20	3.00E-18	9.00E-21
Ho-166m	4.14E-10	2.06E-07	2.06E-07	6.19E-11	8.05E-14	1.24E-11	3.71E-14	8.28E-11	8.57E-08	8.58E-08	2.57E-11	3.35E-14	5.15E-12	1.54E-14
Ru-103	1.21E-08	5.64E-07	5.76E-07	1.73E-10	2.25E-13	3.46E-11	1.04E-13	2.41E-09	3.76E-07	3.78E-07	1.13E-10	1.47E-13	2.27E-11	6.80E-14
Ru-106	0.00E+00	2.74E-14	2.74E-14	8.21E-18	1.07E-20	1.64E-18	4.93E-21	0.00E+00	1.91E-14	1.91E-14	5.72E-18	7.43E-21	1.14E-18	3.43E-21
Cs-134	1.11E-06	1.03E-04	1.04E-04	3.11E-08	4.05E-11	6.23E-09	1.87E-11	2.22E-07	6.46E-05	6.48E-05	1.94E-08	2.53E-11	3.89E-09	1.17E-11
Cs-137	6.07E-10	1.07E-03	1.07E-03	3.21E-07	4.17E-10	6.43E-08	1.93E-10	1.21E-10	5.48E-04	5.48E-04	1.64E-07	2.14E-10	3.29E-08	9.86E-11
Ce-141	3.80E-20	1.47E-17	1.48E-17	4.43E-21	5.76E-24	8.88E-22	2.66E-24	7.59E-21	9.30E-18	9.31E-18	2.79E-21	3.63E-24	5.59E-22	1.68E-24
Ce-144	7.72E-10	1.68E-05	1.68E-05	5.03E-09	6.54E-12	1.01E-09	3.02E-12	1.54E-10	1.14E-05	1.14E-05	3.41E-09	4.44E-12	6.84E-10	2.05E-12
TOTAL	1.68E-01	1.53E+01	1.55E+01	4.65E-03	6.04E-06	9.31E-04	2.79E-06	3.35E-02	8.70E+00	8.73E+00	2.62E-03	3.41E-06	5.24E-04	1.57E-06

	Infant 1-2y at 500m							Infant 1-2y at 1000m						
Nuclide	E	E(70)	DT	DTb	DTcc	DTcs	DTcc+cs	E	E(70)	DT	DTb	DTcc	DTcs	DTcc+cs
H-3	4.66E-17	4.93E-11	4.93E-11	1.48E-14	1.92E-17	2.96E-15	8.87E-18	1.62E-17	1.72E-11	1.72E-11	5.15E-15	6.69E-18	1.03E-15	3.09E-18
Be-10	1.09E-17	3.09E-11	3.09E-11	9.26E-15	1.20E-17	1.85E-15	5.56E-18	3.78E-18	1.08E-11	1.08E-11	3.23E-15	4.19E-18	6.46E-16	1.94E-18
C-14	8.68E-12	2.31E-04	2.31E-04	6.92E-08	9.00E-11	1.39E-08	4.15E-11	3.02E-12	8.03E-05	8.03E-05	2.41E-08	3.13E-11	4.82E-09	1.45E-11
P-32	5.13E-36	2.72E-31	2.72E-31	8.16E-35	1.06E-37	1.63E-35	4.90E-38	1.79E-36	9.47E-32	9.47E-32	2.84E-35	3.69E-38	5.69E-36	1.71E-38
P-33	1.09E-25	2.14E-19	2.14E-19	6.41E-23	8.33E-26	1.28E-23	3.85E-26	3.80E-26	7.44E-20	7.44E-20	2.23E-23	2.90E-26	4.47E-24	1.34E-26
S-35	2.04E-16	1.76E-09	1.76E-09	5.29E-13	6.88E-16	1.06E-13	3.17E-16	7.11E-17	6.14E-10	6.14E-10	1.84E-13	2.40E-16	3.69E-14	1.11E-16
Cl-36	2.21E-15	9.02E-10	9.02E-10	2.71E-13	3.52E-16	5.42E-14	1.62E-16	7.70E-16	3.14E-10	3.14E-10	9.42E-14	1.23E-16	1.89E-14	5.65E-17
Cr-51	1.11E-17	5.42E-16	5.53E-16	1.66E-19	2.16E-22	3.32E-20	9.95E-23	3.88E-18	1.89E-16	1.93E-16	5.78E-20	7.51E-23	1.16E-20	3.47E-23
Mn-54	7.12E-06	3.78E-04	3.85E-04	1.15E-07	1.50E-10	2.31E-08	6.93E-11	2.48E-06	1.32E-04	1.34E-04	4.02E-08	5.23E-11	8.05E-09	2.41E-11
Fe-55	0.00E+00	1.57E-01	1.57E-01	4.71E-05	6.12E-08	9.43E-06	2.83E-08	0.00E+00	5.47E-02	5.47E-02	1.64E-05	2.13E-08	3.28E-06	9.84E-09
Fe-59	1.67E-12	1.27E-10	1.29E-10	3.86E-14	5.02E-17	7.72E-15	2.31E-17	5.80E-13	4.42E-11	4.48E-11	1.34E-14	1.75E-17	2.69E-15	8.06E-18
Co-58	1.66E-09	9.16E-08	9.32E-08	2.80E-11	3.64E-14	5.60E-12	1.68E-14	5.78E-10	3.19E-08	3.25E-08	9.74E-12	1.27E-14	1.95E-12	5.85E-15
Co-60	9.86E-03	2.35E+00	2.36E+00	7.09E-04	9.22E-07	1.42E-04	4.26E-07	3.43E-03	8.20E-01	8.24E-01	2.47E-04	3.21E-07	4.95E-05	1.48E-07
Ni-59	0.00E+00	1.23E-04	1.23E-04	3.69E-08	4.80E-11	7.40E-09	2.22E-11	0.00E+00	4.29E-05	4.29E-05	1.29E-08	1.67E-11	2.58E-09	7.72E-12
Ni-63	0.00E+00	4.74E-02	4.74E-02	1.42E-05	1.85E-08	2.85E-06	8.53E-09	0.00E+00	1.65E-02	1.65E-02	4.95E-06	6.44E-09	9.91E-07	2.97E-09
Zn-65	9.99E-09	8.08E-07	8.18E-07	2.45E-10	3.19E-13	4.91E-11	1.47E-13	3.48E-09	2.81E-07	2.85E-07	8.55E-11	1.11E-13	1.71E-11	5.13E-14
Zr-93	0.00E+00	6.73E-12	6.73E-12	2.02E-15	2.62E-18	4.04E-16	1.21E-18	0.00E+00	2.34E-12	2.34E-12	7.03E-16	9.14E-19	1.41E-16	4.22E-19
Zr-95	2.59E-14	4.78E-12	4.80E-12	1.44E-15	1.87E-18	2.89E-16	8.65E-19	9.01E-15	1.66E-12	1.67E-12	5.02E-16	6.53E-19	1.00E-16	3.01E-19
Nb-93m	2.10E-13	1.07E-07	1.07E-07	3.22E-11	4.19E-14	6.45E-12	1.93E-14	7.30E-14	3.74E-08	3.74E-08	1.12E-11	1.46E-14	2.25E-12	6.73E-15
Nb-94	4.26E-08	2.32E-05	2.33E-05	6.98E-09	9.07E-12	1.40E-09	4.19E-12	1.48E-08	8.08E-06	8.10E-06	2.43E-09	3.16E-12	4.86E-10	1.46E-12
Nb-95	1.78E-17	9.85E-16	1.00E-15	3.01E-19	3.91E-22	6.03E-20	1.81E-22	6.22E-18	3.43E-16	3.49E-16	1.05E-19	1.36E-22	2.10E-20	6.29E-23
Mo-93	3.34E-12	2.69E-07	2.69E-07	8.06E-11	1.05E-13	1.61E-11	4.84E-14	1.16E-12	9.36E-08	9.36E-08	2.81E-11	3.65E-14	5.62E-12	1.68E-14
Tc-99	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Ag-108m	2.08E-09	8.10E-07	8.12E-07	2.44E-10	3.17E-13	4.88E-11	1.46E-13	7.23E-10	2.82E-07	2.83E-07	8.49E-11	1.10E-13	1.70E-11	5.09E-14
Ag-108	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Ag-109m	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Cd-109	5.40E-11	2.38E-06	2.38E-06	7.14E-10	9.28E-13	1.43E-10	4.29E-13	1.88E-11	8.29E-07	8.29E-07	2.49E-10	3.23E-13	4.98E-11	1.49E-13

	Infant 1-2y at 500m							Infant 1-2y at 1000m						
Nuclide	E	E(70)	DT	DTb	DTcc	DTcs	DTcc+cs	E	E(70)	DT	DTb	DTcc	DTcs	DTcc+cs
Ag-110m	1.17E-08	1.23E-06	1.24E-06	3.73E-10	4.85E-13	7.47E-11	2.24E-13	4.07E-09	4.29E-07	4.33E-07	1.30E-10	1.69E-13	2.60E-11	7.80E-14
Ag-110	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Sm-151	2.74E-16	2.66E-08	2.66E-08	7.98E-12	1.04E-14	1.60E-12	4.79E-15	9.56E-17	9.27E-09	9.27E-09	2.78E-12	3.61E-15	5.57E-13	1.67E-15
Eu-152	1.94E-11	1.20E-08	1.21E-08	3.62E-12	4.70E-15	7.24E-13	2.17E-15	6.77E-12	4.19E-09	4.20E-09	1.26E-12	1.64E-15	2.52E-13	7.56E-16
Eu-154	5.32E-08	4.55E-05	4.56E-05	1.37E-08	1.78E-11	2.74E-09	8.20E-12	1.85E-08	1.59E-05	1.59E-05	4.76E-09	6.19E-12	9.53E-10	2.86E-12
Tb-160	9.26E-17	1.46E-14	1.47E-14	4.42E-18	5.74E-21	8.84E-19	2.65E-21	3.23E-17	5.09E-15	5.13E-15	1.54E-18	2.00E-21	3.08E-19	9.23E-22
Ho-166m	2.44E-11	2.52E-08	2.53E-08	7.58E-12	9.85E-15	1.52E-12	4.55E-15	8.49E-12	8.79E-09	8.79E-09	2.64E-12	3.43E-15	5.28E-13	1.58E-15
Ru-103	7.11E-10	1.11E-07	1.11E-07	3.34E-11	4.34E-14	6.68E-12	2.00E-14	2.48E-10	3.85E-08	3.87E-08	1.16E-11	1.51E-14	2.33E-12	6.97E-15
Ru-106	0.00E+00	5.61E-15	5.61E-15	1.68E-18	2.19E-21	3.37E-19	1.01E-21	0.00E+00	1.95E-15	1.95E-15	5.86E-19	7.62E-22	1.17E-19	3.52E-22
Cs-134	6.53E-08	1.90E-05	1.91E-05	5.72E-09	7.44E-12	1.15E-09	3.43E-12	2.27E-08	6.62E-06	6.64E-06	1.99E-09	2.59E-12	3.99E-10	1.20E-12
Cs-137	3.57E-11	1.61E-04	1.61E-04	4.84E-08	6.29E-11	9.69E-09	2.90E-11	1.24E-11	5.62E-05	5.62E-05	1.69E-08	2.19E-11	3.37E-09	1.01E-11
Ce-141	2.24E-21	2.74E-18	2.74E-18	8.22E-22	1.07E-24	1.65E-22	4.93E-25	7.79E-22	9.53E-19	9.54E-19	2.86E-22	3.72E-25	5.73E-23	1.72E-25
Ce-144	4.54E-11	3.35E-06	3.35E-06	1.01E-09	1.31E-12	2.01E-10	6.03E-13	1.58E-11	1.17E-06	1.17E-06	3.50E-10	4.55E-13	7.01E-11	2.10E-13
TOTAL	9.87E-03	2.56E+00	2.57E+00	7.71E-04	1.00E-06	1.54E-04	4.63E-07	3.44E-03	8.92E-01	8.95E-01	2.69E-04	3.49E-07	5.38E-05	1.61E-07

ANNEX IV - ACCIDENT SCENARIOS ANALYSIS

As per the results of the hazards and initiating events screening, three different initiating events will be analysed in detail within this Annex:

- IE.1. Loss of local confinement and/or HEPA filtration during segmentation activities.
- IE.2. Fire or explosion/overpressure.
- IE.3. Drop of loads.

For each of these initiating events, credible scenarios that may occur will be described and most limiting ones will be analysed, establishing the calculation methodology and associated results.

NOTE: Calculation methodologies and associated parameters included within this document are proposals justified on best available information and maintaining a high level of conservatism. Indeed, IE.2 and IE.3 include two different and justified approaches, showing how the calculation of potential consequences is very dependent in the radioactive inventory defined for each case, the volume considered for its dispersion, and the staying time of workers.

It is recommended that End Users adapt the parameters to their actual conditions, justifying their selection (especially when using realistic approaches), and based on potential technical discussions and on an iterative process with their national regulators.

The results show low to high potential consequences, with the higher doses potentially occurring in case of fire or explosion/overpressure (IE.2) (with the unmitigated consequences driven by the burning of HEPA filters).

Adequate safety systems should be in place for mitigating its consequences. For this purpose, recommendation on prevention, detection and mitigation safety measures are provided for each accident scenario.

IE.1. Loss of local confinement and/or HEPA filtration during segmentation activities.

<u>Scenarios</u>

Loss of local confinement and/or HEPA filtration during segmentation activities may occur in the reactor cavity, when the segmentation of the RPV is performed by laser cutting in air, or when the RVI is segmented underwater in the Refuelling Cavity or Dryer/Separator Storage Pool. This accident may cover other potential causes that may result in a loss of local confinement and/or HEPA filtration affecting the segmented area. Potential causes of the confinement rupture may include the volatized molten metal (in-air), pinching due to equipment movements and operations, impacts with tools, etc.

As a result of the loss of local confinement and/or HEPA filtration, the confined space and/or HEPA filters will be affected, potentially releasing radioactive material into the reactor building and, subsequently, to the atmosphere through the off-gas system.

Two scenarios are envisaged as per Figure A4.1. In the first scenario (a), the local confinement integrity is lost, releasing radioactivity in the working environment, and then to the atmosphere through the off-gas system. In the second scenario (b), the local confinement integrity is maintained, but their associated HEPA filters do not work as prescribed, and so, releasing radioactivity to the atmosphere through the off-gas system without affecting the working environment. The first scenario will be evaluated as it implies higher radiological risks to workers. For the public, both scenarios imply the same radiological risks, considering that off-gas building filtration capabilities are maintained.

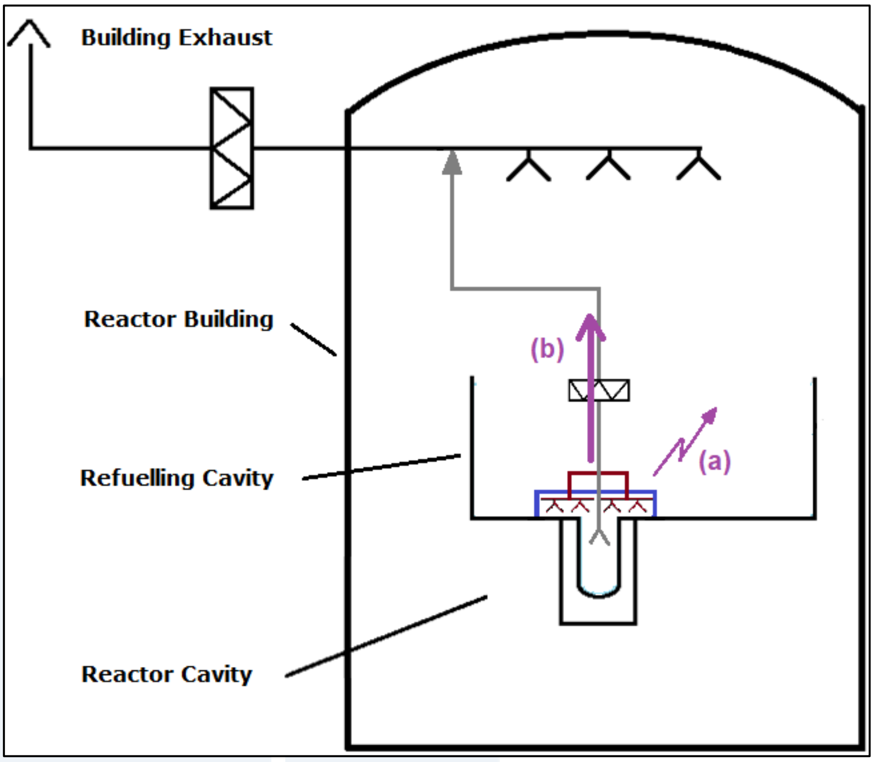

Figure A4.1. Potential Scenarios for Radioactivity Release for IE.1.

<u>Methodology of Calculation</u>

The methodology of calculation is similar to that detailed in section 4.3.4, with adjustments to the formula of dose to workers:

The Effective Dose (E) for workers, in mSv, from external exposure to the airborne cloud-shine is calculated as follows (adaptation of Eq. A3.2):

$$E = \sum_i Ac_i \cdot CFE_i \cdot T \cdot 3600 \cdot 10^3 \qquad \text{Eq. A4.1.}$$

Where:

- Aci, in Bq/m^3, is the activity concentration for each radionuclide. It would be assumed that the workers could be positioned right were the confinement system was ruptured (without considering dilution), and so, the same activity concentrations that were calculated in Annex VI for in-air or 5-m underwater cutting will be used.

- T is the time that a worker may be exposed to the release, which will be considered of 5 minutes (0.08 hours). Air quality and discharge monitoring systems are capable of detecting this loss of containment in a period below the 5 minutes as mentioned in NUREG/CR-0130 [Ref. 48]. it is not considered credible that a large leak could occur for one hour of cutting before it is detected (as per NUREG/CR-0672 [Ref. 49]) without having either an early indication in Radiation Monitoring Systems or a negative pressure loss indication of the confinement system.

- CFEi is the effective dose coefficient for each radionuclide, in (Sv·m^3) / (Bq·s) [Ref. 24]

- The factor 3600·10^3 is used for adjusting units (s·mSv/h·Sv).

The inhalation Committed Effective Dose E(50) for workers, in mSv, is calculated as follows (adaptation of Eq. A3.3).

$$E(50) = \sum_i Ac_i \cdot BR \cdot CFE(50)_i \cdot T \cdot 10^3 \qquad \text{Eq. A4.2.}$$

Where:

- Aci, in Bq/m^3, is the activity concentration for each radionuclide.

- CFE(50)i is the inhalation dose coefficient for each radionuclide (i), in Sv/Bq. [Ref. 27]. Values are selected for AMAD of 0.3 µm for underwater cutting and for 0.1 µm for in-air cutting [Ref. 43]. Type S is selected since is more representative of the type of particles (i.e., cobalt oxide).

- The factor 10^3 is used for adjusting units (mSv/Sv).

For calculating doses to the public, Eq. A3.4 and A3.5 will be used considering off-gas building filtration of 99.97%. The accident-specific activity release (Ai), is obtained assuming the following:

- It is assumed that, as a result of the projection of molten metal globules or some other similar cause, there is a total loss of efficiency of the containment system [Ref. 48] (more conservative than the 50% consideration of NUREG/CR-0672 [Ref. 49]), for 5 minutes of cutting before it is detected.

- It is assumed that, during this interval, the specific activity of the most activated part of the RPV (Vessel wall specific activity (Cm Vessel) from section 2.3, as the inner cladding layer is not considered representative of the potential release) or RVI (Shroud specific activity (Cm Shroud) from section 2.3) is released to the air of the containment building due to the segmentation process [Ref. 48, 49]. Dispersion of contamination of RPV and RVI during segmentation will also be considered. Reference contamination values are shown in Tables 2.6 (PWR) and 2.9 (BWR). This source term will be referred as A_{iSeg}.

- The air contained inside the contamination confinement is released, for which the same activity concentrations that were calculated in Annex VI for in-air or 5-m underwater cutting will be used. The total activity is calculated considering the Reactor Cavity volume (485 m^3 [Ref. 48]) for the RPV cutting and the Refuelling Cavity or Dryer/Separator Storage Pool (750 m^3 [Ref. 48]) for the RVI segmentation, aligned with the calculations of Annex VI. This source term will be referred as $A_{iConf\text{-}a}$.
- The total source term (Ai) is the sum of A_{iSeg} and $A_{iConf\text{-}a}$.

Results

The detailed results are summarized in tables A4.2 to A4.5, with the summary provided in Table A4.1. Public doses are only calculated at 100 m.

Table A4.1. Estimation of doses to the public and workers, in mSv, for IE.1.

Accident Scenario	Doses	PWR		BWR	
		RVI	RPV	RVI	RPV
IE.1. Loss of local confinement and/or HEPA filtration during segmentation activities.	Public	2.56E-04	5.36E-08	8.23E-05	7.79E-05
	Workers	3.18E+01	1.39E-02	1.13E+01	1.68E-02

Recommendation on Prevention, Detection and Mitigation Safety Measures

For reducing the associated risks to ALARA, different safety measures and controls are recommended to be implemented:

- Confinement system and HEPA filters should be periodically checked, and should be equipped with early detection of failures, as provided in Table 6.3. This would ensure that workers are alerted of any potential malfunction and laser cutting could be automatically stopped.
- Atmospheric airborne contamination control (Radiation Monitoring Surveillance and Monitoring Systems) should be located in the working environment to ensure that workers are alerted of high concentrations of airborne activity and evacuate the area accordingly.

- Doses to workers in case of IE.1 would result mainly from inhalation. Radiation Protection procedures and controls should be followed (i.e., use of necessary personnel protective equipment) in any associated corrective action.
- Building off-gas system monitoring and filtration should be in place for reducing the doses to the public to ALARA in case of confinement system malfunction.

Table A4.2. Initiating Event IE.1 Results: PWR, RPV.

Nuclide	Cm Shroud (Bq/g)	Cs (Bq/cm2)	AiSeg (Bq)	ACi (Bq/m3)	AiConf-a(Bq)	Ai (Bq)	CFE	CFE(50)w	CFE(70)1-2y	CFE(50)a
Nb-95	5.31E-11	5.72E-09	8.90E-11	0.00E+00	0.00E+00	8.90E-11	3.74E-14	2.50E-09	5.90E-09	1.80E-09
Fe-59	2.16E-04	3.99E-05	2.21E-04	0.00E+00	0.00E+00	2.21E-04	5.97E-14	4.40E-09	1.30E-08	4.00E-09
Co-58	8.70E-02	2.03E-01	9.03E-02	7.98E-04	3.87E-01	4.77E-01	4.76E-14	4.50E-09	7.50E-09	2.10E-09
Zr-95	2.55E-06	4.26E-08	2.61E-06	0.00E+00	0.00E+00	2.61E-06	3.60E-14	8.60E-09	1.90E-08	5.90E-09
Zn-65	2.76E-03	8.77E-01	8.15E-03	3.19E-03	1.55E+00	1.56E+00	2.90E-14	2.50E-09	6.70E-09	2.00E-09
Mn-54	7.21E+03	1.06E+03	7.38E+03	1.97E+01	9.54E+03	1.69E+04	4.09E-14	9.90E-09	6.20E-09	1.50E-09
Fe-55	8.60E+05	1.73E+05	8.81E+05	2.53E+03	1.23E+06	2.11E+06	0.00E+00	5.60E-10	8.50E-10	1.80E-10
Co-60	1.39E+05	1.92E+05	1.43E+05	1.04E+03	5.02E+05	6.46E+05	1.26E-13	1.10E-07	8.60E-08	3.10E-08
Ni-63	1.09E+04	3.87E+04	1.14E+04	1.72E+02	8.32E+04	9.46E+04	0.00E+00	6.00E-09	4.30E-09	1.30E-09
Mo-93	3.81E+00	1.27E-01	3.90E+00	8.58E-03	4.16E+00	8.06E+00	2.52E-17	4.00E-10	5.80E-09	2.30E-09
C-14	5.57E+01	4.93E+01	5.73E+01	3.09E-01	1.50E+02	2.07E+02	2.24E-19	2.30E-08	1.70E-08	5.80E-09
Nb-94	0.00E+00	1.57E+00	9.55E-03	5.85E-03	2.84E+00	2.85E+00	7.70E-14	3.50E-07	1.20E-07	4.90E-08
Ni-59	9.38E+01	2.62E+02	9.76E+01	1.20E+00	5.84E+02	6.82E+02	0.00E+00	2.90E-09	1.50E-09	4.40E-10
Ru-103	0.00E+00	1.97E+02	1.19E+00	7.52E-01	3.65E+02	3.66E+02	2.25E-14	3.10E-09	1.00E-08	3.00E-09
Ru-106	0.00E+00	4.34E-07	2.64E-09	0.00E+00	0.00E+00	2.64E-09	0.00E+00	1.30E-07	2.30E-07	6.60E-08
Cs-134	0.00E+00	5.37E+03	3.26E+01	2.05E+01	9.96E+03	9.99E+03	7.57E-14	5.30E-08	6.30E-08	2.00E-08
Cs-137	0.00E+00	2.87E+04	1.74E+02	1.10E+02	5.32E+04	5.34E+04	7.74E-18	1.90E-07	1.00E-07	3.90E-08
Ce-141	0.00E+00	4.06E-09	2.47E-11	0.00E+00	0.00E+00	2.47E-11	3.43E-15	2.60E-09	1.20E-08	3.80E-09
Ce-144	0.00E+00	3.31E+02	2.01E+00	1.27E+00	6.14E+02	6.16E+02	8.53E-16	8.40E-08	1.80E-07	5.30E-08
TOTAL	1.02E+06	4.40E+05	1.04E+06	3.89E+03	1.89E+06	2.93E+06				

	Workers			Infants 1-2y at 100m			Adults at 100m		
Nuclide	E	E(50)	DT	E	E(70)	DT	E	E(50)	DT
Nb-95	0.00E+00	0.00E+00	0.00E+00	7.95E-27	4.39E-25	4.47E-25	7.95E-27	1.34E-25	1.42E-25
Fe-59	0.00E+00	0.00E+00	0.00E+00	3.15E-20	2.40E-18	2.44E-18	3.15E-20	7.40E-19	7.71E-19
Co-58	1.14E-11	3.59E-10	3.70E-10	5.43E-17	2.99E-15	3.05E-15	5.43E-17	8.38E-16	8.92E-16
Zr-95	0.00E+00	0.00E+00	0.00E+00	2.24E-22	4.14E-20	4.17E-20	2.24E-22	1.29E-20	1.31E-20
Zn-65	2.78E-11	7.98E-10	8.26E-10	1.08E-16	8.71E-15	8.82E-15	1.08E-16	2.60E-15	2.71E-15
Mn-54	2.41E-07	1.95E-05	1.97E-05	1.65E-12	8.77E-11	8.93E-11	1.65E-12	2.12E-11	2.29E-11
Fe-55	0.00E+00	1.41E-04	1.41E-04	0.00E+00	1.50E-09	1.50E-09	0.00E+00	3.17E-10	3.17E-10
Co-60	3.92E-05	1.14E-02	1.14E-02	1.94E-10	4.64E-08	4.66E-08	1.94E-10	1.67E-08	1.69E-08
Ni-63	0.00E+00	1.03E-04	1.03E-04	0.00E+00	3.40E-10	3.40E-10	0.00E+00	1.03E-10	1.03E-10
Mo-93	6.48E-14	3.43E-10	3.43E-10	4.85E-19	3.91E-14	3.91E-14	4.85E-19	1.55E-14	1.55E-14
C-14	2.08E-14	7.10E-07	7.10E-07	1.11E-19	2.94E-12	2.94E-12	1.11E-19	1.00E-12	1.00E-12
Nb-94	1.35E-10	2.05E-07	2.05E-07	5.23E-16	2.85E-13	2.86E-13	5.23E-16	1.17E-13	1.17E-13
Ni-59	0.00E+00	3.49E-07	3.49E-07	0.00E+00	8.55E-13	8.55E-13	0.00E+00	2.51E-13	2.51E-13
Ru-103	5.08E-09	2.33E-07	2.38E-07	1.97E-14	3.06E-12	3.08E-12	1.97E-14	9.18E-13	9.37E-13
Ru-106	0.00E+00	0.00E+00	0.00E+00	0.00E+00	5.07E-22	5.07E-22	0.00E+00	1.45E-22	1.45E-22
Cs-134	4.66E-07	1.09E-04	1.09E-04	1.81E-12	5.26E-10	5.28E-10	1.81E-12	1.67E-10	1.69E-10
Cs-137	2.55E-10	2.09E-03	2.09E-03	9.87E-16	4.46E-09	4.46E-09	9.87E-16	1.74E-09	1.74E-09
Ce-141	0.00E+00	0.00E+00	0.00E+00	2.02E-28	2.47E-25	2.48E-25	2.02E-28	7.83E-26	7.85E-26
Ce-144	3.24E-10	1.06E-05	1.06E-05	1.26E-15	9.27E-11	9.27E-11	1.26E-15	2.73E-11	2.73E-11
TOTAL	3.99E-05	1.39E-02	1.39E-02	1.98E-10	5.34E-08	5.36E-08	1.98E-10	1.91E-08	1.93E-08

Table A4.3. Initiating Event IE.1 Results: PWR, RVI.

Nuclide	Cm Vessel (Bq/g)	Cs (Bq/cm2)	AiSeg (Bq)	ACi (Bq/m3)	AiConf-a(Bq)	Ai (Bq)	CFE	CFE(50)w	CFE(70)1-2y	CFE(50)a
Nb-95	7.40E-05	5.72E-09	2.06E-05	0.00E+00	0.00E+00	2.06E-05	3.74E-14	1.70E-09	5.90E-09	1.80E-09
Fe-59	4.36E-01	3.99E-05	1.22E-01	6.31E-04	4.73E-01	5.95E-01	5.97E-14	3.20E-09	1.30E-08	4.00E-09
Co-58	2.34E+03	2.03E-01	6.54E+02	4.29E+00	3.21E+03	3.87E+03	4.76E-14	3.20E-09	7.50E-09	2.10E-09
Zr-95	4.62E-04	4.26E-08	1.29E-04	0.00E+00	0.00E+00	1.29E-04	3.60E-14	6.10E-09	1.90E-08	5.90E-09
Zn-65	1.12E+04	8.77E-01	3.13E+03	2.05E+01	1.54E+04	1.85E+04	2.90E-14	2.00E-09	6.70E-09	2.00E-09
Mn-54	1.24E+07	1.06E+03	3.45E+06	2.26E+04	1.70E+07	2.04E+07	4.09E-14	7.10E-09	6.20E-09	1.50E-09
Fe-55	1.84E+09	1.73E+05	5.13E+08	3.36E+06	2.52E+09	3.04E+09	0.00E+00	4.10E-10	8.50E-10	1.80E-10
Co-60	2.11E+09	1.92E+05	5.87E+08	3.85E+06	2.89E+09	3.48E+09	1.26E-13	8.10E-08	8.60E-08	3.10E-08
Ni-63	4.07E+08	3.87E+04	1.14E+08	7.44E+05	5.58E+08	6.72E+08	0.00E+00	4.30E-09	4.30E-09	1.30E-09
Mo-93	1.25E+03	1.27E-01	3.49E+02	2.29E+00	1.71E+03	2.06E+03	2.52E-17	2.90E-10	5.80E-09	2.30E-09
C-14	5.21E+05	4.93E+01	1.45E+05	9.53E+02	7.15E+05	8.60E+05	2.24E-19	1.60E-08	1.70E-08	5.80E-09
Nb-94	1.88E+04	1.57E+00	5.24E+03	3.43E+01	2.57E+04	3.10E+04	7.70E-14	2.50E-07	1.20E-07	4.90E-08
Ni-59	2.57E+06	2.62E+02	7.18E+05	4.70E+03	3.53E+06	4.24E+06	0.00E+00	2.10E-09	1.50E-09	4.40E-10
Ru-103	0.00E+00	1.97E+02	3.60E+00	6.41E-02	4.80E+01	5.16E+01	2.25E-14	2.20E-09	1.00E-08	3.00E-09
Ru-106	0.00E+00	4.34E-07	7.93E-09	0.00E+00	0.00E+00	7.93E-09	0.00E+00	9.60E-08	2.30E-07	6.60E-08
Cs-134	0.00E+00	5.37E+03	9.81E+01	1.75E+00	1.31E+03	1.41E+03	7.57E-14	3.80E-08	6.30E-08	2.00E-08
Cs-137	0.00E+00	2.87E+04	5.25E+02	9.37E+00	7.03E+03	7.55E+03	7.74E-18	1.30E-07	1.00E-07	3.90E-08
Ce-141	0.00E+00	4.06E-09	7.42E-11	0.00E+00	0.00E+00	7.42E-11	3.43E-15	1.20E-09	1.20E-08	3.80E-09
Ce-144	0.00E+00	3.31E+02	6.05E+00	1.08E-01	8.10E+01	8.70E+01	8.53E-16	3.90E-08	1.80E-07	5.30E-08
TOTAL	4.37E+09	4.40E+05	1.22E+09	7.99E+06	5.99E+09	7.21E+09				

	Workers			Infants 1-2y at 100m			Adults at 100m		
Nuclide	E	E(50)	DT	E	E(70)	DT	E	E(50)	DT
Nb-95	0.00E+00	0.00E+00	0.00E+00	1.84E-21	1.02E-19	1.04E-19	1.84E-21	3.11E-20	3.29E-20
Fe-59	1.13E-11	2.02E-10	2.13E-10	8.48E-17	6.46E-15	6.55E-15	8.48E-17	1.99E-15	2.07E-15
Co-58	6.12E-08	1.37E-06	1.43E-06	4.40E-13	2.43E-11	2.47E-11	4.40E-13	6.79E-12	7.23E-12
Zr-95	0.00E+00	0.00E+00	0.00E+00	1.11E-20	2.05E-18	2.06E-18	1.11E-20	6.35E-19	6.47E-19
Zn-65	1.79E-07	4.11E-06	4.29E-06	1.28E-12	1.04E-10	1.05E-10	1.28E-12	3.10E-11	3.23E-11
Mn-54	2.77E-04	1.60E-02	1.63E-02	1.99E-09	1.06E-07	1.08E-07	1.99E-09	2.56E-08	2.76E-08
Fe-55	0.00E+00	1.38E-01	1.38E-01	0.00E+00	2.16E-06	2.16E-06	0.00E+00	4.57E-07	4.57E-07
Co-60	1.46E-01	3.12E+01	3.13E+01	1.05E-06	2.50E-04	2.51E-04	1.05E-06	9.00E-05	9.11E-05
Ni-63	0.00E+00	3.20E-01	3.20E-01	0.00E+00	2.41E-06	2.41E-06	0.00E+00	7.30E-07	7.30E-07
Mo-93	1.73E-11	6.63E-08	6.63E-08	1.24E-16	1.00E-11	1.00E-11	1.24E-16	3.97E-12	3.97E-12
C-14	6.40E-11	1.52E-03	1.52E-03	4.60E-16	1.22E-08	1.22E-08	4.60E-16	4.17E-09	4.17E-09
Nb-94	7.93E-07	8.58E-04	8.59E-04	5.69E-12	3.11E-09	3.11E-09	5.69E-12	1.27E-09	1.27E-09
Ni-59	0.00E+00	9.88E-04	9.88E-04	0.00E+00	5.32E-09	5.32E-09	0.00E+00	1.56E-09	1.56E-09
Ru-103	4.32E-10	1.41E-08	1.45E-08	2.77E-15	4.32E-13	4.34E-13	2.77E-15	1.29E-13	1.32E-13
Ru-106	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.52E-21	1.52E-21	0.00E+00	4.38E-22	4.38E-22
Cs-134	3.98E-08	6.66E-06	6.70E-06	2.55E-13	7.44E-11	7.46E-11	2.55E-13	2.36E-11	2.39E-11
Cs-137	2.18E-11	1.22E-04	1.22E-04	1.40E-16	6.31E-10	6.31E-10	1.40E-16	2.46E-10	2.46E-10
Ce-141	0.00E+00	0.00E+00	0.00E+00	6.08E-28	7.44E-25	7.45E-25	6.08E-28	2.36E-25	2.36E-25
Ce-144	2.76E-11	4.21E-07	4.21E-07	1.77E-16	1.31E-11	1.31E-11	1.77E-16	3.86E-12	3.86E-12
TOTAL	1.46E-01	3.17E+01	3.18E+01	1.05E-06	2.55E-04	2.56E-04	1.05E-06	9.13E-05	9.23E-05

Table A4.4. Initiating Event IE.1 Results: BWR, RPV.

Nuclide	Cm Shroud (Bq/g)	Cs (Bq/cm^2)	AiSeg (Bq)	ACi (Bq/m3)	AiConf-a(Bq)	Ai (Bq)	CFE	CFE(50)w	CFE(70)1-2y	CFE(50)a
H-3	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	3.31E-19	1.00E-09	1.00E-09	2.60E-10
Be-10	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.12E-17	1.70E-07	9.10E-08	3.50E-08
C-14	5.81E+00	0.00E+00	5.94E+00	4.42E-02	5.81E+02	2.82E+05	2.24E-19	2.30E-08	1.70E-08	5.80E-09
P-32	7.72E-25	0.00E+00	7.90E-25	0.00E+00	7.72E-23	3.74E-20	9.90E-17	4.40E-09	1.50E-08	3.40E-09
P-33	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	8.23E-19	1.20E-09	4.60E-09	1.50E-09
S-35	6.17E-04	0.00E+00	6.31E-04	0.00E+00	6.17E-02	2.99E+01	2.43E-19	1.60E-09	6.00E-09	1.90E-09
Cl-36	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.23E-17	1.90E-07	2.60E-08	7.30E-09
Cr-51	2.07E-11	3.68E-10	1.07E-09	0.00E+00	2.07E-09	1.00E-06	1.51E-15	7.90E-11	2.10E-10	3.70E-11
Mn-54	4.76E+02	2.72E+04	7.75E+04	8.92E+01	4.76E+04	2.31E+07	4.09E-14	9.90E-09	6.20E-09	1.50E-09
Fe-55	1.17E+05	0.00E+00	1.20E+05	8.93E+02	1.17E+07	5.68E+09	0.00E+00	5.60E-10	3.20E-09	7.70E-10
Fe-59	2.21E-05	9.09E-05	2.80E-04	0.00E+00	2.21E-03	1.07E+00	5.97E-14	4.40E-09	1.30E-08	4.00E-09
Co-58	5.75E-03	5.57E-02	1.64E-01	5.27E-05	5.75E-01	2.79E+02	4.76E-14	4.50E-09	7.50E-09	2.10E-09
Co-60	3.52E+03	3.95E+05	1.12E+06	1.27E+03	3.52E+05	1.71E+08	1.26E-13	1.10E-07	8.60E-08	3.10E-08
Ni-59	1.25E+01	0.00E+00	1.28E+01	9.54E-02	1.25E+03	6.08E+05	0.00E+00	2.90E-09	1.50E-09	4.40E-10
Ni-63	1.45E+03	0.00E+00	1.48E+03	1.11E+01	1.45E+05	7.03E+07	0.00E+00	6.00E-09	4.30E-09	1.30E-09
Zn-65	4.34E-05	2.19E+02	6.20E+02	6.89E-01	4.34E-03	2.11E+00	2.90E-14	2.50E-09	6.70E-09	2.00E-09
Zr-93	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.40E-08	6.40E-09	2.50E-08
Zr-95	1.68E-07	6.44E-03	1.82E-02	0.00E+00	1.68E-05	8.15E-03	3.60E-14	8.60E-09	1.90E-08	5.90E-09
Nb-93m	2.88E-01	0.00E+00	2.95E-01	2.03E-03	2.88E+01	1.40E+04	4.44E-18	7.20E-09	6.50E-09	1.80E-09
Nb-94	7.12E-04	0.00E+00	7.29E-04	0.00E+00	7.12E-02	3.45E+01	7.70E-14	3.50E-07	1.20E-07	4.90E-08
Nb-95	3.44E-12	5.67E-08	1.61E-07	0.00E+00	3.44E-10	1.67E-07	3.74E-14	2.50E-09	5.90E-09	1.80E-09

Nuclide	Cm Shroud (Bq/g)	Cs (Bq/cm^2)	AiSeg (Bq)	ACi (Bq/m3)	AiConf-a(Bq)	Ai (Bq)	CFE	CFE(50)w	CFE(70)1-2y	CFE(50)a
Mo-93	8.05E-01	0.00E+00	8.24E-01	5.98E-03	8.05E+01	3.91E+04	2.52E-17	4.00E-10	5.80E-09	2.30E-09
Tc-99	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.62E-18	5.50E-08	3.70E-08	1.30E-08
Ag-108m	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	7.80E-14	3.10E-07	8.70E-08	3.70E-08
Ag-108	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	9.28E-16	0.00E+00	0.00E+00	0.00E+00
Ag-109m	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.92E-16	0.00E+00	0.00E+00	0.00E+00
Cd-109	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.94E-16	6.00E-09	3.70E-08	8.10E-09
Ag-110m	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.36E-13	3.20E-08	4.10E-08	1.20E-08
Ag-110	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.78E-15	0.00E+00	0.00E+00	0.00E+00
Sm-151	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	3.61E-20	4.70E-09	1.00E-08	4.00E-09
Eu-152	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	5.65E-14	6.70E-08	1.00E-07	4.20E-08
Eu-154	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	6.14E-14	6.90E-08	1.50E-07	5.30E-08
Tb-160	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	5.54E-14	7.60E-09	2.50E-08	7.00E-09
Ho-166m	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	8.45E-14	1.60E-07	2.50E-07	1.20E-07
Ru-103	1.23E+05	2.86E+02	1.26E+05	9.02E-01	1.23E+07	5.94E+09	2.25E-14	3.10E-09	1.00E-08	3.00E-09
Ru-106	0.00E+00	6.32E-07	1.79E-06	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.30E-07	2.30E-07	6.60E-08
Cs-134	0.00E+00	7.82E+03	2.22E+04	2.46E+01	0.00E+00	0.00E+00	7.57E-14	5.30E-08	6.30E-08	2.00E-08
Cs-137	0.00E+00	4.18E+04	1.18E+05	1.32E+02	0.00E+00	0.00E+00	7.74E-18	1.90E-07	1.00E-07	3.90E-08
Ce-141	0.00E+00	5.91E-09	1.67E-08	0.00E+00	0.00E+00	0.00E+00	3.43E-15	2.60E-09	1.20E-08	3.80E-09
Ce-144	0.00E+00	4.82E+02	1.37E+03	1.52E+00	0.00E+00	0.00E+00	8.53E-16	8.40E-08	1.80E-07	5.30E-08
TOTAL	2.45E+05	4.73E+05	1.59E+06	2.43E+03	2.45E+07	1.19E+10				

	Workers			Infants 1-2y at 100m			Adults at 100m		
Nuclide	E	E(50)	DT	E	E(70)	DT	E	E(50)	DT
H-3	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Be-10	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
C-14	2.97E-15	1.02E-07	1.02E-07	1.51E-16	4.00E-09	4.00E-09	1.51E-16	1.37E-09	1.37E-09
P-32	0.00E+00	0.00E+00	0.00E+00	8.85E-39	4.69E-34	4.69E-34	8.85E-39	1.06E-34	1.06E-34
P-33	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
S-35	0.00E+00	0.00E+00	0.00E+00	1.74E-20	1.50E-13	1.50E-13	1.74E-20	4.75E-14	4.75E-14
Cl-36	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Cr-51	0.00E+00	0.00E+00	0.00E+00	3.62E-24	1.76E-22	1.80E-22	3.62E-24	3.11E-23	3.47E-23
Mn-54	1.09E-06	8.83E-05	8.94E-05	2.25E-09	1.20E-07	1.22E-07	2.25E-09	2.89E-08	3.12E-08
Fe-55	0.00E+00	5.00E-05	5.00E-05	0.00E+00	1.52E-05	1.52E-05	0.00E+00	3.66E-06	3.66E-06
Fe-59	0.00E+00	0.00E+00	0.00E+00	1.53E-16	1.17E-14	1.18E-14	1.53E-16	3.58E-15	3.74E-15
Co-58	7.52E-13	2.37E-11	2.45E-11	3.17E-14	1.75E-12	1.78E-12	3.17E-14	4.90E-13	5.21E-13
Co-60	4.81E-05	1.40E-02	1.40E-02	5.13E-08	1.23E-05	1.23E-05	5.13E-08	4.42E-06	4.47E-06
Ni-59	0.00E+00	2.77E-08	2.77E-08	0.00E+00	7.62E-10	7.62E-10	0.00E+00	2.24E-10	2.24E-10
Ni-63	0.00E+00	6.63E-06	6.63E-06	0.00E+00	2.53E-07	2.53E-07	0.00E+00	7.64E-08	7.64E-08
Zn-65	5.99E-09	1.72E-07	1.78E-07	1.46E-16	1.18E-14	1.19E-14	1.46E-16	3.52E-15	3.67E-15
Zr-93	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Zr-95	0.00E+00	0.00E+00	0.00E+00	7.00E-19	1.29E-16	1.30E-16	7.00E-19	4.02E-17	4.09E-17
Nb-93m	2.71E-15	1.46E-09	1.46E-09	1.48E-16	7.59E-11	7.59E-11	1.48E-16	2.10E-11	2.10E-11
Nb-94	0.00E+00	0.00E+00	0.00E+00	6.35E-15	3.47E-12	3.47E-12	6.35E-15	1.41E-12	1.42E-12
Nb-95	0.00E+00	0.00E+00	0.00E+00	1.49E-23	8.22E-22	8.37E-22	1.49E-23	2.51E-22	2.66E-22
Mo-93	4.52E-14	2.39E-10	2.39E-10	2.35E-15	1.89E-10	1.89E-10	2.35E-15	7.51E-11	7.51E-11

	Workers			Infants 1-2y at 100m			Adults at 100m		
Nuclide	E	E(50)	DT	E	E(70)	DT	E	E(50)	DT
Tc-99	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Ag-108m	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Ag-108	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Ag-109m	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Cd-109	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Ag-110m	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Ag-110	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Sm-151	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Eu-152	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Eu-154	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Tb-160	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Ho-166m	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Ru-103	6.09E-09	2.80E-07	2.86E-07	3.19E-07	4.97E-05	5.00E-05	3.19E-07	1.49E-05	1.52E-05
Ru-106	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Cs-134	5.60E-07	1.31E-04	1.31E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Cs-137	3.06E-10	2.50E-03	2.50E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Ce-141	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Ce-144	3.89E-10	1.28E-05	1.28E-05	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
TOTAL	4.97E-05	1.68E-02	1.68E-02	3.73E-07	7.75E-05	7.79E-05	3.73E-07	2.31E-05	2.35E-05

Table A4.5. Initiating Event IE.1 Results: BWR, RVI.

Nuclide	Cm Vessel (Bq/g)	Cs (Bq/cm^2)	AiSeg (Bq)	ACi (Bq/m3)	AiConf-a(Bq)	Ai (Bq)	CFE	CFE(50)w	CFE(70)1-2y	CFE(50)a
H-3	1.85E-01	0.00E+00	5.17E-02	2.26E-03	1.70E+00	1.75E+00	3.31E-19	7.20E-10	1.00E-09	2.60E-10
Be-10	1.28E-03	0.00E+00	3.56E-04	0.00E+00	0.00E+00	3.56E-04	1.12E-17	1.20E-07	9.10E-08	3.50E-08
C-14	5.10E+04	0.00E+00	1.42E+04	6.67E+02	5.00E+05	5.14E+05	2.24E-19	1.60E-08	1.70E-08	5.80E-09
P-32	5.27E-23	0.00E+00	1.47E-23	0.00E+00	0.00E+00	1.47E-23	9.90E-17	3.20E-09	1.50E-08	3.40E-09
P-33	1.75E-10	0.00E+00	4.88E-11	0.00E+00	0.00E+00	4.88E-11	8.23E-19	8.00E-10	4.60E-09	1.50E-09
S-35	1.09E+00	0.00E+00	3.05E-01	1.42E-02	1.06E+01	1.09E+01	2.43E-19	1.10E-09	6.00E-09	1.90E-09
Cl-36	1.31E-01	0.00E+00	3.64E-02	1.54E-03	1.16E+00	1.19E+00	2.23E-17	1.40E-07	2.60E-08	7.30E-09
Cr-51	9.71E-06	3.68E-10	2.71E-06	0.00E+00	0.00E+00	2.71E-06	1.51E-15	5.70E-11	2.10E-10	3.70E-11
Mn-54	2.16E+05	2.72E+04	6.20E+04	2.85E+03	2.14E+06	2.20E+06	4.09E-14	7.10E-09	6.20E-09	1.50E-09
Fe-55	1.82E+08	0.00E+00	5.09E+07	2.39E+06	1.79E+09	1.84E+09	0.00E+00	4.10E-10	3.20E-09	7.70E-10
Fe-59	3.63E-02	9.09E-05	1.01E-02	3.08E-04	2.31E-01	2.42E-01	5.97E-14	3.20E-09	1.30E-08	4.00E-09
Co-58	4.59E+01	5.57E-02	1.28E+01	6.00E-01	4.50E+02	4.63E+02	4.76E-14	3.20E-09	7.50E-09	2.10E-09
Co-60	1.03E+08	3.95E+05	2.88E+07	1.35E+06	1.01E+09	1.04E+09	1.26E-13	8.10E-08	8.60E-08	3.10E-08
Ni-59	3.09E+05	0.00E+00	8.62E+04	4.04E+03	3.03E+06	3.12E+06	0.00E+00	2.10E-09	1.50E-09	4.40E-10
Ni-63	4.15E+07	0.00E+00	1.16E+07	5.43E+05	4.07E+08	4.19E+08	0.00E+00	4.30E-09	4.30E-09	1.30E-09
Zn-65	4.22E+02	2.19E+02	1.32E+02	5.72E+00	4.29E+03	4.42E+03	2.90E-14	2.00E-09	6.70E-09	2.00E-09
Zr-93	3.96E-03	0.00E+00	1.10E-03	0.00E+00	0.00E+00	1.10E-03	0.00E+00	1.00E-08	6.40E-09	2.50E-08
Zr-95	8.27E-06	6.44E-03	4.27E-04	0.00E+00	0.00E+00	4.27E-04	3.60E-14	6.10E-09	1.90E-08	5.90E-09
Nb-93m	5.64E+01	0.00E+00	1.57E+01	7.38E-01	5.54E+02	5.69E+02	4.44E-18	5.10E-09	6.50E-09	1.80E-09
Nb-94	7.28E+02	0.00E+00	2.03E+02	9.53E+00	7.15E+03	7.35E+03	7.70E-14	2.50E-07	1.20E-07	4.90E-08
Nb-95	6.21E-07	5.67E-08	1.77E-07	0.00E+00	0.00E+00	1.77E-07	3.74E-14	1.70E-09	5.90E-09	1.80E-09

Nuclide	Cm Vessel (Bq/g)	Cs (Bq/cm^2)	AiSeg (Bq)	ACi (Bq/m3)	AiConf-a(Bq)	Ai (Bq)	CFE	CFE(50)w	CFE(70)1-2y	CFE(50)a
Mo-93	1.58E+02	0.00E+00	4.41E+01	2.07E+00	1.55E+03	1.60E+03	2.52E-17	2.90E-10	5.80E-09	2.30E-09
Tc-99	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.62E-18	4.00E-08	3.70E-08	1.30E-08
Ag-108m	3.51E+01	0.00E+00	9.78E+00	4.59E-01	3.44E+02	3.54E+02	7.80E-14	2.20E-07	8.70E-08	3.70E-08
Ag-108	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	9.28E-16	0.00E+00	0.00E+00	0.00E+00
Ag-109m	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.92E-16	0.00E+00	0.00E+00	0.00E+00
Cd-109	2.42E+02	0.00E+00	6.76E+01	3.17E+00	2.38E+03	2.45E+03	2.94E-16	4.30E-09	3.70E-08	8.10E-09
Ag-110m	1.13E+02	0.00E+00	3.16E+01	1.48E+00	1.11E+03	1.14E+03	1.36E-13	2.30E-08	4.10E-08	1.20E-08
Ag-110	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.78E-15	0.00E+00	0.00E+00	0.00E+00
Sm-151	9.55E+04	0.00E+00	2.66E+04	1.25E+03	9.37E+05	9.63E+05	3.61E-20	3.30E-09	1.00E-08	4.00E-09
Eu-152	8.58E+00	0.00E+00	2.39E+00	1.12E-01	8.41E+01	8.65E+01	5.65E-14	4.80E-08	1.00E-07	4.20E-08
Eu-154	4.10E-01	0.00E+00	1.14E-01	5.20E-03	3.90E+00	4.02E+00	6.14E-14	4.90E-08	1.50E-07	5.30E-08
Tb-160	7.25E-03	0.00E+00	2.02E-03	0.00E+00	0.00E+00	2.02E-03	5.54E-14	5.40E-09	2.50E-08	7.00E-09
Ho-166m	4.59E-01	0.00E+00	1.28E-01	5.85E-03	4.38E+00	4.51E+00	8.45E-14	1.60E-07	2.50E-07	1.20E-07
Ru-103	3.27E+08	2.86E+02	9.14E+07	2.51E-01	1.88E+02	9.14E+07	2.25E-14	2.20E-09	1.00E-08	3.00E-09
Ru-106	0.00E+00	6.32E-07	4.17E-08	0.00E+00	0.00E+00	4.17E-08	0.00E+00	9.60E-08	2.30E-07	6.60E-08
Cs-134	0.00E+00	7.82E+03	5.16E+02	6.85E+00	5.14E+03	5.65E+03	7.57E-14	3.80E-08	6.30E-08	2.00E-08
Cs-137	0.00E+00	4.18E+04	2.76E+03	3.66E+01	2.75E+04	3.02E+04	7.74E-18	1.30E-07	1.00E-07	3.90E-08
Ce-141	0.00E+00	5.91E-09	3.90E-10	0.00E+00	0.00E+00	3.90E-10	3.43E-15	1.20E-09	1.20E-08	3.80E-09
Ce-144	0.00E+00	4.82E+02	3.18E+01	4.22E-01	3.17E+02	3.49E+02	8.53E-16	3.90E-08	1.80E-07	5.30E-08
TOTAL	6.55E+08	4.73E+05	1.83E+08	4.29E+06	3.21E+09	3.40E+09				

	Workers			Infants 1-2y at 100m			Adults at 100m		
Nuclide	E	E(50)	DT	E	E(70)	DT	E	E(50)	DT
H-3	2.24E-16	1.63E-10	1.63E-10	1.38E-21	1.46E-15	1.46E-15	1.38E-21	3.80E-16	3.80E-16
Be-10	0.00E+00	0.00E+00	0.00E+00	9.53E-24	2.71E-17	2.71E-17	9.53E-24	1.04E-17	1.04E-17
C-14	4.48E-11	1.07E-03	1.07E-03	2.75E-16	7.31E-09	7.31E-09	2.75E-16	2.49E-09	2.49E-09
P-32	0.00E+00	0.00E+00	0.00E+00	3.48E-42	1.84E-37	1.84E-37	3.48E-42	4.18E-38	4.18E-38
P-33	0.00E+00	0.00E+00	0.00E+00	9.59E-32	1.88E-25	1.88E-25	9.59E-32	6.12E-26	6.12E-26
S-35	1.03E-15	1.56E-09	1.56E-09	6.34E-21	5.48E-14	5.48E-14	6.34E-21	1.73E-14	1.73E-14
Cl-36	1.03E-14	2.16E-08	2.16E-08	6.36E-20	2.59E-14	2.59E-14	6.36E-20	7.28E-15	7.28E-15
Cr-51	0.00E+00	0.00E+00	0.00E+00	9.77E-24	4.76E-22	4.85E-22	9.77E-24	8.38E-23	9.36E-23
Mn-54	3.50E-05	2.02E-03	2.06E-03	2.15E-10	1.14E-08	1.16E-08	2.15E-10	2.76E-09	2.97E-09
Fe-55	0.00E+00	9.78E-02	9.78E-02	0.00E+00	4.92E-06	4.92E-06	0.00E+00	1.18E-06	1.18E-06
Fe-59	5.52E-12	9.87E-11	1.04E-10	3.44E-17	2.62E-15	2.66E-15	3.44E-17	8.07E-16	8.42E-16
Co-58	8.57E-09	1.92E-07	2.01E-07	5.26E-14	2.90E-12	2.95E-12	5.26E-14	8.12E-13	8.65E-13
Co-60	5.10E-02	1.09E+01	1.10E+01	3.13E-07	7.47E-05	7.51E-05	3.13E-07	2.69E-05	2.73E-05
Ni-59	0.00E+00	8.49E-04	8.49E-04	0.00E+00	3.91E-09	3.91E-09	0.00E+00	1.15E-09	1.15E-09
Ni-63	0.00E+00	2.33E-01	2.33E-01	0.00E+00	1.50E-06	1.50E-06	0.00E+00	4.55E-07	4.55E-07
Zn-65	4.97E-08	1.14E-06	1.19E-06	3.06E-13	2.48E-11	2.51E-11	3.06E-13	7.39E-12	7.70E-12
Zr-93	0.00E+00	0.00E+00	0.00E+00	0.00E+00	5.91E-18	5.91E-18	0.00E+00	2.31E-17	2.31E-17
Zr-95	0.00E+00	0.00E+00	0.00E+00	3.67E-20	6.78E-18	6.81E-18	3.67E-20	2.10E-18	2.14E-18
Nb-93m	9.83E-13	3.76E-07	3.76E-07	6.04E-18	3.09E-12	3.09E-12	6.04E-18	8.56E-13	8.56E-13
Nb-94	2.20E-07	2.38E-04	2.39E-04	1.35E-12	7.37E-10	7.39E-10	1.35E-12	3.01E-10	3.02E-10
Nb-95	0.00E+00	0.00E+00	0.00E+00	1.58E-23	8.72E-22	8.88E-22	1.58E-23	2.66E-22	2.82E-22
Mo-93	1.57E-11	6.00E-08	6.01E-08	9.61E-17	7.74E-12	7.74E-12	9.61E-17	3.07E-12	3.07E-12

	Workers			Infants 1-2y at 100m			Adults at 100m		
Nuclide	E	E(50)	DT	E	E(70)	DT	E	E(50)	DT
Tc-99	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Ag-108m	1.07E-08	1.01E-05	1.01E-05	6.59E-14	2.57E-11	2.58E-11	6.59E-14	1.09E-11	1.10E-11
Ag-108	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Ag-109m	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Cd-109	2.80E-10	1.36E-06	1.36E-06	1.72E-15	7.56E-11	7.56E-11	1.72E-15	1.66E-11	1.66E-11
Ag-110m	6.04E-08	3.41E-06	3.47E-06	3.71E-13	3.91E-11	3.95E-11	3.71E-13	1.15E-11	1.18E-11
Ag-110	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Sm-151	1.35E-11	4.12E-04	4.12E-04	8.31E-17	8.05E-09	8.05E-09	8.31E-17	3.22E-09	3.22E-09
Eu-152	1.90E-09	5.38E-07	5.40E-07	1.17E-14	7.23E-12	7.24E-12	1.17E-14	3.04E-12	3.05E-12
Eu-154	9.58E-11	2.55E-08	2.56E-08	5.89E-16	5.03E-13	5.04E-13	5.89E-16	1.78E-13	1.78E-13
Tb-160	0.00E+00	0.00E+00	0.00E+00	2.68E-19	4.23E-17	4.25E-17	2.68E-19	1.18E-17	1.21E-17
Ho-166m	1.48E-10	9.35E-08	9.37E-08	9.11E-16	9.43E-13	9.44E-13	9.11E-16	4.53E-13	4.54E-13
Ru-103	1.69E-09	5.52E-08	5.69E-08	4.91E-09	7.64E-07	7.69E-07	4.91E-09	2.29E-07	2.34E-07
Ru-106	0.00E+00	0.00E+00	0.00E+00	0.00E+00	8.01E-21	8.01E-21	0.00E+00	2.30E-21	2.30E-21
Cs-134	1.56E-07	2.60E-05	2.62E-05	1.02E-12	2.98E-10	2.99E-10	1.02E-12	9.45E-11	9.55E-11
Cs-137	8.50E-11	4.76E-04	4.76E-04	5.58E-16	2.53E-09	2.53E-09	5.58E-16	9.85E-10	9.85E-10
Ce-141	0.00E+00	0.00E+00	0.00E+00	3.19E-27	3.91E-24	3.91E-24	3.19E-27	1.24E-24	1.24E-24
Ce-144	1.08E-10	1.65E-06	1.65E-06	7.10E-16	5.24E-11	5.24E-11	7.10E-16	1.54E-11	1.54E-11
TOTAL	5.10E-02	1.13E+01	1.13E+01	3.18E-07	8.20E-05	8.23E-05	3.18E-07	2.88E-05	2.91E-05

IE.2. Fire or explosion/overpressure.

Scenarios

Fire and Explosion may occur in the reactor cavity, when the segmentation of the RPV is performed by laser cutting in air (i.e., due to the residual laser beam power), or when the RVI is segmented underwater (i.e., overpressure in air flow supply). This accident may cover other potential causes that may result in a fire or explosion/overpressure affecting the segmented area.

As a result of the fire or explosion/overpressure, the confined space and HEPA filters will be affected, releasing radioactive material into the reactor building and, subsequently, to the atmosphere through the off-gas system.

The scenario will assume that for both RPV and RVI segmentation, a contamination control envelope is in place with HEPA filtration. This should be adjusted by End Users as needed.

It is important to remark that the Generic Safety Assessment considers that the most restrictive situation in terms of radiological consequences brought by the laser cutting process would be the burning of HEPA filters. Burning of other radioactive material not related to the segmentation process itself should be addressed in the overall decommissioning safety assessment.

Methodology of Calculation

The methodology of calculation is similar to that detailed in section 4.3.4, with adjustments to the formula of dose to workers as per equations Eq. A4.3, A4.4 and A4.5 (see below).

The Effective Dose E, in mSv, from external exposure to the airborne cloud-shine will be calculated as follows:

$$E = \sum_i A_i \cdot \frac{1}{Vf} \cdot CFE_i \cdot T \cdot 3600 \cdot 10^3 \qquad \text{Eq. A4.3.}$$

Where:

- Ai, in Bq, is the accident-specific activity release, which is detailed later in this section.
- Vf will be the assumed to be conservatively a 3-meter radius semi-sphere (approximately 57 m^3). This value is quite conservative as it limits radioactivity dispersion (a more realistic approach could consider that smoke plume could be quickly spread all over the Reactor Building).
- T, the time that a worker may be exposed to the release will be assumed to be 5 minutes. Time sufficient to evacuate the affected area (early fire detection could occur even before reaching the HEPA filters, allowing workers to previous evacuation of the building, and additionally, radiation monitoring systems would provide early detection of high levels of airborne activity).
- The factor $3600 \cdot 10^3$ is used for adjusting units (s·mSv/h·Sv).

The inhalation Committed Effective Dose E(50) for workers is calculated following two different methodologies (two options). Option 1 relies in a fraction of radioactive material that a workers could inhale in case of fire. Option 2 relies in the calculation of the activity concentration that a worker could inhale before it evacuates the area.

For option 1, the inhalation Committed Effective Dose E(50) for workers, in mSv, is calculated as follows:

$$E(50) = \sum_i A_i \cdot f_{inh} \cdot CFE(50)_i \cdot 10^3 \qquad \text{Eq. A4.4.}$$

Where:

- f_{inh} represents the fraction of the material dispersed into the air that is inhaled by an individual, taken as 0.001 [Ref. 51].
- The factor 10^3 is used for adjusting units (mSv/Sv).

For option 2, the inhalation Committed Effective Dose E(50) for workers, in mSv, is calculated as follows:

$$E(50) = \sum_i A_{av.i} \cdot 1/Vf \cdot BR \cdot CFE(50)_i \cdot T \cdot 10^3 \qquad \text{Eq. A4.5.}$$

Where:

- A_i, Vf, and T are the same parameters used in Eq. A4.3.
- BR is the breathing rate of the worker of 1.2 m^3/h [Ref. 22, 23].
- CFE(50)i is the inhalation dose coefficient for each radionuclide (i), in Sv/Bq. [Ref. 27]. Values are selected for AMAD of 0.3 μm for underwater cutting and for 0.1 μm for in-air cutting [Ref. 43]. Type S is selected since is more representative of the type of particles (i.e., cobalt oxide).
- The factor 10^3 is used for adjusting units (mSv/Sv).

For obtaining the accident-specific activity release (Ai), the following will be assumed:

- As a result of the fire or explosion/overpressure, the activity content of a certain number of HEPA filters, with a dust load of 2.3 kg each, is released into the atmosphere of the containment building [Ref. 48, 49]. HEPA filters contain the specific activity of the most activated part of the RPV (Vessel wall specific activity (Cm Vessel) from section 2.3, as the inner cladding layer is not considered representative of the potential release), using the same approach as the NUREGS [Ref. 48, 49]. It is important to remark that HEPA filters are replaced or cleaned based on pressure differential drop or dose rates (due to handling and operational issues), and so, HEPA filters replacement/cleaning during RVI segmentation would be adjusted accordingly. Number of HEPA filters that may be affected by the fire or explosion/overpressure may be adjusted by End Users, considering that different values are provided by the NUREGs: two [Ref. 48] or six [Ref. 49] HEPA filters were considered. For this evaluation, the most conservative value was assumed (six HEPA filters, corresponding to 13.8 kg). This source term will be referred as A_{iHEPA}.

- The fire or explosion/overpressure resuspends the dust deposited on the walls of the contamination confinement. Approximately 0.2% of the total activity released during the RPV segmentation process is deposited on the surfaces [Ref. 48, 49]. For the RVI (underwater cutting, since there will be less free volume due to the presence of water), it would be considered similar to that of the RPV (less free air). The total activity is obtained from the average release rate (Aav) from Tables A3.3 to Table A3.6, multiplied by the cutting time (Tc) (refer to section 2.5.2). This source term will be referred as $A_{iConf\text{-}w}$.

- The fire or explosion/overpressure produces the release of the air contained inside the contamination confinement (Aci-a), for which the same activity concentrations that were calculated in Annex VI for in-air or 5-m underwater cutting will be used. The total activity is calculated considering the Reactor Cavity volume (485 m^3 [Ref. 48]) for the RPV cutting and the Refuelling Cavity or Dryer/Separator Storage Pool (750 m^3 [Ref. 48]) for the RVI segmentation, aligned with the calculations of Annex VI. This source term will be referred as $A_{iConf\text{-}a}$.

- HEPA filters of the reactor building are not affected by the fire or explosion/overpressure [Ref. 48, 49].

For calculating doses to the public, Eq. A3.4 and A3.5 will be used considering off-gas building filtration of 99.97%.

<u>Results</u>

The detailed results are summarized in tables A4.7 and A4.8, with the summary provided in Table A4.6. Public doses are only calculated at 100 m.

Table A4.6. Estimation of doses to the public and workers, in mSv, for IE.2.

Accident Scenario	Doses	PWR		BWR	
		RVI	RPV	RVI	RPV
IE.2. Fire or explosion. Option 1	Public	1.48E-04		3.24E-05	
	Workers	2.21E+02		2.68E+01	
IE.2. Fire or explosion. Option 2	Public	1.48E-04		3.24E-05	
	Workers	3.90E+02		4.71E+01	

It is important to remark that doses to workers in IE.2 would mainly result from inhalation, and the parameters defined are critical in the results. For option 1 and option 2, similar results are obtained, but it is important to remark that both are very conservative in the assumptions and more realistic parameters and assumptions could be considered, adjusting them to End Users actual conditions. For instance:

- Six HEPA filters are considered to be burned with high levels of radioactivity. This should be adjusted to plant conditions, for instance, considering if online cleaning of HEPA filters is available or actual activity limits for their change following Radiation protection criteria.
- HEPA filters are instantaneously burned without early indication of the fire, and the activity is released into a limited volume, with minimum dilution into the Reactor Building. The implementation of a more realistic approach could be considered.

Recommendation on Prevention, Detection and Mitigation Safety Measures

For reducing the associated risks to ALARA, different safety measures and controls are recommended to be implemented:

- For preventing the occurrence of fires, attention should be paid to fire loads and the use of the laser system. Recommendation of automatic shutdown of the laser source as per the parameters detailed in Table 6.3 should be addressed.
- Fire detection and mitigation systems should be available in the facility as to reduce the risk to ALARA. Fire detection would provide early indication to workers to evacuate the area, reducing the time exposed to the smoke plume (even before HEPA filters are reached). Fire mitigation would reduce the potential for the fire reaching the HEPA filters.
- Atmospheric airborne contamination control (Radiation Monitoring Surveillance and Monitoring Systems) should be located in the working environment to ensure that workers are alerted of high concentrations of airborne activity and evacuate the area accordingly.
- HEPA filters radioactive inventory should be evaluated, considering the potential for online cleaning or optimizing their replacement.
- Doses to workers in case of IE.2 would result mainly from inhalation. Radiation Protection procedures and controls should be followed (i.e., use of necessary personnel protective equipment) for firefighting activities.
- Building off-gas system monitoring and filtration should be in place for reducing the doses to the public to ALARA in case of confinement system malfunction.

Table A4.7. Initiating Event IE.2 Results: PWR.

Nuclide	Cm Vessel (Bq/g)	AiHEPA (Bq)	AiConf-w (Bq)	ACi-a (Bq/m3)	AiConf-a(Bq)	Ai (Bq)	CFE	CFE(50)w	CFE(70)1-2y	CFE(50)a
Nb-95	5.31E-11	7.32E-07	1.29E-09	0.00E+00	0.00E+00	7.34E-07	3.74E-14	2.50E-09	5.90E-09	1.80E-09
Fe-59	2.16E-04	2.98E+00	2.95E-03	0.00E+00	0.00E+00	2.98E+00	5.97E-14	4.40E-09	1.30E-08	4.00E-09
Co-58	8.70E-02	1.20E+03	1.66E+00	7.98E-04	3.87E-01	1.20E+03	4.76E-14	4.50E-09	7.50E-09	2.10E-09
Zr-95	2.55E-06	3.52E-02	3.39E-05	0.00E+00	0.00E+00	3.52E-02	3.60E-14	8.60E-09	1.90E-08	5.90E-09
Zn-65	2.76E-03	3.81E+01	1.29E-01	3.19E-03	1.55E+00	3.98E+01	2.90E-14	2.50E-09	6.70E-09	2.00E-09
Mn-54	7.21E+03	9.95E+07	9.76E+04	1.97E+01	9.54E+03	9.96E+07	4.09E-14	9.90E-09	6.20E-09	1.50E-09
Fe-55	8.60E+05	1.19E+10	1.19E+07	2.53E+03	1.23E+06	1.19E+10	0.00E+00	5.60E-10	8.50E-10	1.80E-10
Co-60	1.39E+05	1.92E+09	2.37E+06	1.04E+03	5.02E+05	1.92E+09	1.26E-13	1.10E-07	8.60E-08	3.10E-08
Ni-63	1.09E+04	1.50E+08	2.63E+05	1.72E+02	8.32E+04	1.50E+08	0.00E+00	6.00E-09	4.30E-09	1.30E-09
Mo-93	3.81E+00	5.26E+04	5.08E+01	8.58E-03	4.16E+00	5.26E+04	2.52E-17	4.00E-10	5.80E-09	2.30E-09
C-14	5.57E+01	7.68E+05	8.73E+02	3.09E-01	1.50E+02	7.70E+05	2.24E-19	2.30E-08	1.70E-08	5.80E-09
Nb-94	0.00E+00	0.00E+00	3.27E+00	5.85E-03	2.84E+00	6.11E+00	7.70E-14	3.50E-07	1.20E-07	4.90E-08
Ni-59	9.38E+01	1.29E+06	2.25E+03	1.20E+00	5.84E+02	1.30E+06	0.00E+00	2.90E-09	1.50E-09	4.40E-10
Ru-103	0.00E+00	0.00E+00	1.94E+01	7.52E-01	3.65E+02	3.84E+02	2.25E-14	3.10E-09	1.00E-08	3.00E-09
Ru-106	0.00E+00	0.00E+00	4.29E-08	0.00E+00	0.00E+00	4.29E-08	0.00E+00	1.30E-07	2.30E-07	6.60E-08
Cs-134	0.00E+00	0.00E+00	5.30E+02	2.05E+01	9.96E+03	1.05E+04	7.57E-14	5.30E-08	6.30E-08	2.00E-08
Cs-137	0.00E+00	0.00E+00	2.83E+03	1.10E+02	5.32E+04	5.61E+04	7.74E-18	1.90E-07	1.00E-07	3.90E-08
Ce-141	0.00E+00	0.00E+00	4.01E-10	0.00E+00	0.00E+00	4.01E-10	3.43E-15	2.60E-09	1.20E-08	3.80E-09
Ce-144	0.00E+00	0.00E+00	3.27E+01	1.27E+00	6.14E+02	6.47E+02	8.53E-16	8.40E-08	1.80E-07	5.30E-08
TOTAL	1.02E+06	1.40E+10	1.46E+07	3.89E+03	1.89E+06	1.40E+10				

	Workers (Option 1)			Workers (Option 2)			Infants 1-2y at 100m			Adults at 100m		
Nuclide	E	E(50)	DT	E	E(50)	DT	E	E(70)	DT	E	E(50)	DT
Nb-95	1.46E-16	1.83E-15	1.98E-15	1.46E-16	3.24E-15	3.39E-15	6.55E-23	3.62E-21	3.68E-21	6.55E-23	1.10E-21	1.17E-21
Fe-59	9.45E-10	1.31E-08	1.41E-08	9.45E-10	2.32E-08	2.42E-08	4.25E-16	3.24E-14	3.28E-14	4.25E-16	9.98E-15	1.04E-14
Co-58	3.04E-07	5.41E-06	5.72E-06	3.04E-07	9.57E-06	9.88E-06	1.37E-13	7.54E-12	7.68E-12	1.37E-13	2.11E-12	2.25E-12
Zr-95	6.73E-12	3.03E-10	3.10E-10	6.73E-12	5.36E-10	5.43E-10	3.03E-18	5.60E-16	5.63E-16	3.03E-18	1.74E-16	1.77E-16
Zn-65	6.12E-09	9.95E-08	1.06E-07	6.12E-09	1.76E-07	1.82E-07	2.76E-15	2.23E-13	2.26E-13	2.76E-15	6.65E-14	6.93E-14
Mn-54	2.16E-02	9.86E-01	1.01E+00	2.16E-02	1.74E+00	1.76E+00	9.73E-09	5.16E-07	5.26E-07	9.73E-09	1.25E-07	1.35E-07
Fe-55	0.00E+00	6.65E+00	6.65E+00	0.00E+00	1.18E+01	1.18E+01	0.00E+00	8.44E-06	8.44E-06	0.00E+00	1.79E-06	1.79E-06
Co-60	1.28E+00	2.11E+02	2.12E+02	1.28E+00	3.73E+02	3.74E+02	5.77E-07	1.38E-04	1.38E-04	5.77E-07	4.97E-05	5.03E-05
Ni-63	0.00E+00	9.03E-01	9.03E-01	0.00E+00	1.60E+00	1.60E+00	0.00E+00	5.41E-07	5.41E-07	0.00E+00	1.63E-07	1.63E-07
Mo-93	7.03E-09	2.10E-05	2.11E-05	7.03E-09	3.72E-05	3.72E-05	3.17E-15	2.55E-10	2.55E-10	3.17E-15	1.01E-10	1.01E-10
C-14	9.14E-10	1.77E-02	1.77E-02	9.14E-10	3.13E-02	3.13E-02	4.12E-16	1.09E-08	1.09E-08	4.12E-16	3.73E-09	3.73E-09
Nb-94	2.49E-09	2.14E-06	2.14E-06	2.49E-09	3.78E-06	3.78E-06	1.12E-15	6.12E-13	6.13E-13	1.12E-15	2.50E-13	2.51E-13
Ni-59	0.00E+00	3.76E-03	3.76E-03	0.00E+00	6.65E-03	6.65E-03	0.00E+00	1.63E-09	1.63E-09	0.00E+00	4.77E-10	4.77E-10
Ru-103	4.59E-08	1.19E-06	1.24E-06	4.59E-08	2.11E-06	2.15E-06	2.06E-14	3.21E-12	3.23E-12	2.06E-14	9.63E-13	9.84E-13
Ru-106	0.00E+00	5.57E-15	5.57E-15	0.00E+00	9.85E-15	9.85E-15	0.00E+00	8.24E-21	8.24E-21	0.00E+00	2.36E-21	2.36E-21
Cs-134	4.21E-06	5.56E-04	5.60E-04	4.21E-06	9.83E-04	9.87E-04	1.90E-12	5.52E-10	5.54E-10	1.90E-12	1.75E-10	1.77E-10
Cs-137	2.30E-09	1.07E-02	1.07E-02	2.30E-09	1.88E-02	1.88E-02	1.04E-15	4.69E-09	4.69E-09	1.04E-15	1.83E-09	1.83E-09
Ce-141	7.29E-21	1.04E-18	1.05E-18	7.29E-21	1.84E-18	1.85E-18	3.28E-27	4.02E-24	4.02E-24	3.28E-27	1.27E-24	1.28E-24
Ce-144	2.93E-09	5.44E-05	5.44E-05	2.93E-09	9.61E-05	9.61E-05	1.32E-15	9.74E-11	9.74E-11	1.32E-15	2.87E-11	2.87E-11
TOTAL	1.30E+00	2.20E+02	2.21E+02	1.30E+00	3.88E+02	3.90E+02	5.87E-07	1.47E-04	1.48E-04	5.87E-07	5.18E-05	5.24E-05

Table A4.8. Initiating Event IE.2 Results: BWR

Nuclide	Cm Vessel (Bq/g)	AiHEPA (Bq)	AiConf-w (Bq)	ACi-a (Bq/m3)	AiConf-a(Bq)	Ai (Bq)	CFE	CFE(50)w	CFE(70)1-2y	CFE(50)a
H-3	0.00E+00	0.00E+00	2.33E-01	0.00E+00	0.00E+00	2.33E-01	3.31E-19	1.00E-09	1.00E-09	2.60E-10
Be-10	0.00E+00	0.00E+00	1.60E-03	0.00E+00	0.00E+00	1.60E-03	1.12E-17	1.70E-07	9.10E-08	3.50E-08
C-14	5.81E+00	8.02E+04	6.41E+04	4.42E-02	2.14E+01	1.44E+05	2.24E-19	2.30E-08	1.70E-08	5.80E-09
P-32	7.72E-25	1.07E-20	8.57E-23	0.00E+00	0.00E+00	1.07E-20	9.90E-17	4.40E-09	1.50E-08	3.40E-09
P-33	0.00E+00	0.00E+00	2.20E-10	0.00E+00	0.00E+00	2.20E-10	8.23E-19	1.20E-09	4.60E-09	1.50E-09
S-35	6.17E-04	8.51E+00	1.39E+00	0.00E+00	0.00E+00	9.90E+00	2.43E-19	1.60E-09	6.00E-09	1.90E-09
Cl-36	0.00E+00	0.00E+00	1.64E-01	0.00E+00	0.00E+00	1.64E-01	2.23E-17	1.90E-07	2.60E-08	7.30E-09
Cr-51	2.07E-11	2.86E-07	1.22E-05	0.00E+00	0.00E+00	1.25E-05	1.51E-15	7.90E-11	2.10E-10	3.70E-11
Mn-54	4.76E+02	6.57E+06	2.88E+05	8.92E+01	4.33E+04	6.90E+06	4.09E-14	9.90E-09	6.20E-09	1.50E-09
Fe-55	1.17E+05	1.62E+09	2.32E+08	8.93E+02	4.33E+05	1.85E+09	0.00E+00	5.60E-10	3.20E-09	7.70E-10
Fe-59	2.21E-05	3.05E-01	4.61E-02	0.00E+00	0.00E+00	3.51E-01	5.97E-14	4.40E-09	1.30E-08	4.00E-09
Co-58	5.75E-03	7.94E+01	5.77E+01	5.27E-05	2.55E-02	1.37E+02	4.76E-14	4.50E-09	7.50E-09	2.10E-09
Co-60	3.52E+03	4.85E+07	1.29E+08	1.27E+03	6.17E+05	1.79E+08	1.26E-13	1.10E-07	8.60E-08	3.10E-08
Ni-59	1.25E+01	1.73E+05	3.88E+05	9.54E-02	4.63E+01	5.61E+05	0.00E+00	2.90E-09	1.50E-09	4.40E-10
Ni-63	1.45E+03	2.00E+07	5.21E+07	1.11E+01	5.36E+03	7.21E+07	0.00E+00	6.00E-09	4.30E-09	1.30E-09
Zn-65	4.34E-05	6.00E-01	5.70E+02	6.89E-01	3.34E+02	9.05E+02	2.90E-14	2.50E-09	6.70E-09	2.00E-09
Zr-93	0.00E+00	0.00E+00	4.97E-03	0.00E+00	0.00E+00	4.97E-03	0.00E+00	1.40E-08	6.40E-09	2.50E-08
Zr-95	1.68E-07	2.32E-03	1.19E-03	0.00E+00	0.00E+00	3.51E-03	3.60E-14	8.60E-09	1.90E-08	5.90E-09
Nb-93m	2.88E-01	3.97E+03	7.81E+01	2.03E-03	9.85E-01	4.05E+03	4.44E-18	7.20E-09	6.50E-09	1.80E-09
Nb-94	7.12E-04	9.83E+00	9.14E+02	0.00E+00	0.00E+00	9.24E+02	7.70E-14	3.50E-07	1.20E-07	4.90E-08
Nb-95	3.44E-12	4.74E-08	7.89E-07	0.00E+00	0.00E+00	8.37E-07	3.74E-14	2.50E-09	5.90E-09	1.80E-09

Nuclide	Cm Vessel (Bq/g)	AiHEPA (Bq)	AiConf-w (Bq)	ACi-a (Bq/m3)	AiConf-a(Bq)	Ai (Bq)	CFE	CFE(50)w	CFE(70)1-2y	CFE(50)a
Mo-93	8.05E-01	1.11E+04	2.19E+02	5.98E-03	2.90E+00	1.13E+04	2.52E-17	4.00E-10	5.80E-09	2.30E-09
Tc-99	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.62E-18	5.50E-08	3.70E-08	1.30E-08
Ag-108m	0.00E+00	0.00E+00	4.40E+01	0.00E+00	0.00E+00	4.40E+01	7.80E-14	3.10E-07	8.70E-08	3.70E-08
Ag-108	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	9.28E-16	0.00E+00	0.00E+00	0.00E+00
Ag-109m	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.92E-16	0.00E+00	0.00E+00	0.00E+00
Cd-109	0.00E+00	0.00E+00	3.04E+02	0.00E+00	0.00E+00	3.04E+02	2.94E-16	6.00E-09	3.70E-08	8.10E-09
Ag-110m	0.00E+00	0.00E+00	1.42E+02	0.00E+00	0.00E+00	1.42E+02	1.36E-13	3.20E-08	4.10E-08	1.20E-08
Ag-110	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.78E-15	0.00E+00	0.00E+00	0.00E+00
Sm-151	0.00E+00	0.00E+00	1.26E+01	0.00E+00	0.00E+00	1.26E+01	3.61E-20	4.70E-09	1.00E-08	4.00E-09
Eu-152	0.00E+00	0.00E+00	5.69E-01	0.00E+00	0.00E+00	5.69E-01	5.65E-14	6.70E-08	1.00E-07	4.20E-08
Eu-154	0.00E+00	0.00E+00	1.43E+03	0.00E+00	0.00E+00	1.43E+03	6.14E-14	6.90E-08	1.50E-07	5.30E-08
Tb-160	0.00E+00	0.00E+00	2.77E-06	0.00E+00	0.00E+00	2.77E-06	5.54E-14	7.60E-09	2.50E-08	7.00E-09
Ho-166m	0.00E+00	0.00E+00	4.77E-01	0.00E+00	0.00E+00	4.77E-01	8.45E-14	1.60E-07	2.50E-07	1.20E-07
Ru-103	1.23E+05	1.69E+09	5.22E+01	9.02E-01	4.38E+02	1.69E+09	2.25E-14	3.10E-09	1.00E-08	3.00E-09
Ru-106	0.00E+00	0.00E+00	1.15E-07	0.00E+00	0.00E+00	1.15E-07	0.00E+00	1.30E-07	2.30E-07	6.60E-08
Cs-134	0.00E+00	0.00E+00	1.43E+03	2.46E+01	1.19E+04	1.34E+04	7.57E-14	5.30E-08	6.30E-08	2.00E-08
Cs-137	0.00E+00	0.00E+00	7.62E+03	1.32E+02	6.39E+04	7.15E+04	7.74E-18	1.90E-07	1.00E-07	3.90E-08
Ce-141	0.00E+00	0.00E+00	1.08E-09	0.00E+00	0.00E+00	1.08E-09	3.43E-15	2.60E-09	1.20E-08	3.80E-09
Ce-144	0.00E+00	0.00E+00	8.80E+01	1.52E+00	7.37E+02	8.25E+02	8.53E-16	8.40E-08	1.80E-07	5.30E-08
TOTAL	2.45E+05	3.38E+09	4.14E+08	2.43E+03	1.18E+06	3.80E+09				

	Workers (Option 1)			Workers (Option 2)			Infants 1-2y at 100m			Adults at 100m		
Nuclide	E	E(50)	DT	E	E(50)	DT	E	E(70)	DT	E	E(50)	DT
H-3	4.09E-16	2.33E-10	2.33E-10	4.09E-16	4.12E-10	4.12E-10	1.84E-22	1.95E-16	1.95E-16	1.84E-22	5.06E-17	5.06E-17
Be-10	9.53E-17	2.73E-10	2.73E-10	9.53E-17	4.82E-10	4.82E-10	4.29E-23	1.22E-16	1.22E-16	4.29E-23	4.69E-17	4.69E-17
C-14	1.71E-10	3.32E-03	3.32E-03	1.71E-10	5.87E-03	5.87E-03	7.72E-17	2.05E-09	2.05E-09	7.72E-17	7.00E-10	7.00E-10
P-32	5.64E-33	4.73E-29	4.73E-29	5.64E-33	8.36E-29	8.36E-29	2.54E-39	1.35E-34	1.35E-34	2.54E-39	3.05E-35	3.05E-35
P-33	9.58E-25	2.63E-19	2.63E-19	9.58E-25	4.66E-19	4.66E-19	4.31E-31	8.44E-25	8.44E-25	4.31E-31	2.75E-25	2.75E-25
S-35	1.28E-14	1.58E-08	1.58E-08	1.28E-14	2.80E-08	2.80E-08	5.74E-21	4.96E-14	4.96E-14	5.74E-21	1.57E-14	1.57E-14
Cl-36	1.94E-14	3.12E-08	3.12E-08	1.94E-14	5.51E-08	5.51E-08	8.73E-21	3.56E-15	3.56E-15	8.73E-21	1.00E-15	1.00E-15
Cr-51	1.00E-16	9.86E-16	1.09E-15	1.00E-16	1.74E-15	1.84E-15	4.50E-23	2.19E-21	2.24E-21	4.50E-23	3.86E-22	4.31E-22
Mn-54	1.50E-03	6.83E-02	6.98E-02	1.50E-03	1.21E-01	1.22E-01	6.74E-10	3.57E-08	3.64E-08	6.74E-10	8.65E-09	9.32E-09
Fe-55	0.00E+00	1.04E+00	1.04E+00	0.00E+00	1.83E+00	1.83E+00	0.00E+00	4.94E-06	4.94E-06	0.00E+00	1.19E-06	1.19E-06
Fe-59	1.11E-10	1.55E-09	1.66E-09	1.11E-10	2.73E-09	2.84E-09	5.01E-17	3.82E-15	3.87E-15	5.01E-17	1.17E-15	1.22E-15
Co-58	3.46E-08	6.17E-07	6.52E-07	3.46E-08	1.09E-06	1.13E-06	1.56E-14	8.59E-13	8.75E-13	1.56E-14	2.41E-13	2.56E-13
Co-60	1.19E-01	1.96E+01	1.98E+01	1.19E-01	3.47E+01	3.49E+01	5.37E-08	1.28E-05	1.29E-05	5.37E-08	4.63E-06	4.68E-06
Ni-59	0.00E+00	1.63E-03	1.63E-03	0.00E+00	2.88E-03	2.88E-03	0.00E+00	7.03E-10	7.03E-10	0.00E+00	2.06E-10	2.06E-10
Ni-63	0.00E+00	4.33E-01	4.33E-01	0.00E+00	7.65E-01	7.65E-01	0.00E+00	2.59E-07	2.59E-07	0.00E+00	7.83E-08	7.83E-08
Zn-65	1.39E-07	2.26E-06	2.40E-06	1.39E-07	4.00E-06	4.14E-06	6.27E-14	5.07E-12	5.13E-12	6.27E-14	1.51E-12	1.58E-12
Zr-93	0.00E+00	6.96E-11	6.96E-11	0.00E+00	1.23E-10	1.23E-10	0.00E+00	2.66E-17	2.66E-17	0.00E+00	1.04E-16	1.04E-16
Zr-95	6.70E-13	3.02E-11	3.08E-11	6.70E-13	5.33E-11	5.40E-11	3.01E-19	5.57E-17	5.60E-17	3.01E-19	1.73E-17	1.76E-17
Nb-93m	9.55E-11	2.92E-05	2.92E-05	9.55E-11	5.16E-05	5.16E-05	4.30E-17	2.20E-11	2.20E-11	4.30E-17	6.10E-12	6.10E-12
Nb-94	3.77E-07	3.23E-04	3.24E-04	3.77E-07	5.72E-04	5.72E-04	1.70E-13	9.27E-11	9.29E-11	1.70E-13	3.78E-11	3.80E-11
Nb-95	1.66E-16	2.09E-15	2.26E-15	1.66E-16	3.70E-15	3.87E-15	7.47E-23	4.13E-21	4.20E-21	7.47E-23	1.26E-21	1.33E-21
Mo-93	1.52E-09	4.53E-06	4.54E-06	1.52E-09	8.02E-06	8.02E-06	6.82E-16	5.50E-11	5.50E-11	6.82E-16	2.18E-11	2.18E-11

	Workers (Option 1)			Workers (Option 2)			Infants 1-2y at 100m			Adults at 100m		
Nuclide	E	E(50)	DT	E	E(50)	DT	E	E(70)	DT	E	E(50)	DT
Tc-99	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Ag-108m	1.82E-08	1.36E-05	1.37E-05	1.82E-08	2.41E-05	2.41E-05	8.20E-15	3.20E-12	3.21E-12	8.20E-15	1.36E-12	1.37E-12
Ag-108	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Ag-109m	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Cd-109	4.74E-10	1.82E-06	1.83E-06	4.74E-10	3.23E-06	3.23E-06	2.14E-16	9.40E-12	9.40E-12	2.14E-16	2.06E-12	2.06E-12
Ag-110m	1.03E-07	4.55E-06	4.65E-06	1.03E-07	8.04E-06	8.14E-06	4.61E-14	4.87E-12	4.91E-12	4.61E-14	1.42E-12	1.47E-12
Ag-110	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Sm-151	2.41E-15	5.91E-08	5.91E-08	2.41E-15	1.05E-07	1.05E-07	1.08E-21	1.05E-13	1.05E-13	1.08E-21	4.20E-14	4.20E-14
Eu-152	1.71E-10	3.81E-08	3.83E-08	1.71E-10	6.74E-08	6.76E-08	7.68E-17	4.75E-14	4.76E-14	7.68E-17	2.00E-14	2.00E-14
Eu-154	4.67E-07	9.90E-05	9.94E-05	4.67E-07	1.75E-04	1.75E-04	2.10E-13	1.80E-10	1.80E-10	2.10E-13	6.35E-11	6.38E-11
Tb-160	8.13E-16	2.10E-14	2.18E-14	8.13E-16	3.72E-14	3.80E-14	3.66E-22	5.78E-20	5.81E-20	3.66E-22	1.62E-20	1.65E-20
Ho-166m	2.14E-10	7.63E-08	7.65E-08	2.14E-10	1.35E-07	1.35E-07	9.62E-17	9.97E-14	9.98E-14	9.62E-17	4.78E-14	4.79E-14
Ru-103	2.02E-01	5.24E+00	5.45E+00	2.02E-01	9.27E+00	9.47E+00	9.09E-08	1.41E-05	1.42E-05	9.09E-08	4.24E-06	4.33E-06
Ru-106	0.00E+00	1.50E-14	1.50E-14	0.00E+00	2.65E-14	2.65E-14	0.00E+00	2.22E-20	2.22E-20	0.00E+00	6.36E-21	6.36E-21
Cs-134	5.37E-06	7.09E-04	7.14E-04	5.37E-06	1.25E-03	1.26E-03	2.42E-12	7.04E-10	7.07E-10	2.42E-12	2.24E-10	2.26E-10
Cs-137	2.94E-09	1.36E-02	1.36E-02	2.94E-09	2.40E-02	2.40E-02	1.32E-15	5.98E-09	5.98E-09	1.32E-15	2.33E-09	2.33E-09
Ce-141	1.96E-20	2.80E-18	2.82E-18	1.96E-20	4.96E-18	4.98E-18	8.83E-27	1.08E-23	1.08E-23	8.83E-27	3.42E-24	3.43E-24
Ce-144	3.73E-09	6.93E-05	6.93E-05	3.73E-09	1.23E-04	1.23E-04	1.68E-15	1.24E-10	1.24E-10	1.68E-15	3.65E-11	3.65E-11
TOTAL	3.23E-01	2.64E+01	2.68E+01	3.23E-01	4.68E+01	4.71E+01	1.45E-07	3.22E-05	3.24E-05	1.45E-07	1.01E-05	1.03E-05

IE.3. Drop of loads.

Scenarios

Accidents related to the handling of radioactive materials (excluding those related to the fuel) considered within the scope of this evaluation may be those mentioned below:

- Drop of a segmented piece of the RPV, in-air:

  An accidental drop of a segmented piece of the RPV may occur when handling them in-air (i.e., moving them to the waste package). This may happen due to, among others, a failure in the handling equipment, or a human error.

  Because of the drop, surface contamination of the component may be partially released, resulting in the release of aerosols to the air of the Containment Building and to the atmosphere through the off-gas system.

- Drop of RVI segmented piece of the RVI, underwater:

  An accidental underwater drop of a segmented piece of the RVI may occur during its handling (i.e., moving it to the waste packaged). This may happen due to, among others, a failure in the handling equipment, or a human error.

  Because of the drop, surface contamination of the component may be partially released, contaminating the water, and subsequently, resulting in the release of aerosols to the air of the Containment Building and to the atmosphere through the off-gas system.

Both scenarios will be assessed.

The drop of the entire RPV or RVI components if they are required to be relocated is not considered within the scope of this assessment. However, Potential End Users may assess their consequences following the methodology presented in this evaluation.

Other potential drops of contaminated materials may include concrete slabs or, if space needs to be created, concrete cubes, that may need also to be evaluated. However, these events are considered plant-specific and out of the scope of this evaluation.

Methodology of Calculation

The methodology of calculation is similar to that detailed in section 4.3.4, with adjustments to the formula of dose to workers as per equations Eq. A4.3, A4.4, and A4.5 (refer to IE.2).

As in IE.2, the inhalation Committed Effective Dose E(50) for workers is calculated following two different methodologies (two options):

- Option 1 relies in a fraction of radioactive material that a workers could inhale in case of drop of load.
- Option 2 relies in the calculation of the activity concentration that a worker could inhale before it evacuates the area. Additionally, the Number of Derived Air Concentrations (N.DAC) is estimated for obtaining a representative indication of the risk. This value is obtained as depicted in Annex VI (section A6.4.1)[13].

The following parameters are considered:

- Ai, in Bq, is the accident-specific activity release, which is detailed later in this section.
- Vf is the volume where the activity release is diluted[14]. The assumed volume differs from Option 1 and Option 2 as follows:
    - For Option 1, it is assumed that the piece will fall within the Reactor Cavity for RPV segmentation or the Refuelling Cavity or Dryer/Separator Storage Pool for RVI segmentation where they are being cut. The contamination will be dispersed within the cavity before reaching the working area (this is considered justifiable due to the limited width of the Reactor Cavity in comparison with its height, and for the Refuelling Cavity or Dryer/Separator Storage Pool since this will occur underwater). Therefore, Vf will be the assumed to be the Reactor Cavity volume (485 m3 [Ref. 48]) for the RPV cutting and the (750 m3 [Ref. 48]) for the RVI segmentation.
    - For Option 2, Vf will be the assumed to be conservatively a 3-meter radius semi-sphere (approximately 57 m3), limiting radioactivity dispersion.
- T, the time that a worker may be exposed to the release. Two values are considered:
    - For Option 1, the time that a worker may be exposed to the release will be assumed to be 30 minutes. Time sufficient to evacuate the building in case is deemed necessary. It is important to remark that this value is very conservative, and it is commonly used for members of the public that do not acknowledge the nature of the incident. Shorter evacuation times could be considered for a worker that is acknoledgeble of the activities being performed and the associated risks (as it is considered in Option 2).
    - For Option 2, the time that a worker may be exposed to the release will be assumed to be 1 minute. Time sufficient to evacuate the affected area by a worker.

[13] In this case, using the CFE(50)w specific for each AMAD for calculating ALI.
[14] Since the radiological consequences are mainly driven by the committed dose from inhalation, the dilution volume is more relevant in Option 2. The estimation of committed doses from inhalation in Option 1 relies on the inhalation fraction, using the dilution volume only for calculating external doses from cloud-shine.

- Rest of parameters will be used as per IE.2, including fraction of material dispersed into the air that is inhaled by an individual (for Option 1), and breathing rate of a worker (for Option 2).

For obtaining the accident-specific activity release (Ai), the following will be assumed:

- Activation products of the RPV and RVI are incorporated in the solid matrix, and thus, would require some type of mechanical, thermal, or chemical action for being dispersed. Consequently, the release of activation products due to drop of loads will be considered negligible.
- Contamination of the RPV and RVI may be released because of the drop. Reference contamination values are shown in Tables 2.6 (PWR) and 2.9 (BWR).
- The eventual resuspension of activity deposited in the liner of the Reactor Cavity, Refuelling Cavity or Dryer/Separator Storage Pool is assumed to be negligible.
- A fraction of 1E-03 of the contamination is released due to the drop load [Ref. 51].
- A scrubbing factor of 99% is considered for drops during RVI underwater cutting in PWR and BWR. This is aligned with scrubbing factors for Plasma Arc Cutting underwater [Ref. 43]. Since during Plasma Arc Cutting air is injected (and it produces a raising bubbling effect) and in this case no assist gas is present, scrubbing factors would be higher (so the value is considered conservative).
- For each scenario, the following components and associated contaminated surfaces will be considered:
    - PWR, RVI: the biggest segmented piece, as per the segmentation plan [Ref. 52], would be from the Upper Core Barrel, with the biggest piece resulting from the cut in 10 segments of 62 inches each, with an outside diameter of 3.899 m. This results in a contaminated surface of 3.86E+05 cm^2, considering both the internal and outer sides of the piece.
    - PWR, RPV: the biggest segmented piece, as per the segmentation plan [Ref. 52], would be from the RPV wall, which will be cut in 11 segments of 50 inches each, with an inside diameter of 390 cm (1.59E+04 cm^2). Only the internal side of the piece is contaminated.
    - BWR, RVI: the biggest segmented piece, as per the segmentation plan [Ref. 53], would be the Shroud Support Cylinder with the biggest piece resulting from the cut in 18 segments of 69 inches each, with an inside diameter of 4.953 m. This results in a contaminated surface of 5.45E+05 cm^2, considering both the internal and outer sides of the piece.
    - BWR, RPV: the biggest segmented piece, as per the segmentation plan [Ref. 53], would be from the upper section of the RPV wall, which will be cut in 18 segments of 87 inches each, with an inside diameter of 6.375 m (2.46E4 cm^2). Only the internal side of the piece is contaminated.

For calculating doses to the public, Eq. A3.4 and A3.5 will be used considering off-gas building filtration of 99.97%.

Results

The detailed results are summarized in tables A4.10 to A4.13, with the summary provided in Table A4.9. Public doses are only calculated at 100 m.

Table A4.9. Estimation of doses to the public and workers, in mSv, for IE.3.

Accident Scenario	Doses	PWR		BWR	
		RVI	RPV	RVI	RPV
IE.3. Drop of loads. Option 1	Public	6.52E-08	2.69E-07	1.78E-07	8.03E-07
	Workers	7.66E-02	4.36E-01	2.07E-01	1.29E+00
IE.3. Drop of loads. Option 2	Public	6.52E-08	2.69E-07	1.78E-07	8.03E-07
	Workers	2.71E-02	1.54E-01	7.34E-02	4.55E-01

It is important to remark that doses to workers in IE.3 would mainly result from inhalation, and the parameters defined are critical in the results. For option 1 and option 2, similar results are obtained, with slightly higher values in Option 1 (higher time of exposure is considered).

Recommendation on Prevention, Detection and Mitigation Safety Measures

For reducing the associated risks to ALARA, different safety measures and controls are recommended to be implemented:

- For preventing the occurrence of drop of loads, attention should be paid to the use of fail-safe design of handling equipment, which shall be certified and with a scale, HSE procedures and controls, as well as human error minimization techniques and training.
- It is not considered plausible that workers would not be alerted by the drop of load itself and that they were not aware of the associated radiological risk due to the special relevance of cutting operations. However, atmospheric airborne contamination control (Radiation Monitoring Surveillance and Monitoring Systems) may be located in the working environment to ensure that workers are alerted of high concentrations of airborne activity and evacuate the area accordingly,
- Building off-gas system monitoring and filtration should be in place for reducing the doses to the public to ALARA in case of confinement system malfunction.

Table A4.10. Initiating Event IE.3 Results: PWR, RVI.

Nuclide	Total Cont. (Bq/cm²)	Ai (Bq)	CFE	CFE(50)w	CFE(70)1-2y	CFE(50)a	*Only for Option 2*			
							Aci (Bq/m³)	ALI (Bq)	DAC (Bq/m³)	NºDAC
Nb-95	5.72E-09	2.21E-08	3.74E-14	1.70E-09	5.90E-09	1.80E-09	3.90E-10	1.18E+07	5.35E+03	7.30E-14
Fe-59	3.99E-05	1.54E-04	5.97E-14	3.20E-09	1.30E-08	4.00E-09	2.72E-06	6.25E+06	2.84E+03	9.58E-10
Co-58	2.03E-01	7.84E-01	4.76E-14	3.20E-09	7.50E-09	2.10E-09	1.39E-02	6.25E+06	2.84E+03	4.88E-06
Zr-95	4.26E-08	1.65E-07	3.60E-14	6.10E-09	1.90E-08	5.90E-09	2.91E-09	3.28E+06	1.49E+03	1.95E-12
Zn-65	8.77E-01	3.38E+00	2.90E-14	2.00E-09	6.70E-09	2.00E-09	5.98E-02	1.00E+07	4.55E+03	1.32E-05
Mn-54	1.06E+03	4.08E+03	4.09E-14	7.10E-09	6.20E-09	1.50E-09	7.21E+01	2.82E+06	1.28E+03	5.63E-02
Fe-55	1.73E+05	6.69E+05	0.00E+00	4.10E-10	8.50E-10	1.80E-10	1.18E+04	4.88E+07	2.22E+04	5.34E-01
Co-60	1.92E+05	7.42E+05	1.26E-13	8.10E-08	8.60E-08	3.10E-08	1.31E+04	2.47E+05	1.12E+02	1.17E+02
Ni-63	3.87E+04	1.49E+05	0.00E+00	4.30E-09	4.30E-09	1.30E-09	2.64E+03	4.65E+06	2.11E+03	1.25E+00
Mo-93	1.27E-01	4.92E-01	2.52E-17	2.90E-10	5.80E-09	2.30E-09	8.70E-03	6.90E+07	3.13E+04	2.78E-07
C-14	4.93E+01	1.90E+02	2.24E-19	1.60E-08	1.70E-08	5.80E-09	3.36E+00	1.25E+06	5.68E+02	5.92E-03
Nb-94	1.57E+00	6.07E+00	7.70E-14	2.50E-07	1.20E-07	4.90E-08	1.07E-01	8.00E+04	3.64E+01	2.95E-03
Ni-59	2.62E+02	1.01E+03	0.00E+00	2.10E-09	1.50E-09	4.40E-10	1.79E+01	9.52E+06	4.33E+03	4.13E-03
Ru-103	1.97E+02	7.60E+02	2.25E-14	2.20E-09	1.00E-08	3.00E-09	1.34E+01	9.09E+06	4.13E+03	3.25E-03
Ru-106	4.34E-07	1.68E-06	0.00E+00	9.60E-08	2.30E-07	6.60E-08	2.96E-08	2.08E+05	9.47E+01	3.13E-10
Cs-134	5.37E+03	2.07E+04	7.57E-14	3.80E-08	6.30E-08	2.00E-08	3.67E+02	5.26E+05	2.39E+02	1.53E+00
Cs-137	2.87E+04	1.11E+05	7.74E-18	1.30E-07	1.00E-07	3.90E-08	1.96E+03	1.54E+05	6.99E+01	2.80E+01
Ce-141	4.06E-09	1.57E-08	3.43E-15	1.20E-09	1.20E-08	3.80E-09	2.77E-10	1.67E+07	7.58E+03	3.66E-14
Ce-144	3.31E+02	1.28E+03	8.53E-16	3.90E-08	1.80E-07	5.30E-08	2.26E+01	5.13E+05	2.33E+02	9.70E-02
TOTAL	4.40E+05	1.70E+06					3.01E+04			8.45E+02

	Workers (Option 1)			Workers (Option 2)			Infants 1-2y at 100m			Adults at 100m		
Nuclide	E	E(50)	DT	E	E(50)	DT	E	E(70)	DT	E	E(50)	DT
Nb-95	1.98E-18	3.75E-17	3.95E-17	8.76E-19	1.33E-17	1.42E-17	1.97E-24	1.09E-22	1.11E-22	1.97E-24	3.32E-23	3.52E-23
Fe-59	2.21E-14	4.93E-13	5.15E-13	9.75E-15	1.74E-13	1.84E-13	2.19E-20	1.67E-18	1.69E-18	2.19E-20	5.15E-19	5.37E-19
Co-58	8.95E-11	2.51E-09	2.60E-09	3.96E-11	8.87E-10	9.26E-10	8.91E-17	4.91E-15	5.00E-15	8.91E-17	1.38E-15	1.46E-15
Zr-95	1.42E-17	1.00E-15	1.02E-15	6.28E-18	3.55E-16	3.61E-16	1.41E-23	2.61E-21	2.63E-21	1.41E-23	8.11E-22	8.26E-22
Zn-65	2.36E-10	6.77E-09	7.00E-09	1.04E-10	2.39E-09	2.50E-09	2.34E-16	1.89E-14	1.92E-14	2.34E-16	5.66E-15	5.89E-15
Mn-54	4.00E-07	2.90E-05	2.94E-05	1.77E-07	1.02E-05	1.04E-05	3.98E-13	2.11E-11	2.15E-11	3.98E-13	5.11E-12	5.51E-12
Fe-55	0.00E+00	2.74E-04	2.74E-04	0.00E+00	9.70E-05	9.70E-05	0.00E+00	4.75E-10	4.75E-10	0.00E+00	1.01E-10	1.01E-10
Co-60	2.24E-04	6.01E-02	6.03E-02	9.92E-05	2.13E-02	2.14E-02	2.23E-10	5.34E-08	5.36E-08	2.23E-10	1.92E-08	1.95E-08
Ni-63	0.00E+00	6.43E-04	6.43E-04	0.00E+00	2.27E-04	2.27E-04	0.00E+00	5.37E-10	5.37E-10	0.00E+00	1.62E-10	1.62E-10
Mo-93	2.98E-14	1.43E-10	1.43E-10	1.32E-14	5.05E-11	5.05E-11	2.96E-20	2.39E-15	2.39E-15	2.96E-20	9.46E-16	9.46E-16
C-14	1.02E-13	3.04E-06	3.04E-06	4.52E-14	1.08E-06	1.08E-06	1.02E-19	2.70E-12	2.70E-12	1.02E-19	9.22E-13	9.22E-13
Nb-94	1.12E-09	1.52E-06	1.52E-06	4.96E-10	5.37E-07	5.37E-07	1.12E-15	6.09E-13	6.10E-13	1.12E-15	2.49E-13	2.50E-13
Ni-59	0.00E+00	2.12E-06	2.12E-06	0.00E+00	7.51E-07	7.51E-07	0.00E+00	1.27E-12	1.27E-12	0.00E+00	3.72E-13	3.72E-13
Ru-103	4.10E-08	1.67E-06	1.71E-06	1.81E-08	5.91E-07	6.09E-07	4.08E-14	6.35E-12	6.39E-12	4.08E-14	1.90E-12	1.95E-12
Ru-106	0.00E+00	1.61E-13	1.61E-13	0.00E+00	5.69E-14	5.69E-14	0.00E+00	3.22E-19	3.22E-19	0.00E+00	9.25E-20	9.25E-20
Cs-134	3.77E-06	7.88E-04	7.92E-04	1.67E-06	2.79E-04	2.80E-04	3.75E-12	1.09E-09	1.10E-09	3.75E-12	3.47E-10	3.50E-10
Cs-137	2.06E-09	1.44E-02	1.44E-02	9.10E-10	5.10E-03	5.10E-03	2.05E-15	9.26E-09	9.26E-09	2.05E-15	3.61E-09	3.61E-09
Ce-141	1.29E-19	1.88E-17	1.89E-17	5.70E-20	6.65E-18	6.71E-18	1.28E-25	1.57E-22	1.57E-22	1.28E-25	4.98E-23	4.99E-23
Ce-144	2.62E-09	4.99E-05	4.99E-05	1.16E-09	1.76E-05	1.76E-05	2.61E-15	1.92E-10	1.92E-10	2.61E-15	5.67E-11	5.67E-11
TOTAL	2.29E-04	7.63E-02	7.66E-02	1.01E-04	2.70E-02	2.71E-02	2.28E-10	6.49E-08	6.52E-08	2.28E-10	2.35E-08	2.37E-08

Table A411. Initiating Event IE.3 Results: PWR, RPV.

Nuclide	Total Cont. (Bq/cm²)	Ai (Bq)	CFE	CFE(50)w	CFE(70)1-2y	CFE(50)a	*Only for Option 2*			
							Aci (Bq/m³)	ALI (Bq)	DAC (Bq/m³)	NºDAC
Nb-95	5.72E-09	9.12E-08	3.74E-14	2.50E-09	5.90E-09	1.80E-09	1.61E-09	8.00E+06	3.64E+03	4.43E-13
Fe-59	3.99E-05	6.36E-04	5.97E-14	4.40E-09	1.30E-08	4.00E-09	1.12E-05	4.55E+06	2.07E+03	5.44E-09
Co-58	2.03E-01	3.24E+00	4.76E-14	4.50E-09	7.50E-09	2.10E-09	5.72E-02	4.44E+06	2.02E+03	2.83E-05
Zr-95	4.26E-08	6.79E-07	3.60E-14	8.60E-09	1.90E-08	5.90E-09	1.20E-08	2.33E+06	1.06E+03	1.14E-11
Zn-65	8.77E-01	1.40E+01	2.90E-14	2.50E-09	6.70E-09	2.00E-09	2.47E-01	8.00E+06	3.64E+03	6.79E-05
Mn-54	1.06E+03	1.68E+04	4.09E-14	9.90E-09	6.20E-09	1.50E-09	2.98E+02	2.02E+06	9.18E+02	3.24E-01
Fe-55	1.73E+05	2.76E+06	0.00E+00	5.60E-10	8.50E-10	1.80E-10	4.89E+04	3.57E+07	1.62E+04	3.01E+00
Co-60	1.92E+05	3.06E+06	1.26E-13	1.10E-07	8.60E-08	3.10E-08	5.42E+04	1.82E+05	8.26E+01	6.56E+02
Ni-63	3.87E+04	6.17E+05	0.00E+00	6.00E-09	4.30E-09	1.30E-09	1.09E+04	3.33E+06	1.52E+03	7.20E+00
Mo-93	1.27E-01	2.03E+00	2.52E-17	4.00E-10	5.80E-09	2.30E-09	3.59E-02	5.00E+07	2.27E+04	1.58E-06
C-14	4.93E+01	7.85E+02	2.24E-19	2.30E-08	1.70E-08	5.80E-09	1.39E+01	8.70E+05	3.95E+02	3.51E-02
Nb-94	1.57E+00	2.51E+01	7.70E-14	3.50E-07	1.20E-07	4.90E-08	4.43E-01	5.71E+04	2.60E+01	1.71E-02
Ni-59	2.62E+02	4.18E+03	0.00E+00	2.90E-09	1.50E-09	4.40E-10	7.38E+01	6.90E+06	3.13E+03	2.36E-02
Ru-103	1.97E+02	3.14E+03	2.25E-14	3.10E-09	1.00E-08	3.00E-09	5.55E+01	6.45E+06	2.93E+03	1.89E-02
Ru-106	4.34E-07	6.92E-06	0.00E+00	1.30E-07	2.30E-07	6.60E-08	1.22E-07	1.54E+05	6.99E+01	1.75E-09
Cs-134	5.37E+03	8.56E+04	7.57E-14	5.30E-08	6.30E-08	2.00E-08	1.51E+03	3.77E+05	1.72E+02	8.83E+00
Cs-137	2.87E+04	4.58E+05	7.74E-18	1.90E-07	1.00E-07	3.90E-08	8.09E+03	1.05E+05	4.78E+01	1.69E+02
Ce-141	4.06E-09	6.47E-08	3.43E-15	2.60E-09	1.20E-08	3.80E-09	1.14E-09	7.69E+06	3.50E+03	3.27E-13
Ce-144	3.31E+02	5.28E+03	8.53E-16	8.40E-08	1.80E-07	5.30E-08	9.34E+01	2.38E+05	1.08E+02	8.63E-01
TOTAL	4.40E+05	7.02E+06					1.24E+05			8.45E+02

	Workers (Option 1)			Workers (Option 2)			Infants 1-2y at 100m			Adults at 100m		
Nuclide	E	E(50)	DT	E	E(50)	DT	E	E(70)	DT	E	E(50)	DT
Nb-95	1.27E-17	2.28E-16	2.41E-16	3.62E-18	8.06E-17	8.42E-17	8.14E-24	4.50E-22	4.58E-22	8.14E-24	1.37E-22	1.45E-22
Fe-59	1.41E-13	2.80E-12	2.94E-12	4.03E-14	9.89E-13	1.03E-12	9.06E-20	6.91E-18	7.00E-18	9.06E-20	2.12E-18	2.22E-18
Co-58	5.72E-10	1.46E-08	1.51E-08	1.63E-10	5.15E-09	5.31E-09	3.68E-16	2.03E-14	2.06E-14	3.68E-16	5.68E-15	6.05E-15
Zr-95	9.08E-17	5.84E-15	5.93E-15	2.59E-17	2.07E-15	2.09E-15	5.84E-23	1.08E-20	1.08E-20	5.84E-23	3.35E-21	3.41E-21
Zn-65	1.50E-09	3.49E-08	3.64E-08	4.30E-10	1.24E-08	1.28E-08	9.68E-16	7.82E-14	7.92E-14	9.68E-16	2.34E-14	2.43E-14
Mn-54	2.56E-06	1.67E-04	1.69E-04	7.31E-07	5.90E-05	5.97E-05	1.65E-12	8.73E-11	8.89E-11	1.65E-12	2.11E-11	2.28E-11
Fe-55	0.00E+00	1.55E-03	1.55E-03	0.00E+00	5.47E-04	5.47E-04	0.00E+00	1.96E-09	1.96E-09	0.00E+00	4.16E-10	4.16E-10
Co-60	1.43E-03	3.37E-01	3.39E-01	4.10E-04	1.19E-01	1.20E-01	9.22E-10	2.20E-07	2.21E-07	9.22E-10	7.94E-08	8.03E-08
Ni-63	0.00E+00	3.70E-03	3.70E-03	0.00E+00	1.31E-03	1.31E-03	0.00E+00	2.22E-09	2.22E-09	0.00E+00	6.70E-10	6.70E-10
Mo-93	1.90E-13	8.13E-10	8.13E-10	5.43E-14	2.87E-10	2.88E-10	1.22E-19	9.85E-15	9.85E-15	1.22E-19	3.91E-15	3.91E-15
C-14	6.53E-13	1.81E-05	1.81E-05	1.87E-13	6.39E-06	6.39E-06	4.20E-19	1.12E-11	1.12E-11	4.20E-19	3.81E-12	3.81E-12
Nb-94	7.16E-09	8.77E-06	8.78E-06	2.05E-09	3.10E-06	3.11E-06	4.61E-15	2.51E-12	2.52E-12	4.61E-15	1.03E-12	1.03E-12
Ni-59	0.00E+00	1.21E-05	1.21E-05	0.00E+00	4.28E-06	4.28E-06	0.00E+00	5.23E-12	5.23E-12	0.00E+00	1.54E-12	1.54E-12
Ru-103	2.62E-07	9.72E-06	9.98E-06	7.49E-08	3.44E-06	3.51E-06	1.69E-13	2.62E-11	2.64E-11	1.69E-13	7.86E-12	8.03E-12
Ru-106	0.00E+00	9.00E-13	9.00E-13	0.00E+00	3.18E-13	3.18E-13	0.00E+00	1.33E-18	1.33E-18	0.00E+00	3.82E-19	3.82E-19
Cs-134	2.41E-05	4.54E-03	4.56E-03	6.88E-06	1.60E-03	1.61E-03	1.55E-11	4.51E-09	4.52E-09	1.55E-11	1.43E-09	1.45E-09
Cs-137	1.31E-08	8.69E-02	8.69E-02	3.76E-09	3.07E-02	3.07E-02	8.46E-15	3.82E-08	3.82E-08	8.46E-15	1.49E-08	1.49E-08
Ce-141	8.24E-19	1.68E-16	1.69E-16	2.36E-19	5.95E-17	5.98E-17	5.30E-25	6.49E-22	6.50E-22	5.30E-25	2.06E-22	2.06E-22
Ce-144	1.67E-08	4.44E-04	4.44E-04	4.78E-09	1.57E-04	1.57E-04	1.08E-14	7.95E-10	7.95E-10	1.08E-14	2.34E-10	2.34E-10
TOTAL	1.46E-03	4.35E-01	4.36E-01	4.17E-04	1.54E-01	1.54E-01	9.39E-10	2.68E-07	2.69E-07	9.39E-10	9.71E-08	9.81E-08

Table A4.12. Initiating Event IE.3 Results: BWR, RVI.

Nuclide	Total Cont. (Bq/cm^2)	Ai (Bq)	CFE	CFE(50)w	CFE(70)1-2y	CFE(50)a	*Only for Option 2*			
							Aci (Bq/m^3)	ALI (Bq)	DAC (Bq/m^3)	NºDAC
Cr-51	3.68E-10	2.01E-09	1.51E-15	5.70E-11	2.10E-10	3.70E-11	3.55E-11	3.51E+08	1.59E+05	2.23E-16
Mn-54	2.72E+04	1.48E+05	4.09E-14	7.10E-09	6.20E-09	1.50E-09	2.62E+03	2.82E+06	1.28E+03	2.05E+00
Fe-59	9.09E-05	4.95E-04	5.97E-14	3.20E-09	1.30E-08	4.00E-09	8.76E-06	6.25E+06	2.84E+03	3.08E-09
Co-58	5.57E-02	3.04E-01	4.76E-14	3.20E-09	7.50E-09	2.10E-09	5.37E-03	6.25E+06	2.84E+03	1.89E-06
Co-60	3.95E+05	2.15E+06	1.26E-13	8.10E-08	8.60E-08	3.10E-08	3.81E+04	2.47E+05	1.12E+02	3.39E+02
Zn-65	2.19E+02	1.19E+03	2.90E-14	2.00E-09	6.70E-09	2.00E-09	2.11E+01	1.00E+07	4.55E+03	4.64E-03
Zr-95	6.44E-03	3.51E-02	3.60E-14	6.10E-09	1.90E-08	5.90E-09	6.20E-04	3.28E+06	1.49E+03	4.16E-07
Nb-95	5.67E-08	3.09E-07	3.74E-14	1.70E-09	5.90E-09	1.80E-09	5.47E-09	1.18E+07	5.35E+03	1.02E-12
Ru-103	2.86E+02	1.56E+03	2.25E-14	2.20E-09	1.00E-08	3.00E-09	2.76E+01	9.09E+06	4.13E+03	6.68E-03
Ru-106	6.32E-07	3.44E-06	0.00E+00	9.60E-08	2.30E-07	6.60E-08	6.09E-08	2.08E+05	9.47E+01	6.43E-10
Cs-134	7.82E+03	4.26E+04	7.57E-14	3.80E-08	6.30E-08	2.00E-08	7.54E+02	5.26E+05	2.39E+02	3.15E+00
Cs-137	4.18E+04	2.28E+05	7.74E-18	1.30E-07	1.00E-07	3.90E-08	4.03E+03	1.54E+05	6.99E+01	5.76E+01
Ce-141	5.91E-09	3.22E-08	3.43E-15	1.20E-09	1.20E-08	3.80E-09	5.70E-10	1.67E+07	7.58E+03	7.52E-14
Ce-144	4.82E+02	2.63E+03	8.53E-16	3.90E-08	1.80E-07	5.30E-08	4.65E+01	5.13E+05	2.33E+02	1.99E-01
TOTAL	4.73E+05	2.58E+06					4.56E+04			4.02E+02

	Workers (Option 1)			Workers (Option 2)			Infants 1-2y at 100m			Adults at 100m		
Nuclide	E	E(50)	DT	E	E(50)	DT	E	E(70)	DT	E	E(50)	DT
Cr-51	7.28E-21	1.14E-19	1.22E-19	3.22E-21	4.05E-20	4.37E-20	7.24E-27	3.52E-25	3.60E-25	7.24E-27	6.21E-26	6.93E-26
Mn-54	1.45E-05	1.05E-03	1.07E-03	6.43E-06	3.72E-04	3.78E-04	1.45E-11	7.67E-10	7.82E-10	1.45E-11	1.86E-10	2.00E-10
Fe-59	7.09E-14	1.58E-12	1.66E-12	3.14E-14	5.60E-13	5.92E-13	7.06E-20	5.38E-18	5.45E-18	7.06E-20	1.66E-18	1.73E-18
Co-58	3.47E-11	9.71E-10	1.01E-09	1.53E-11	3.44E-10	3.59E-10	3.45E-17	1.90E-15	1.94E-15	3.45E-17	5.33E-16	5.67E-16
Co-60	6.51E-04	1.74E-01	1.75E-01	2.88E-04	6.17E-02	6.20E-02	6.48E-10	1.55E-07	1.55E-07	6.48E-10	5.58E-08	5.64E-08
Zn-65	8.30E-08	2.38E-06	2.47E-06	3.67E-08	8.43E-07	8.80E-07	8.26E-14	6.68E-12	6.76E-12	8.26E-14	1.99E-12	2.08E-12
Zr-95	3.03E-12	2.14E-10	2.17E-10	1.34E-12	7.57E-11	7.70E-11	3.02E-18	5.57E-16	5.60E-16	3.02E-18	1.73E-16	1.76E-16
Nb-95	2.78E-17	5.26E-16	5.53E-16	1.23E-17	1.86E-16	1.98E-16	2.76E-23	1.52E-21	1.55E-21	2.76E-23	4.65E-22	4.93E-22
Ru-103	8.43E-08	3.43E-06	3.52E-06	3.73E-08	1.21E-06	1.25E-06	8.39E-14	1.30E-11	1.31E-11	8.39E-14	3.91E-12	4.00E-12
Ru-106	0.00E+00	3.31E-13	3.31E-13	0.00E+00	1.17E-13	1.17E-13	0.00E+00	6.62E-19	6.62E-19	0.00E+00	1.90E-19	1.90E-19
Cs-134	7.74E-06	1.62E-03	1.63E-03	3.42E-06	5.73E-04	5.76E-04	7.70E-12	2.24E-09	2.25E-09	7.70E-12	7.12E-10	7.20E-10
Cs-137	4.23E-09	2.96E-02	2.96E-02	1.87E-09	1.05E-02	1.05E-02	4.21E-15	1.90E-08	1.90E-08	4.21E-15	7.43E-09	7.43E-09
Ce-141	2.65E-19	3.87E-17	3.89E-17	1.17E-19	1.37E-17	1.38E-17	2.64E-25	3.23E-22	3.23E-22	2.64E-25	1.02E-22	1.03E-22
Ce-144	5.38E-09	1.03E-04	1.03E-04	2.38E-09	3.63E-05	3.63E-05	5.36E-15	3.96E-10	3.96E-10	5.36E-15	1.16E-10	1.16E-10
TOTAL	6.74E-04	2.07E-01	2.07E-01	2.98E-04	7.31E-02	7.34E-02	6.70E-10	1.77E-07	1.78E-07	6.70E-10	6.42E-08	6.49E-08

Table A4.13. Initiating Event IE.3 Results: BWR, RPV.

Nuclide	Total Cont. (Bq/cm²)	Ai (Bq)	CFE	CFE(50)w	CFE(70)1-2y	CFE(50)a	*Only for Option 2*			
							Aci (Bq/m³)	ALI (Bq)	DAC (Bq/m³)	NºDAC
Cr-51	3.68E-10	9.06E-09	1.51E-15	7.90E-11	2.10E-10	3.70E-11	1.60E-10	2.53E+08	1.15E+05	1.39E-15
Mn-54	2.72E+04	6.68E+05	4.09E-14	9.90E-09	6.20E-09	1.50E-09	1.18E+04	2.02E+06	9.18E+02	1.29E+01
Fe-59	9.09E-05	2.23E-03	5.97E-14	4.40E-09	1.30E-08	4.00E-09	3.95E-05	4.55E+06	2.07E+03	1.91E-08
Co-58	5.57E-02	1.37E+00	4.76E-14	4.50E-09	7.50E-09	2.10E-09	2.42E-02	4.44E+06	2.02E+03	1.20E-05
Co-60	3.95E+05	9.71E+06	1.26E-13	1.10E-07	8.60E-08	3.10E-08	1.72E+05	1.82E+05	8.26E+01	2.08E+03
Zn-65	2.19E+02	5.38E+03	2.90E-14	2.50E-09	6.70E-09	2.00E-09	9.51E+01	8.00E+06	3.64E+03	2.62E-02
Zr-95	6.44E-03	1.58E-01	3.60E-14	8.60E-09	1.90E-08	5.90E-09	2.80E-03	2.33E+06	1.06E+03	2.65E-06
Nb-95	5.67E-08	1.39E-06	3.74E-14	2.50E-09	5.90E-09	1.80E-09	2.47E-08	8.00E+06	3.64E+03	6.78E-12
Ru-103	2.86E+02	7.04E+03	2.25E-14	3.10E-09	1.00E-08	3.00E-09	1.25E+02	6.45E+06	2.93E+03	4.25E-02
Ru-106	6.32E-07	1.55E-05	0.00E+00	1.30E-07	2.30E-07	6.60E-08	2.75E-07	1.54E+05	6.99E+01	3.93E-09
Cs-134	7.82E+03	1.92E+05	7.57E-14	5.30E-08	6.30E-08	2.00E-08	3.40E+03	3.77E+05	1.72E+02	1.98E+01
Cs-137	4.18E+04	1.03E+06	7.74E-18	1.90E-07	1.00E-07	3.90E-08	1.82E+04	1.05E+05	4.78E+01	3.80E+02
Ce-141	5.91E-09	1.45E-07	3.43E-15	2.60E-09	1.20E-08	3.80E-09	2.57E-09	7.69E+06	3.50E+03	7.35E-13
Ce-144	4.82E+02	1.19E+04	8.53E-16	8.40E-08	1.80E-07	5.30E-08	2.10E+02	2.38E+05	1.08E+02	1.94E+00
TOTAL	4.73E+05	1.16E+07					2.06E+05			2.49E+03

	Workers (Option 1)			Workers (Option 2)			Infants 1-2y at 100m			Adults at 100m		
Nuclide	E	E(50)	DT	E	E(50)	DT	E	E(70)	DT	E	E(50)	DT
Cr-51	5.08E-20	7.16E-19	7.67E-19	1.45E-20	2.53E-19	2.68E-19	3.27E-26	1.59E-24	1.62E-24	3.27E-26	2.80E-25	3.13E-25
Mn-54	1.01E-04	6.61E-03	6.71E-03	2.90E-05	2.34E-03	2.37E-03	6.52E-11	3.46E-09	3.53E-09	6.52E-11	8.38E-10	9.03E-10
Fe-59	4.95E-13	9.83E-12	1.03E-11	1.42E-13	3.48E-12	3.62E-12	3.18E-19	2.43E-17	2.46E-17	3.18E-19	7.47E-18	7.79E-18
Co-58	2.42E-10	6.16E-09	6.41E-09	6.92E-11	2.18E-09	2.25E-09	1.56E-16	8.59E-15	8.74E-15	1.56E-16	2.40E-15	2.56E-15
Co-60	4.54E-03	1.07E+00	1.07E+00	1.30E-03	3.78E-01	3.79E-01	2.92E-09	6.98E-07	7.01E-07	2.92E-09	2.52E-07	2.55E-07
Zn-65	5.79E-07	1.34E-05	1.40E-05	1.66E-07	4.76E-06	4.92E-06	3.72E-13	3.01E-11	3.05E-11	3.72E-13	8.99E-12	9.36E-12
Zr-95	2.11E-11	1.36E-09	1.38E-09	6.05E-12	4.81E-10	4.87E-10	1.36E-17	2.51E-15	2.53E-15	1.36E-17	7.80E-16	7.94E-16
Nb-95	1.94E-16	3.49E-15	3.68E-15	5.54E-17	1.23E-15	1.29E-15	1.25E-22	6.88E-21	7.00E-21	1.25E-22	2.10E-21	2.22E-21
Ru-103	5.88E-07	2.18E-05	2.24E-05	1.68E-07	7.72E-06	7.89E-06	3.78E-13	5.89E-11	5.93E-11	3.78E-13	1.77E-11	1.80E-11
Ru-106	0.00E+00	2.02E-12	2.02E-12	0.00E+00	7.15E-13	7.15E-13	0.00E+00	2.99E-18	2.99E-18	0.00E+00	8.57E-19	8.57E-19
Cs-134	5.40E-05	1.02E-02	1.02E-02	1.54E-05	3.60E-03	3.62E-03	3.48E-11	1.01E-08	1.02E-08	3.48E-11	3.21E-09	3.25E-09
Cs-137	2.95E-08	1.95E-01	1.95E-01	8.44E-09	6.91E-02	6.91E-02	1.90E-14	8.59E-08	8.59E-08	1.90E-14	3.35E-08	3.35E-08
Ce-141	1.85E-18	3.78E-16	3.80E-16	5.29E-19	1.34E-16	1.34E-16	1.19E-24	1.46E-21	1.46E-21	1.19E-24	4.62E-22	4.63E-22
Ce-144	3.75E-08	9.96E-04	9.96E-04	1.07E-08	3.52E-04	3.52E-04	2.42E-14	1.78E-09	1.78E-09	2.42E-14	5.25E-10	5.25E-10
TOTAL	4.70E-03	1.28E+00	1.29E+00	1.34E-03	4.53E-01	4.55E-01	3.02E-09	8.00E-07	8.03E-07	3.02E-09	2.90E-07	2.93E-07

ANNEX V - WATER DEPTH CONSIDERATIONS FOR UNDERWATER CUTTING

A5.1 Introduction

Radiation protection of workers shall be guaranteed during segmentation of highly activated components.

As per radiation protection principles, doses to workers are to be justified, limited, and optimized. Regarding its optimization (reducing doses to workers to ALARA), the following is of special relevance:

- Water depth provides radiation shielding for segmentation and routinary activities, and so, reduces doses to workers. This is addressed in section A5.2.
- Water depth is a mean of air contamination control, due to the water scrubbing effect of aerosols generated during cutting activities. This is beneficial for avoiding the dispersion of contamination and for reducing potential internal doses to workers. This is addressed in Annex VI.
- Underwater cutting increases the time required for cutting activities if compared with in-air laser cutting. Even if most cutting activities are performed remotely, there might be an impact on routinary doses to workers (increased maintenance, increased time devoted to supervision activities, etc.) that should be considered.

The following information is aimed to provide guidance for defining underwater cutting configurations considering radiation protection aspects. This information should be adjusted as necessary per the actual conditions and configurations of potential End Users.

A5.2 Radiation Shielding by Means of Water Depth

Adequate radiation shielding shall be provided for dealing with highly radioactive components. This can be achieved by underwater cutting of the RPV and/or RVI.

This section presents the main results and conclusions from the dose rates evaluations. Annex IV provides further details about the methodology, inputs, assumptions, and results of the calculations.

A5.2.1 Cutting Configurations

Following the assumptions under D4.1, Risk Analysis [Ref. 35], the most representative cutting configurations are[15]: RVI to be cut underwater and RPV. Additionally, the LD-Safe report D1.3 [Ref. 37]

[15] Cutting configurations are adjustable by updating the segmentation plan (mainly number of cuts and cutting linear meters) and associated source term (activation/contamination of components). The conceptual differentiation of RPV/RVI is of less importance as that of the segmentation plan and source term.

considered the potential for cutting the RVI within the RPV, avoiding the need to relocate the internals to the Refuelling Cavity (PWR) or Dryer and Separator Pool (BWR).

These cutting configurations are considered for evaluating different water depths of radiation shielding. Calculations were performed for a generic PWR for simplification purposes, but conclusions can also be applied to a generic BWR since levels of activation in both reactors are similar, being the PWR slightly more conservative in term of components dose rates (refer to D4.1 for further information). In particular, the following cutting configurations were evaluated:

1. Following the cutting strategy of D1.3 [Ref. 37], cutting of the RVI within the RPV. In-air cutting or with different levels of water shielding is analysed.
2. Following the strategy depicted in NUREG-CR-5884 [Ref. 52], cutting of specific RVI components in the Refuelling Cavity. Cutting of the Lower Core Assembly in-air or with different levels of water shielding is analysed.
3. Following the strategy depicted in NUREG-CR-5884, cutting in-air just above water level. Additionally, cutting of the RPV in-air will be also evaluated.

RPV and RVI components considered within the evaluation are those detailed in section 2.2.2 of this document. The geometries assumed for the dose rates evaluation are detailed in Annex IV of D4.2 [Ref. 43].

A5.2.2 Radioactive Inventory

The source terms considered within this evaluation are those detailed in section 2.3 of this document. It should be remarked that a relatively large PWR of approximately 1,000 MW is considered, allowing only 3.5 years of decay after final shutdown of the reactor before laser cutting activities begin.

RPV and RVI are highly activated due to the neutron flux during operation, mainly in the core region, resulting in intense radiation fields (Co-60 is the main contributor to dose rates), as it can be observed in Table A5.1. Radiation fields reduction is limited after 3.5 years of decay, as shown in Figure A5.1.

These radiation fields should be considered when defining the laser cutting configurations, following the ALARA principle.

Table A5.1. Computed Dose Rates from Activated Components [Ref. 48].

Component	Dose Rates (mSv/h) (1)			
	Co-60 (gamma)	Nb-94 (gamma)	Fe-55 (gamma & inner bremsstrahlung)	Ni-59 (gamma & inner bremsstrahlung)
Shroud - Inner Wall	1.9 to 5.6 E+06	2.0 E+01	1.1 E+00	9.1 E-01
Shroud - Outer Wall	1.0 to 3.0 E+06	1.0 E+01	5.6 E-01	4.7 E-01
Core Barrel - Inner Wall	2.6 to 7.9 E+05	1.7 E+00	5.7 E-02	2.1 E-01
Core Barrel - Outer Wall	9.7 E+03 to 2.9 E+04	5.9 E-01	1.3 E-02	6.4 E-02
RPV - Inner Wall	2.3 to 5.4 E+03	N/A	3.4 E-03	1.6 E-03
RPV - Outer Wall	2.3 to 5.3 E+01	N/A	1.6 E-04	1.0 E-05
Biological Shield - Inner Liner	1.9 to 3.7 E+01	N/A	2.0 E-04	6.0 E-07
Biological Shield - Concrete (max)	0.3 to 0.7 E+01	N/A	8.0 E-07	N/A

(1) Dose rates computed at a distance of 1 cm from the surface of the activated material, at the vertical centre line of the reactor core, at final shutdown.

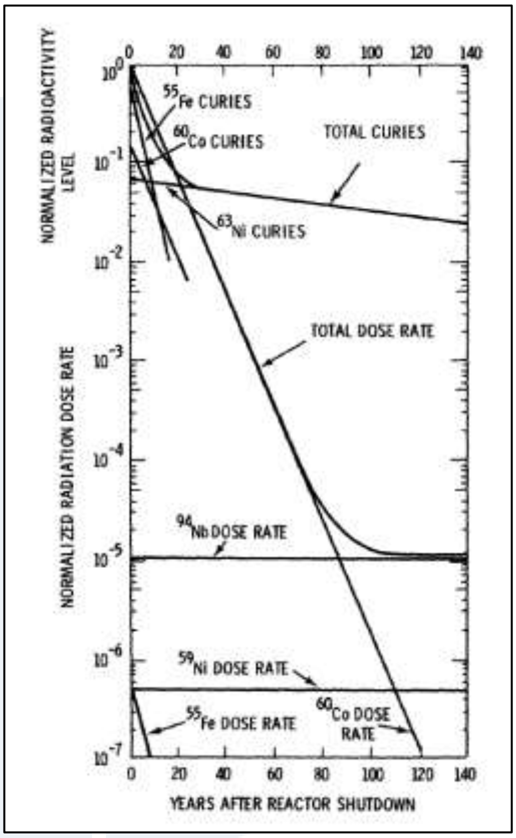

Figure A5.1. Time Dependence of Radioactivity Levels and Dose Rates in the Activated Reactor Components [Ref. 48].

Other sources of radiation are not considered, such as the activation of the biological shield or other activated or contaminated systems, structures, and components within the surroundings of the cutting area.

Further information about radioactive inventory considerations is included in Annex IV of D4.2 [Ref. 43].

A5.2.3 Dose Rates Evaluation

The main results from the dose rates evaluation are summarized in Table A5.2.

A5.3 Conclusions

From the dose rates evaluation and associated results, the following can be extracted:

- In terms of dose rates, and following the ALARA principle, RVI should be cut underwater. In-air cutting configurations, both within the Reactor and Refueling Cavities, may result in high radiation fields that, even if cutting is performed remotely, may interfere in routinary plant operations within the Reactor Building. The benefit of an enclosure shielding would be quite limited in terms of radiation shielding.
- In-air cutting of the RPV results in relevant radiation fields on the working floor. If in-air cutting is envisaged, different Radiation Protection measures should be in place as to reduce doses from cutting activities to ALARA (i.e., remote operation, time limits, access control, temporary shielding...).
- 3.5 years of decay was considered for both the RPV and RVI, which is a quite conservative assumption. However, it should be remarked that only long periods of decay would result in significant reductions of dose rates for each cutting configuration. As per Figure A5.1, every 20 years of decay dose rates are reduced by a factor of 10.
- Water depth provides shielding to protect workers from radiation fields. 3 meters of water depth would reduce dose rates coming from the RVI to negligible values.
- Underwater cutting also provides means for aerosols scrubbing. Its efficiency is a function of water depth, and this should be optimized. However, water scrubbing laboratory results indicate that additional means of contamination control might need to be in place for effectively controlling contamination dispersion and potential doses to workers from inhalation.

Table A5.2. Results of Dose Rates

ID	Scenario Description	**Dose Rates (μSv/h) at** Working Floor and at 1m
P.1.1	Cutting of the RVI within the RPV in the Reactor Cavity, in-air.	8.01 E+02 (*)
P.1.2	Cutting of the RVI within the RPV in the Reactor Cavity, 1 m underwater.	5.29 E+01 (*)
P.1.3	Cutting of the RVI within the RPV in the Reactor Cavity, 2 m underwater.	1.53 E+01 (*)
P.1.4	Cutting of the RVI within the RPV in the Reactor Cavity, 5 m underwater.	Negligible (<1 E-06)
P.1.5	Cutting of the RVI within the RPV in the Reactor Cavity, in-air, with 2 cm of enclosure shielding. Cutting at most activated zone (shroud area).	2.96 E+06
P.1.6	Cutting of the RVI within the RPV in the Reactor Cavity, 1m in-air, the rest underwater, with 2 cm of enclosure shielding. Cutting at most activated zone (shroud area).	1.03 E+06
P.1.7	Cutting of the RVI within the RPV in the Reactor Cavity, 1m in-air, the rest underwater. Cutting at most activated zone (shroud area).	2.16 E+06
P.2.1	Cutting of the Lower Core Assembly in the Refueling Cavity, in-air.	3.18 E+07
P.2.2	Cutting of the Lower Core Assembly in the Refueling Cavity, 1 m underwater.	3.23 E+03
P.2.3	Cutting of the Lower Core Assembly in the Refueling Cavity, 2 m underwater.	5.45 E+00
P.2.4	Cutting of the Lower Core Assembly in the Refueling Cavity, 3 m underwater.	3.62 E-03
P.2.5	Cutting of the Lower Core Assembly in the Refueling Cavity, in-air, with 2 cm of enclosure shielding.	1.36 E+07
P.2.6	Cutting of the Lower Core Assembly in the Refueling Cavity, 1 m in-air, the rest underwater, with 2 cm of enclosure shielding. Cutting at most activated zone (shroud area).	5.32 E+06
P.2.7	Cutting of the Lower Core Assembly in the Refueling Cavity, 1 m in-air, the rest underwater. Cutting at most activated zone (shroud area).	1.34 E+07
P.3.1	Cutting of the RPV in the Reactor Cavity, in-air.	5.45 E+03
P.3.2	Cutting of the RPV in the Reactor Cavity, 1 m in-air, the rest underwater. Cutting at most activated zone (lower 5 m of pressure vessel).	2.54 E+03
P.3.3	Cutting of the RPV in the Reactor Cavity, in-air, with 2 cm of enclosure shielding.	1.03 E+03

(*) These values should be addressed with caution. The evaluation was not performed at the most restrictive cutting location (mid-plane), and so, results are affected by important self-shielding effects. A more restrictive scenario, such as P1.5, shows the range of radiation fields when cutting is performed at the most activated zone.

ANNEX VI - CONTAMINATION CONTROL SYSTEMS

A6.1 Contamination Control Objectives and Criteria

Nuclear power plant decommissioning activities shall comply with regulatory requirements and criteria. In this regard:

- Dose limits and constraints for workers and the public are defined in international references [Ref. 18]. Additionally, nuclear facilities may self-impose lower values following the dose restriction concept.
- Exposures shall be optimized in order to be as low as reasonably achievable (ALARA), emphasizing not only on the reduction of individual doses but also on the reduction of the number of people exposed and the probability of radiation exposures occurrences.

As per these requirements, the IAEA [Ref. 22] indicates that the workplace should be supplied with air of a quantity and quality sufficient to ensure that exposure due to airborne contamination is minimized, and the work should be conducted in a manner that minimizes the spread of contamination.

For achieving the above, the facility shall establish measures for protection and safety, including, as appropriate, physical measures to control the spread of contamination [Ref. 18]. The IAEA [Ref. 28] indicates that these measures may include temporary engineered controls, such as temporary shielding, contamination control arrangements, and auxiliary ventilation systems, to be used during non-routinary operations such as those performed during decommissioning. The potential for spread of contamination and the measures for its minimization should be evaluated.

The criteria to be considered for contamination control confinements is described within ISO 16647:2018, Design and operation of confinement systems[16] for nuclear worksite and for nuclear installations under decommissioning [Ref. 29]. This document will serve as the main guide for recommending contamination control features for the segmentation of the RPV and RVI using laser cutting technology.

A6.2 Operational Experience: RPV/RVI Segmentation using Thermal Cutting and Associated Contamination Control Measures

When using thermal techniques for the segmentation of the RPV and RVI, experience has shown that arrangements should be made to capture airborne releases the closest to the source as possible to avoid dispersion of contamination but sufficiently away from hot spots to avoid any fire starting from a clogged

[16] Confined system is a system constituted by a coherent set of physical barriers and/or dynamic systems intended to confine radioactive substances [Ref. 29].

filter [Ref. 45, 31, 52, 29]. The following contamination control measures were implemented in different decommissioning projects that used thermal cutting techniques:

- Air filtration at water surface during the underwater cutting of the internals of Yankee Nuclear Power Station using Plasma Arc Cutting. A floating hood was located above the cutting table for capturing the gases, which included High Efficiency Particulate Air (HEPA) filters. After filtering, the air was discharged into the containment air purge system and monitored for airborne contamination [Ref. 6].
- Air filtration at water surface during the underwater cutting of the internals of San Onofre-1 NPP using Metal Disintegration Machining, even if only a few parts were segmented using thermal cutting. A suspended gas collection hood was used [Ref. 11].
- Air filtration with special suction device at water surface during the underwater cutting of the internals of Gundremmingen KRB-A NPP using Plasma Arc Cutting [Ref. 12].
- Confinement and filtration for the in-air cutting of the RPV of Zion NPP using oxy-propane (similar approach/technique used in Stade NPP) [Ref. 11]. This included the following features:
    - Confinement of the cutting area with an opening for extracting the cut pieces.
    - Filtration of the exhaust gases right into the opening.

Figure A6.1. Contamination Control for Zion NPP RPV segmentation. Top part of confinement (left), ventilation of opening while cutting (center), and cut piece removal through opening (right) [Ref. 11]

Operational experience is therefore aligned with the recommendations of the risk analysis performed under the LD-SAFE project. The risk matrix for normal segmentation conditions of this document identified (among others) the following design options for reducing the risks to ALARA:

- Dust/aerosols collection system
- Contamination Control Confinement

Contamination control design options will be evaluated in the following sections of this Annex.

A6.3 Contamination Control Design Features

Confinement system functions to ensure safety and radiation protection include the confinement itself to control the release and spread of radioactive substances in the environment and to protect workers from its potential inhalation, as well as for the cleaning and purification of the atmosphere contained within the area (and thus, eliminating potential hazards as hydrogen concentration increase or minimizing the contamination of equipment and the area itself) [Ref. 29].

For ensuring these functions are met, a risk evaluation should be performed for designing the appropriate confinement system, which should follow the ALARA principle, as well as considering:

- Potential for contamination.
- Permissible levels of surface or airborne contamination inside the room or rooms where are contained confined enclosures.
- Requirements for airborne contamination monitoring.
- Verification of discharge authorization limits in respect of actual discharges through existing ventilation systems or ventilation systems to be set up. In this regard, the goal is to maintain, in any case, the functionality of at least one stage of effective containment and filtration between the contaminated areas and the environment under all circumstances.

In this regard, ISO 16647:2018 [Ref. 29] provides guidance on selecting the contamination control arrangements (static and/or dynamic confinements[17]) following a graded approach. Figure A6.2 establishes a relation between the radiological concerns, in terms of Derived Air Concentration[18] (DAC), and the confinement type. This approach is also used by ISO 17873:2004 [Ref. 28], Nuclear facilities – Criteria for the design and operation of ventilation systems for nuclear installations other than nuclear reactors, although the codification of the confinement areas is slightly different.

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[17] As per ISO 16647:2018 [Ref. 29], confinement systems can be:

- Static containment, which refers to an airtight enclosure containment is an efficient way to prevent the release of radioactive substances in the form of particles or gas medium.
- Dynamic confinement, which refers to any action allowing, by maintaining a preferential air flow circulation, to limit back-flow between two areas or between the inside and outside of an enclosure, in order to prevent radioactive substances being released from a given physical volume. That is, air flow direction, calibrated air velocity, or level of depression.
- Integrated confinement design, which is a dual static-dynamic confinement.

[18] Derived air concentration is the amount of contamination in air, which, if 2200 m^3 is inhaled, would result in the annual limit of intake (ALI), as defined in ICRP 103 [Ref. 25] and calculated using reference coefficients given for each radionuclide in ICRP 119 [Ref. 26].

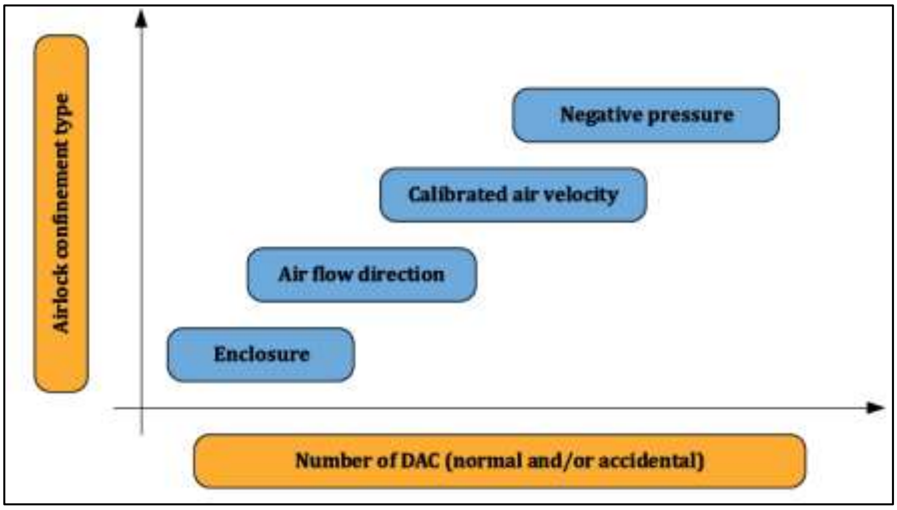

Figure A6.2. Graded Approach for Confinement System Design [Ref. 29]

Table A6.1 shows the proposed confinement systems per ISO 16647:2018, based on the ratio between the contamination concentration in the worksite and the DAC, as well as the number of confinement systems to have in place. It is considered that at the time of RPV/RVI segmentation, building confinement will be active with off-gas filtration system.

Table A6.1. Confinement Classification and Arrangement Guidance based on DAC [Ref. 29]

Ratio Permanent Contamination (Pc) / DAC	Confinement classification	Minimal criterion for two levels of containment (one level already in place)	No. confinement systems to protect workers	Minimal No. of total confinement system	Typical air changes (per hour)
Free from contamination	Unclassified	Atmospheric pressure, or slight overpressure	-	-	-
≤1/10	D1	Enclosure, or air flow direction, or no containment	0 or 1	1	1 to 2
≤1	D2	Enclosure, or air flow direction, or no containment	1	1	1 to 5
≤80	D3	Calibrated air velocity and ≥20 Pa (negative pressure)	1	1 or 2[a]	2 to 10
≤4000	D4	Calibrated air velocity and ≥20 Pa (negative pressure)	1	1[b] or 2[a]	5 to 10[c]
>4000	D4*	To study case by case	1 or 2[a]	2 or 3[a]	5 to 10[c]

a The number depends on the duration, the frequency, the use of specific enclosure, the robustness of the containment barrier, the total activity likely to be spread and the nature of the risks compared to the initial risk inside the volume.

b Exceptional case that requires a risk analysis based on the duration, the frequency, the use of specific enclosure, the robustness of the containment barrier, the total activity likely to be spread and the nature of the risks compared to the initial risk inside the volume.

c For containment as close as possible to the source: 1 to 30 (depending entirely on the process, the volume of the containment enclosure and hazard).

A6.4 Contamination Concentration Estimation

A6.4.1 Calculation Approach and Main Parameters

As shown in Table A6.1, air concentration should be estimated for comparison against the DAC. Air concentration depends on the airborne release rate from cutting activities, the air renovation, and the decay of radioactive products. However, decay will be considered negligible for the segmentation activities under study (due to decay time before segmentation activities are implemented, and actual cutting intervals).

The phenomenology can be expressed with the following formulae:

$$\frac{dA_i(t)}{dt} = CR_i - RR_i - DR_i \qquad \text{Eq. A6.1}$$

Where:

- $dA_i(t)/t$ is the activity variation in a time interval for each nuclide, in Bq/min.
- CR_i is the release rate from cutting activities for each nuclide, in Bq/min.
- RR_i is the air renovation rate for each nuclide, in Bq/min.
- DR_i is the decay rate for each nuclide, in Bq/min, which will be assumed to be neglective.

The air renovation rate can be expressed with the following equation:

$$RR_i = AF \cdot \frac{A_i(t)}{V} \qquad \text{Eq. A6.2}$$

Where:

- AF is the air removal flow, in m^3/min.
- $A_i(t)$ is the activity in a time interval for each nuclide, in Bq.
- V is the volume of concern, in m^3.

This results in the following activity evolution with time:

$$A_i(t) = \frac{V}{AF} \cdot \left(CR_i - e^{-\frac{AF}{V} \cdot t}\right) + A_i(0) \qquad \text{Eq. A6.3}$$

Where $A_i(0)$ is the activity at start of laser cutting, which will be considered neglective in comparison with the laser cutting airborne release. This will serve to focus the case of study in the laser cutting technology needs.

The air concentration (AC), in (Bq/m^3), for each nuclide will be calculated as follows:

$$AC_i(t) = \frac{A_i(t)}{V} = \frac{1}{AF} \cdot \left(CR_i - e^{-\frac{AF}{V} \cdot t}\right) \qquad \text{Eq. A6.4}$$

The air concentration evolution depends on the type of cutting: continuous or discontinuous. A typical curve is represented in next figure:

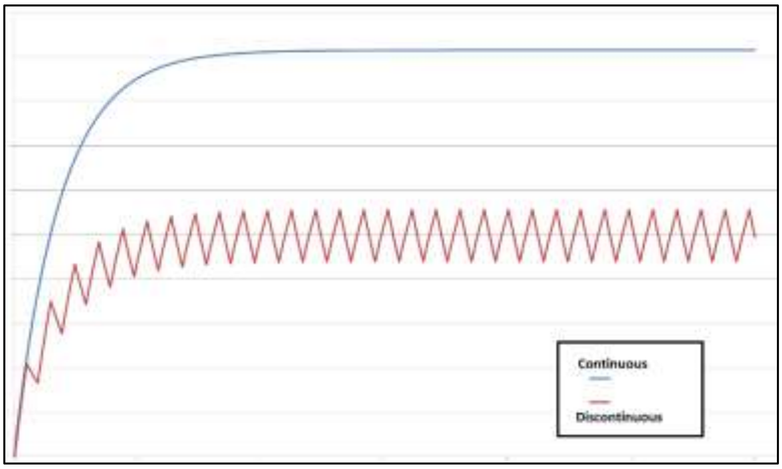

Figure A6.3. Air Concentration Typical Evolution [Ref. 46]

For a generic evaluation of the segmentation of the RPV/RVI using laser cutting technology, some parameters are uncertain (i.e., volume of interest, air renewal flow, uninterrupted cutting time...). In any case, a study of confinement classes will be performed for 3 different cases:

- In-air laser cutting
- 1 m water depth of underwater laser cutting
- 5m water depth of underwater laser cutting

The air concentration (AC), in (Bq/m^3), for each nuclide will be calculated according to Eq. A6.4. Where:

- Air Renewal Flow (AF)

As per ISO 16647:2018, the number of air changes are determined by the conventional ventilation requirements necessary to maintain correct depression and air flows between areas, and to allow efficient air monitoring where this is required.

The air change rates usually used in worksite containments are from 1 to 30 based on the radiological issue, on the sizes of containment and the type of equipment used (refer to Table A6.1 for Ratio Permanent Contamination (Pc) / DAC – referred as N.DAC now on - and confinement class estimation).

Air renewals are expressed in 1/h, so to determine the flow rate (m^3/min), the volume of the reactor cavity will be considered.

A value of 5 renovations per hour will be considered to estimate the Air Concentration for RPV and RVI segmentation (minimum typical value for D4 class as per ISO 16647:2018). This implies an air filtration flow rate of approximately 2400 m^3/h, but this could be increased as necessary based on actual cutting conditions and configurations[19]. Additional calculations were performed with other air renewal values with no modifications on the confinement class.

- Release rate from cutting activities (CR_i)

The release rate from cutting activities for each nuclide, in Bq/min, is based on the total mass released to the air (g/min) from section 4.2.1.2 of D4.2 [Ref. 43]:

- For in-air laser cutting: 6.70 mg/s (4.02E-01 g/min). Considering the adjustment factor, this will imply a release of the elements of interest of 3.41 mg/s.
- For 1 m water depth of underwater laser cutting: 3.5 mg/s (2.1E-01 g/min). Considering the adjustment factor, this will imply a release of the elements of interest of 1.97 mg/s.
- For 5 m water depth of underwater laser cutting: 1.65 mg/s (9.90E-02 g/min). Considering the adjustment factor, this will imply a release of the elements of interest of 0.93 mg/s.

This release rate is converted into Bq/min considering the radioactive inventory from most activated elements (Cm in Bq/g) and their surface contamination (Cs in Bq/cm^2)[20]. The radioactive inventory considered within this evaluation are those detailed in section 2.3 of this document. It should be remarked that a relatively large PWR/BWR of approximately 1,000 MW is considered, allowing only 3.5 years of decay after final shutdown of the reactor before laser cutting activities begin. This radioactive inventory should be adjusted by End Users based on their actual plant conditions.

The parameters used for unit adjustment are the following [Ref. 48, 49, 52, 53]:

- Density of Carbon Steel of the RPV: 7.80 g/cm^3
- Density of Stainless Steel of the RVI: 8.038 g/cm^3
- Thickness of the RPV wall of a PWR: 21.6 cm
- Thickness of the RVI shroud plates of a PWR: 1.9 cm
- Thickness of the RPV wall of a BWR: 17.8 cm
- Thickness of the RVI shroud plates of a BWR: 5.1 cm

[19] During Stade NPP segmentation activities using thermal cutting (oxy-propane), a sealed housing above the spent fuel pool was installed, which included a ventilation system (filtrated) to prevent contamination leakage from the housing with a flow rate of 8.000 m³/h.
[20] Cm: "peak" values for RPV wall or Shroud (RVI), as appropriate [Ref. 35].

- Volume (V)

The volume of concern, in (m^3), will be considered the reactor cavity. It will be assumed to be 485 m^3 [Ref. 35]. If the Refueling Cavity or Dryer/Separator Storage Pool were used for in-air cutting, the contamination control confinement could be reduced to the necessary cutting space.

- Cutting time (t)

The uninterrupted cutting time will be estimated of 1 hour for this study (t=60 min). Additional calculations were performed with other cutting times with no significant modifications on the results or confinement class.

- Number of DAC (N.DAC or Pc/DAC)

Once the Air Concentration is estimated, it is necessary to compare it against the DAC to obtain the Number of DAC (N.DAC or Pc/DAC) to finally determine the airlock classification. N.DAC will be calculated as follows:

$$N.DAC = \sum_i \frac{AC_i(t)}{DACi} = \sum_i N.DAC_i \qquad \text{Eq. A6.5}$$

Where DAC[21] (Bq/m^3) and ALI[22] (Bq) will be calculated as follows:

$$DAC_i = \frac{ALI_i}{2200} \qquad \text{Eq. A6.6}$$

$$ALI_i = \frac{E_{limit,w}}{CFE(50)w} \qquad \text{Eq. A6.7}$$

$E_{limit,w}$ is the annual dose limit for an exposed worker, in Sv.

$CFE(50)_i$ is the inhalation dose coefficient for each radionuclide (i), in Sv/Bq.

[21] DAC, in Bq/m^3, are obtained from ICRP 103 [Ref. 25]
[22] ALI, in Bq, is calculated using dose coefficients from ICRP 119 [Ref. 26]

A6.4.2 Main Results

The results of confinement class estimation for laser cutting of RPV/RVI of PWR and BWR are summarized in Table A6.2.

Table A6.2. Results of confinement class estimation for laser cutting of RPV/RVI of PWR and BWR.

		In air		1m water depth		5m water depth	
		RPV	RVI	RPV	RVI	RPV	RVI
PWR	AC_i (Bq/m^3)	1.43E+04	2.93E+07	8.23E+03	1.69E+07	3.89E+03	7.99E+06
	DAC (Bq/m^3)	1.29E+01	4.57E+04	7.48E+00	2.64E+04	3.53E+00	1.25E+04
	N.DAC	D3	D4*	D3	D4*	D3	D4*
	CLASS	8.89E+03	1.57E+07	5.14E+03	9.08E+06	2.43E+03	4.29E+06
BWR	AC_i (Bq/m^3)	1.55E+01	1.62E+04	8.98E+00	9.38E+03	4.24E+00	4.43E+03
	DAC (Bq/m^3)	1.43E+04	2.93E+07	8.23E+03	1.69E+07	3.89E+03	7.99E+06
	N.DAC	1.29E+01	4.57E+04	7.48E+00	2.64E+04	3.53E+00	1.25E+04
	CLASS	D3	D4*	D3	D4*	D3	D4*

The results show that confinement classes are D3 for RPV and D4* for RVI. For those classes, adequate contamination control arrangements following ISO graded approach should be in place (i.e., confinement, renewal rates…).

It is important to remark that these calculations are based on a specific radioactive inventory defined as boundary conditions, which is considered quite conservative (i.e., only 3.5 years of decay). Confinement classes and associated arrangements should be adjusted to the specific plant conditions.

Detailed calculations are included at the end of this Annex (Tables A6.3 to A6.14).

A6.5 Contamination Control Recommendations

Air quality should be maintained in the working place to ensure that exposure due to airborne contamination and the spread of contamination are minimized.

The results from an evaluation using a predefined radioactive inventory and specific cutting configurations show that confinement classes are D3 for segmenting the RPV and D4* for cutting the

RVI. For those classes, adequate contamination control arrangements following ISO 16647:2018 graded approach should be in place (i.e., static and/or dynamic confinement, renewal rates...).

As per ISO 16647:2018, confinement of radioactive substances as close as possible to the source of release is preferred. These measures can reduce confinement requirements if their efficiency has been demonstrated. Due to the potential contamination levels (as shown in section A6.4.2) and associated operational experience (refer to section A6.2), the following combination of measures are recommended:

- For in-air cutting, dynamic confinement by means of a filtrated exhaust at source of release. The exhaust line should be equipped, as necessary, with spark arrestor prefilters, and filters. For underwater cutting, water scrubbing will have a similar effect in terms of "confining" at source of release, and it should be supported with adequate water filtration and purification systems.
- For both in-air and underwater cutting, static confinement of cutting environment with an airtight enclosure. Since it is understood that a perfect seal might not be possible, this should be supported by an overall cutting environment dynamic confinement (i.e., push and pull filtrated ventilation system with adequate air renewal rates[23]).
- Filtration exhausts should be connected directly into the building ventilation exhaust. Any release to the atmosphere shall comply with permissible release and public exposure limits.

Due to its relevance for avoiding dispersion of contamination into the Reactor Building, a basic description and first elements of design requirement for the static and dynamic confinements are provided below (in accordance with ISO 16647:2018):

- The volume of the static confinement should be limited as much as possible to the components to be cut. In the case of the RPV segmentation, this would imply, for instance, to enclosure the top of the Reactor Cavity. In the case of the Refueling Cavity or Dryer/Separator Storage Pool, they may be compartmentalized to the area where the components are being cut, avoiding the dispersion of contamination to the totality of the pool. This recommendation is aligned with the volume of 485 m^3 considered in the evaluation of confinement classes of this Annex. If a perfect sealing is not possible, then any potential opening of the static confinement should be supported with adequate dynamic confinement means (i.e., calibrated velocity through local extraction hoods).
- The dynamic confinement arrangement for class D3 to D4* should rely on calibrated air velocity, a negative pressure of at least 20 Pa (if feasible), and adequate renewal rates. In this regard, ISO 16647:2018 recommends air renewal rates from 1 to 30 per hour. Within the evaluation of confinement classes of this Annex, an air renewal rate of 5 per hour was considered, based on the assumed volume of 485 m^3 and a 2400 m^3/h of air flow. The implemented air renewal rate

[23] High values of negative pressure might not be achievable due to potential openings (i.e., for management of cut pieces, interface of laser equipment, etc.).

should be optimized for each specific case based on the volume of the cutting environment and the potential contamination, and if possible, by using higher air flows[24].

- The 16647:2018 guidelines for selecting the materials of the static confinement should be observed, with special attention with the negative pressure to be implemented and the risk of fire brought by the laser source.

Both local filtration and overall cutting environment filtration should rely on adequate filtration means. Current practices in nuclear industries are based on High Efficiency Particulate Air (HEPA) filtration as the preferred method for treating radioactive aerosols [Ref. 8]. The volume of confined air should be optimized, balancing the reduction of size of confinement structures and filtration installations with higher contamination concentrations leading to more frequent changing of filters.

Filtration design and associated efficiencies should consider particle size distributions (refer to section 4.2.1.3 of D4.2 [Ref. 43]). This is especially relevant for in-air laser cutting, where the AMAD might be close to minimum efficiency of HEPA filters (most penetrating particle size), as shown in Figure A6.4. For underwater laser cutting, the AMAD might be close to the design point of HEPA filters.

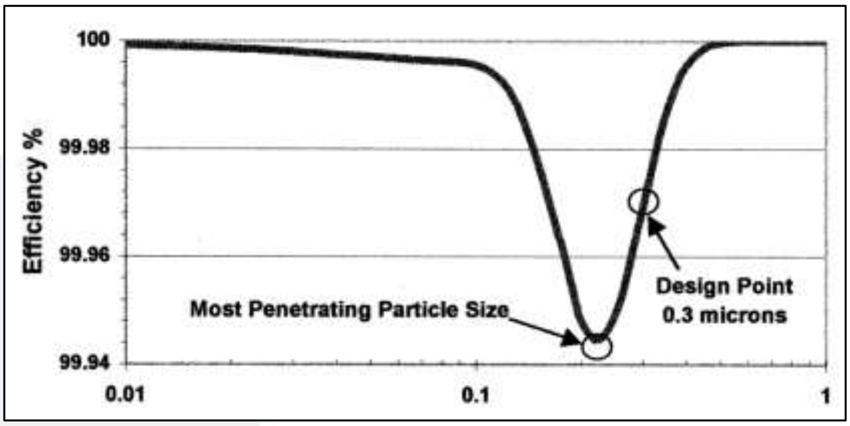

Figure A6.4. HEPA filters typical efficiency curve [Ref. 57]

Contamination control arrangements should consider the potential leaks into occupied and occasionally occupied areas, as to not exceed the DAC established for occupationally exposed persons under normal or abnormal operation conditions. Occupied areas should be, as possible, free of airborne contamination per operating plant procedures (i.e., airborne contamination < 0.1 DAC) and avoiding the need of respiratory protection (i.e., airborne contamination < 0.25 DAC). Additionally, airborne activity shall be adequately monitored in these areas (i.e., by means of installed airborne activity monitors with acoustic and visual alarms, periodic airborne activities surveillance with portable equipment…).

[24] As an example, during Stade NPP segmentation activities using thermal cutting (oxy-propane), a sealed housing above the spent fuel pool was installed, which included a ventilation system (filtrated) to prevent contamination leakage from the housing with a flow rate of 8.000 m³/h.

A6.6 Detailed Calculations

Detailed calculations are included for the following:

- In-air laser cutting: Table A6.3 to Table A6.6.
- 1 m water depth of underwater laser cutting: Table A6.7 to Table A6.10.
- 5m water depth of underwater laser cutting: Table A6.11 to Table A6.14.

Table A6.3. AC, DAC, and N.DAC for in-air laser cutting (RPV, PWR)

Nuclide	Cm "peak" Vessel (Bq/g)	Cs (Bq/cm^2)	CR$_i$ (Bq/min)	AC$_i$ (Bq/m^3)	CFE (50)w	ALI (Bq)	DAC (Bq/m^3)	N.DAC
Nb-95	8.33E-11	5.72E-09	3.26E-09	0.00E+00	1.60E-09	1.25E+07	5.68E+03	0.00E+00
Fe-59	3.39E-04	3.99E-05	9.20E-05	0.00E+00	3.50E-09	5.71E+06	2.60E+03	0.00E+00
Co-58	1.37E-01	2.03E-01	1.43E-01	3.37E-03	2.00E-09	1.00E+07	4.55E+03	7.42E-07
Zr-95	4.00E-06	4.26E-08	8.43E-07	0.00E+00	5.50E-09	3.64E+06	1.65E+03	0.00E+00
Zn-65	4.34E-03	8.77E-01	4.98E-01	1.21E-02	2.90E-09	6.90E+06	3.13E+03	3.87E-06
Mn-54	1.13E+04	1.06E+03	2.91E+03	7.21E+01	1.50E-09	1.33E+07	6.06E+03	1.19E-02
Fe-55	1.35E+06	1.73E+05	3.74E+05	9.26E+03	3.70E-10	5.41E+07	2.46E+04	3.77E-01
Co-60	2.18E+05	1.92E+05	1.54E+05	3.80E+03	2.90E-08	6.90E+05	3.13E+02	1.21E+01
Ni-63	1.71E+04	3.87E+04	2.54E+04	6.29E+02	5.20E-10	3.85E+07	1.75E+04	3.60E-02
Mo-93	5.98E+00	1.27E-01	1.30E+00	3.19E-02	2.20E-09	9.09E+06	4.13E+03	7.72E-06
C-14	8.74E+01	4.93E+01	4.58E+01	1.13E+00	5.80E-09	3.45E+06	1.57E+03	7.23E-04
Nb-94	0.00E+00	1.57E+00	8.91E-01	2.19E-02	4.50E-08	4.44E+05	2.02E+02	1.08E-04
Ni-59	1.47E+02	2.62E+02	1.79E+02	4.42E+00	2.20E-10	9.09E+07	4.13E+04	1.07E-04
Ru-103	0.00E+00	1.97E+02	1.12E+02	2.76E+00	2.80E-09	7.14E+06	3.25E+03	8.50E-04
Ru-106	0.00E+00	4.34E-07	2.46E-07	0.00E+00	6.20E-08	3.23E+05	1.47E+02	0.00E+00
Cs-134	0.00E+00	5.37E+03	3.04E+03	7.53E+01	9.60E-09	2.08E+06	9.47E+02	7.95E-02
Cs-137	0.00E+00	2.87E+04	1.63E+04	4.02E+02	6.70E-09	2.99E+06	1.36E+03	2.97E-01
Ce-141	0.00E+00	4.06E-09	2.30E-09	0.00E+00	3.60E-09	5.56E+06	2.53E+03	0.00E+00
Ce-144	0.00E+00	3.31E+02	1.88E+02	4.65E+00	4.90E-08	4.08E+05	1.86E+02	2.50E-02
TOTAL	1.60E+06	4.40E+05	5.76E+05	1.43E+04				1.29E+01

Table A6.4. AC, DAC, and N.DAC for in-air laser cutting (RVI, PWR)

Nuclide	Cm "peak" Shroud (Bq/g)	Cs (Bq/cm^2)	CR$_i$ (Bq/min)	AC$_i$ (Bq/m^3)	CFE (50)w	ALI (Bq)	DAC (Bq/m^3)	N.DAC
Nb-95	9.80E-05	5.72E-09	2.01E-05	0.00E+00	1.60E-09	1.25E+07	5.68E+03	0.00E+00
Fe-59	5.78E-01	3.99E-05	1.18E-01	2.76E-03	3.50E-09	5.71E+06	2.60E+03	1.06E-06
Co-58	3.10E+03	2.03E-01	6.35E+02	1.57E+01	2.00E-09	1.00E+07	4.55E+03	3.46E-03
Zr-95	6.12E-04	4.26E-08	1.25E-04	0.00E+00	5.50E-09	3.64E+06	1.65E+03	0.00E+00
Zn-65	1.49E+04	8.77E-01	3.04E+03	7.53E+01	2.90E-09	6.90E+06	3.13E+03	2.40E-02
Mn-54	1.64E+07	1.06E+03	3.35E+06	8.29E+04	1.50E-09	1.33E+07	6.06E+03	1.37E+01
Fe-55	2.44E+09	1.73E+05	4.99E+08	1.23E+07	3.70E-10	5.41E+07	2.46E+04	5.02E+02
Co-60	2.79E+09	1.92E+05	5.71E+08	1.41E+07	2.90E-08	6.90E+05	3.13E+02	4.50E+04
Ni-63	5.39E+08	3.87E+04	1.10E+08	2.73E+06	5.20E-10	3.85E+07	1.75E+04	1.56E+02
Mo-93	1.66E+03	1.27E-01	3.39E+02	8.38E+00	2.20E-09	9.09E+06	4.13E+03	2.03E-03
C-14	6.90E+05	4.93E+01	1.41E+05	3.49E+03	5.80E-09	3.45E+06	1.57E+03	2.23E+00
Nb-94	2.49E+04	1.57E+00	5.09E+03	1.26E+02	4.50E-08	4.44E+05	2.02E+02	6.23E-01
Ni-59	3.41E+06	2.62E+02	6.97E+05	1.72E+04	2.20E-10	9.09E+07	4.13E+04	4.17E-01
Ru-103	0.00E+00	1.97E+02	9.52E+00	2.35E-01	2.80E-09	7.14E+06	3.25E+03	7.25E-05
Ru-106	0.00E+00	4.34E-07	2.10E-08	0.00E+00	6.20E-08	3.23E+05	1.47E+02	0.00E+00
Cs-134	0.00E+00	5.37E+03	2.60E+02	6.43E+00	9.60E-09	2.08E+06	9.47E+02	6.79E-03
Cs-137	0.00E+00	2.87E+04	1.39E+03	3.44E+01	6.70E-09	2.99E+06	1.36E+03	2.53E-02
Ce-141	0.00E+00	4.06E-09	1.96E-10	0.00E+00	3.60E-09	5.56E+06	2.53E+03	0.00E+00
Ce-144	0.00E+00	3.31E+02	1.60E+01	3.96E-01	4.90E-08	4.08E+05	1.86E+02	2.14E-03
TOTAL	5.79E+09	4.40E+05	1.18E+09	2.93E+07				4.57E+04

Table A6.5. AC, DAC, and N.DAC for in-air laser cutting (RPV, BWR)

Nuclide	Cm "peak" Vessel (Bq/g)	Cs (Bq/cm²)	CRi (Bq/min)	ACi (Bq/m³)	CFE (50)w	ALI (Bq)	DAC (Bq/m³)	N.DAC
C-14	3.21E+01	0.00E+00	6.57E+00	1.62E-01	5.80E-09	3.45E+06	1.57E+03	1.04E-04
P-32	4.27E-24	0.00E+00	8.73E-25	0.00E+00	3.20E-09	6.25E+06	2.84E+03	0.00E+00
S-35	3.41E-03	0.00E+00	6.97E-04	0.00E+00	1.30E-09	1.54E+07	6.99E+03	0.00E+00
Cr-51	1.15E-10	3.68E-10	1.95E-10	0.00E+00	3.60E-11	5.56E+08	2.53E+05	0.00E+00
Mn-54	2.63E+03	2.72E+04	1.32E+04	3.27E+02	1.50E-09	1.33E+07	6.06E+03	5.40E-02
Fe-55	6.47E+05	0.00E+00	1.32E+05	3.28E+03	3.70E-10	5.41E+07	2.46E+04	1.33E-01
Fe-59	1.22E-04	9.09E-05	6.74E-05	0.00E+00	3.50E-09	5.71E+06	2.60E+03	0.00E+00
Co-58	3.18E-02	5.57E-02	3.25E-02	6.38E-04	2.00E-09	1.00E+07	4.55E+03	1.40E-07
Co-60	1.94E+04	3.95E+05	1.88E+05	4.66E+03	2.90E-08	6.90E+05	3.13E+02	1.49E+01
Ni-59	6.93E+01	0.00E+00	1.42E+01	3.50E-01	2.20E-10	9.09E+07	4.13E+04	8.48E-06
Ni-63	8.01E+03	0.00E+00	1.64E+03	4.05E+01	5.20E-10	3.85E+07	1.75E+04	2.32E-03
Zn-65	2.40E-04	2.19E+02	1.02E+02	2.53E+00	2.90E-09	6.90E+06	3.13E+03	8.06E-04
Zr-95	9.28E-07	6.44E-03	3.01E-03	0.00E+00	5.50E-09	3.64E+06	1.65E+03	0.00E+00
Nb-93m	1.59E+00	0.00E+00	3.26E-01	7.89E-03	1.60E-09	1.25E+07	5.68E+03	1.39E-06
Nb-94	3.94E-03	0.00E+00	8.05E-04	0.00E+00	4.50E-08	4.44E+05	2.02E+02	0.00E+00
Nb-95	1.90E-11	5.67E-08	2.65E-08	0.00E+00	1.60E-09	1.25E+07	5.68E+03	0.00E+00
Mo-93	4.45E+00	0.00E+00	9.11E-01	2.24E-02	2.20E-09	9.09E+06	4.13E+03	5.41E-06
Ru-103	0.00E+00	2.86E+02	1.34E+02	3.31E+00	2.80E-09	7.14E+06	3.25E+03	1.02E-03
Ru-106	0.00E+00	6.32E-07	2.95E-07	0.00E+00	6.20E-08	3.23E+05	1.47E+02	0.00E+00
Cs-134	0.00E+00	7.82E+03	3.65E+03	9.03E+01	9.60E-09	2.08E+06	9.47E+02	9.54E-02
Cs-137	0.00E+00	4.18E+04	1.95E+04	4.83E+02	6.70E-09	2.99E+06	1.36E+03	3.56E-01
Ce-141	0.00E+00	5.91E-09	2.76E-09	0.00E+00	3.60E-09	5.56E+06	2.53E+03	0.00E+00
Ce-144	0.00E+00	4.82E+02	2.25E+02	5.57E+00	4.90E-08	4.08E+05	1.86E+02	3.00E-02
TOTAL	6.77E+05	4.73E+05	3.59E+05	8.89E+03				1.55E+01

Table A6.6. AC, DAC, and N.DAC for in-air laser cutting (RVI, BWR)

Nuclide	Cm "peak" Shroud (Bq/g)	Cs (Bq/cm²)	CRi (Bq/min)	ACi (Bq/m³)	CFE (50)w	ALI (Bq)	DAC (Bq/m³)	N.DAC
H-3	1.76E+00	0.00E+00	3.60E-01	8.73E-03	2.60E-10	7.69E+07	3.50E+04	2.50E-07
Be-10	1.21E-02	0.00E+00	2.48E-03	0.00E+00	3.20E-08	6.25E+05	2.84E+02	0.00E+00
C-14	4.83E+05	0.00E+00	9.88E+04	2.45E+03	5.80E-09	3.45E+06	1.57E+03	1.56E+00
P-33	1.66E-09	0.00E+00	3.39E-10	0.00E+00	1.40E-09	1.43E+07	6.49E+03	0.00E+00
S-35	1.04E+01	0.00E+00	2.12E+00	5.23E-02	1.30E-09	1.54E+07	6.99E+03	7.49E-06
Cl-36	1.24E+00	0.00E+00	2.53E-01	6.10E-03	6.90E-09	2.90E+06	1.32E+03	4.63E-06
Cr-51	9.21E-05	3.68E-10	1.88E-05	0.00E+00	3.60E-11	5.56E+08	2.53E+05	0.00E+00
Mn-54	2.05E+06	2.72E+04	4.22E+05	1.04E+04	1.50E-09	1.33E+07	6.06E+03	1.72E+00
Fe-55	1.73E+09	0.00E+00	3.54E+08	8.75E+06	3.70E-10	5.41E+07	2.46E+04	3.56E+02
Fe-59	3.44E-01	9.09E-05	7.04E-02	1.58E-03	3.50E-09	5.71E+06	2.60E+03	6.07E-07
Co-58	4.35E+02	5.57E-02	8.89E+01	2.20E+00	2.00E-09	1.00E+07	4.55E+03	4.84E-04
Co-60	9.76E+08	3.95E+05	2.00E+08	4.94E+06	2.90E-08	6.90E+05	3.13E+02	1.58E+04
Ni-59	2.93E+06	0.00E+00	5.99E+05	1.48E+04	2.20E-10	9.09E+07	4.13E+04	3.59E-01
Ni-63	3.93E+08	0.00E+00	8.04E+07	1.99E+06	5.20E-10	3.85E+07	1.75E+04	1.14E+02
Zn-65	4.00E+03	2.19E+02	8.47E+02	2.10E+01	2.90E-09	6.90E+06	3.13E+03	6.69E-03
Zr-93	3.75E-02	0.00E+00	7.68E-03	2.32E-05	2.90E-08	6.90E+05	3.13E+02	7.40E-08
Zr-95	7.84E-05	6.44E-03	8.52E-04	0.00E+00	5.50E-09	3.64E+06	1.65E+03	0.00E+00
Nb-93m	5.35E+02	0.00E+00	1.09E+02	2.71E+00	1.60E-09	1.25E+07	5.68E+03	4.76E-04
Nb-94	6.90E+03	0.00E+00	1.41E+03	3.49E+01	4.50E-08	4.44E+05	2.02E+02	1.73E-01
Nb-95	5.88E-06	5.67E-08	1.21E-06	0.00E+00	1.60E-09	1.25E+07	5.68E+03	0.00E+00
Mo-93	1.50E+03	0.00E+00	3.07E+02	7.59E+00	2.20E-09	9.09E+06	4.13E+03	1.84E-03
Ag-108m	3.32E+02	0.00E+00	6.80E+01	1.68E+00	3.50E-08	5.71E+05	2.60E+02	6.48E-03
Cd-109	2.30E+03	0.00E+00	4.70E+02	1.16E+01	9.60E-09	2.08E+06	9.47E+02	1.23E-02
Ag-110m	1.07E+03	0.00E+00	2.19E+02	5.43E+00	1.20E-08	1.67E+06	7.58E+02	7.17E-03
Sm-151	9.05E+05	0.00E+00	1.85E+05	4.58E+03	3.70E-09	5.41E+06	2.46E+03	1.86E+00
Eu-152	8.13E+01	0.00E+00	1.66E+01	4.11E-01	3.90E-08	5.13E+05	2.33E+02	1.77E-03

Nuclide	Cm "peak" Shroud (Bq/g)	Cs (Bq/cm²)	CRi (Bq/min)	ACi (Bq/m³)	CFE (50)w	ALI (Bq)	DAC (Bq/m³)	N.DAC
Eu-154	3.89E+00	0.00E+00	7.96E-01	1.95E-02	5.00E-08	4.00E+05	1.82E+02	1.07E-04
Tb-160	6.87E-02	0.00E+00	1.41E-02	1.81E-04	6.60E-09	3.03E+06	1.38E+03	1.32E-07
Ho-166m	4.35E+00	0.00E+00	8.91E-01	2.19E-02	1.10E-07	1.82E+05	8.26E+01	2.65E-04
Ru-103	0.00E+00	2.86E+02	3.72E+01	9.20E-01	2.80E-09	7.14E+06	3.25E+03	2.83E-04
Ru-106	0.00E+00	6.32E-07	8.21E-08	0.00E+00	6.20E-08	3.23E+05	1.47E+02	0.00E+00
Cs-134	0.00E+00	7.82E+03	1.02E+03	2.51E+01	9.60E-09	2.08E+06	9.47E+02	2.65E-02
Cs-137	0.00E+00	4.18E+04	5.43E+03	1.34E+02	6.70E-09	2.99E+06	1.36E+03	9.89E-02
Ce-141	0.00E+00	5.91E-09	7.67E-10	0.00E+00	3.60E-09	5.56E+06	2.53E+03	0.00E+00
Ce-144	0.00E+00	4.82E+02	6.26E+01	1.55E+00	4.90E-08	4.08E+05	1.86E+02	8.35E-03
TOTAL	3.10E+09	4.73E+05	6.35E+08	1.57E+07				1.62E+04

Table A6.7. AC, DAC, and N.DAC for underwater laser cutting at 1 m depth (RPV, PWR)

Nuclide	Cm "peak" Vessel (Bq/g)	Cs (Bq/cm^2)	CR_i (Bq/min)	AC_i (Bq/m^3)	CFE (50)w	ALI (Bq)	DAC (Bq/m^3)	N.DAC
Nb-95	8.33E-11	5.72E-09	1.88E-09	0.00E+00	1.60E-09	1.25E+07	5.68E+03	0.00E+00
Fe-59	3.39E-04	3.99E-05	5.31E-05	0.00E+00	3.50E-09	5.71E+06	2.60E+03	0.00E+00
Co-58	1.37E-01	2.03E-01	8.26E-02	1.88E-03	2.00E-09	1.00E+07	4.55E+03	4.13E-07
Zr-95	4.00E-06	4.26E-08	4.87E-07	0.00E+00	5.50E-09	3.64E+06	1.65E+03	0.00E+00
Zn-65	4.34E-03	8.77E-01	2.87E-01	6.95E-03	2.90E-09	6.90E+06	3.13E+03	2.22E-06
Mn-54	1.13E+04	1.06E+03	1.68E+03	4.17E+01	1.50E-09	1.33E+07	6.06E+03	6.87E-03
Fe-55	1.35E+06	1.73E+05	2.16E+05	5.35E+03	3.70E-10	5.41E+07	2.46E+04	2.18E-01
Co-60	2.18E+05	1.92E+05	8.87E+04	2.19E+03	2.90E-08	6.90E+05	3.13E+02	7.00E+00
Ni-63	1.71E+04	3.87E+04	1.47E+04	3.63E+02	5.20E-10	3.85E+07	1.75E+04	2.08E-02
Mo-93	5.98E+00	1.27E-01	7.48E-01	1.84E-02	2.20E-09	9.09E+06	4.13E+03	4.44E-06
C-14	8.74E+01	4.93E+01	2.65E+01	6.54E-01	5.80E-09	3.45E+06	1.57E+03	4.18E-04
Nb-94	0.00E+00	1.57E+00	5.15E-01	1.26E-02	4.50E-08	4.44E+05	2.02E+02	6.22E-05
Ni-59	1.47E+02	2.62E+02	1.03E+02	2.55E+00	2.20E-10	9.09E+07	4.13E+04	6.18E-05
Ru-103	0.00E+00	1.97E+02	6.44E+01	1.59E+00	2.80E-09	7.14E+06	3.25E+03	4.91E-04
Ru-106	0.00E+00	4.34E-07	1.42E-07	0.00E+00	6.20E-08	3.23E+05	1.47E+02	0.00E+00
Cs-134	0.00E+00	5.37E+03	1.76E+03	4.35E+01	9.60E-09	2.08E+06	9.47E+02	4.59E-02
Cs-137	0.00E+00	2.87E+04	9.40E+03	2.33E+02	6.70E-09	2.99E+06	1.36E+03	1.71E-01
Ce-141	0.00E+00	4.06E-09	1.33E-09	0.00E+00	3.60E-09	5.56E+06	2.53E+03	0.00E+00
Ce-144	0.00E+00	3.31E+02	1.08E+02	2.68E+00	4.90E-08	4.08E+05	1.86E+02	1.45E-02
TOTAL	1.60E+06	4.40E+05	3.33E+05	8.23E+03				7.48E+00

Table A6.8. AC, DAC, and N.DAC for underwater laser cutting at 1 m depth (RVI, PWR)

Nuclide	Cm "peak" Shroud (Bq/g)	Cs (Bq/cm²)	CRᵢ (Bq/min)	ACᵢ (Bq/m³)	CFE (50)w	ALI (Bq)	DAC (Bq/m³)	N.DAC
Nb-95	9.80E-05	5.72E-09	1.16E-05	0.00E+00	1.60E-09	1.25E+07	5.68E+03	0.00E+00
Fe-59	5.78E-01	3.99E-05	6.83E-02	1.52E-03	3.50E-09	5.71E+06	2.60E+03	5.86E-07
Co-58	3.10E+03	2.03E-01	3.67E+02	9.08E+00	2.00E-09	1.00E+07	4.55E+03	2.00E-03
Zr-95	6.12E-04	4.26E-08	7.23E-05	0.00E+00	5.50E-09	3.64E+06	1.65E+03	0.00E+00
Zn-65	1.49E+04	8.77E-01	1.76E+03	4.35E+01	2.90E-09	6.90E+06	3.13E+03	1.39E-02
Mn-54	1.64E+07	1.06E+03	1.94E+06	4.79E+04	1.50E-09	1.33E+07	6.06E+03	7.90E+00
Fe-55	2.44E+09	1.73E+05	2.88E+08	7.13E+06	3.70E-10	5.41E+07	2.46E+04	2.90E+02
Co-60	2.79E+09	1.92E+05	3.30E+08	8.16E+06	2.90E-08	6.90E+05	3.13E+02	2.60E+04
Ni-63	5.39E+08	3.87E+04	6.37E+07	1.58E+06	5.20E-10	3.85E+07	1.75E+04	9.02E+01
Mo-93	1.66E+03	1.27E-01	1.96E+02	4.84E+00	2.20E-09	9.09E+06	4.13E+03	1.17E-03
C-14	6.90E+05	4.93E+01	8.16E+04	2.02E+03	5.80E-09	3.45E+06	1.57E+03	1.29E+00
Nb-94	2.49E+04	1.57E+00	2.94E+03	7.27E+01	4.50E-08	4.44E+05	2.02E+02	3.60E-01
Ni-59	3.41E+06	2.62E+02	4.03E+05	9.96E+03	2.20E-10	9.09E+07	4.13E+04	2.41E-01
Ru-103	0.00E+00	1.97E+02	5.50E+00	1.36E-01	2.80E-09	7.14E+06	3.25E+03	4.19E-05
Ru-106	0.00E+00	4.34E-07	1.21E-08	0.00E+00	6.20E-08	3.23E+05	1.47E+02	0.00E+00
Cs-134	0.00E+00	5.37E+03	1.50E+02	3.71E+00	9.60E-09	2.08E+06	9.47E+02	3.92E-03
Cs-137	0.00E+00	2.87E+04	8.02E+02	1.98E+01	6.70E-09	2.99E+06	1.36E+03	1.46E-02
Ce-141	0.00E+00	4.06E-09	1.13E-10	0.00E+00	3.60E-09	5.56E+06	2.53E+03	0.00E+00
Ce-144	0.00E+00	3.31E+02	9.26E+00	2.29E-01	4.90E-08	4.08E+05	1.86E+02	1.23E-03
TOTAL	5.79E+09	4.40E+05	6.84E+08	1.69E+07				2.64E+04

Table A6.9. AC, DAC, and N.DAC for underwater laser cutting at 1 m depth (RPV, BWR)

Nuclide	Cm "peak" Vessel (Bq/g)	Cs (Bq/cm²)	CRi (Bq/min)	ACi (Bq/m³)	CFE (50)w	ALI (Bq)	DAC (Bq/m³)	N.DAC
C-14	3.21E+01	0.00E+00	3.79E+00	9.37E-02	5.80E-09	3.45E+06	1.57E+03	5.98E-05
P-32	4.27E-24	0.00E+00	5.04E-25	0.00E+00	3.20E-09	6.25E+06	2.84E+03	0.00E+00
S-35	3.41E-03	0.00E+00	4.03E-04	0.00E+00	1.30E-09	1.54E+07	6.99E+03	0.00E+00
Cr-51	1.15E-10	3.68E-10	1.13E-10	0.00E+00	3.60E-11	5.56E+08	2.53E+05	0.00E+00
Mn-54	2.63E+03	2.72E+04	7.64E+03	1.89E+02	1.50E-09	1.33E+07	6.06E+03	3.12E-02
Fe-55	6.47E+05	0.00E+00	7.65E+04	1.89E+03	3.70E-10	5.41E+07	2.46E+04	7.70E-02
Fe-59	1.22E-04	9.09E-05	3.90E-05	0.00E+00	3.50E-09	5.71E+06	2.60E+03	0.00E+00
Co-58	3.18E-02	5.57E-02	1.88E-02	2.98E-04	2.00E-09	1.00E+07	4.55E+03	6.56E-08
Co-60	1.94E+04	3.95E+05	1.09E+05	2.69E+03	2.90E-08	6.90E+05	3.13E+02	8.59E+00
Ni-59	6.93E+01	0.00E+00	8.19E+00	2.02E-01	2.20E-10	9.09E+07	4.13E+04	4.90E-06
Ni-63	8.01E+03	0.00E+00	9.47E+02	2.34E+01	5.20E-10	3.85E+07	1.75E+04	1.34E-03
Zn-65	2.40E-04	2.19E+02	5.90E+01	1.46E+00	2.90E-09	6.90E+06	3.13E+03	4.66E-04
Zr-95	9.28E-07	6.44E-03	1.74E-03	0.00E+00	5.50E-09	3.64E+06	1.65E+03	0.00E+00
Nb-93m	1.59E+00	0.00E+00	1.88E-01	4.49E-03	1.60E-09	1.25E+07	5.68E+03	7.90E-07
Nb-94	3.94E-03	0.00E+00	4.65E-04	0.00E+00	4.50E-08	4.44E+05	2.02E+02	0.00E+00
Nb-95	1.90E-11	5.67E-08	1.53E-08	0.00E+00	1.60E-09	1.25E+07	5.68E+03	0.00E+00
Mo-93	4.45E+00	0.00E+00	5.26E-01	1.29E-02	2.20E-09	9.09E+06	4.13E+03	3.11E-06
Ru-103	0.00E+00	2.86E+02	7.73E+01	1.91E+00	2.80E-09	7.14E+06	3.25E+03	5.89E-04
Ru-106	0.00E+00	6.32E-07	1.70E-07	0.00E+00	6.20E-08	3.23E+05	1.47E+02	0.00E+00
Cs-134	0.00E+00	7.82E+03	2.11E+03	5.22E+01	9.60E-09	2.08E+06	9.47E+02	5.51E-02
Cs-137	0.00E+00	4.18E+04	1.13E+04	2.79E+02	6.70E-09	2.99E+06	1.36E+03	2.06E-01
Ce-141	0.00E+00	5.91E-09	1.59E-09	0.00E+00	3.60E-09	5.56E+06	2.53E+03	0.00E+00
Ce-144	0.00E+00	4.82E+02	1.30E+02	3.22E+00	4.90E-08	4.08E+05	1.86E+02	1.74E-02
TOTAL	6.77E+05	4.73E+05	2.08E+05	5.14E+03				8.98E+00

Table A6.10. AC, DAC, and N.DAC for underwater laser cutting at 1 m depth (RVI, BWR)

Nuclide	Cm "peak" Shroud (Bq/g)	Cs (Bq/cm²)	CRi (Bq/min)	ACi (Bq/m³)	CFE (50)w	ALI (Bq)	DAC (Bq/m³)	N.DAC
H-3	1.76E+00	0.00E+00	2.08E-01	4.97E-03	2.60E-10	7.69E+07	3.50E+04	1.42E-07
Be-10	1.21E-02	0.00E+00	1.43E-03	0.00E+00	3.20E-08	6.25E+05	2.84E+02	0.00E+00
C-14	4.83E+05	0.00E+00	5.71E+04	1.41E+03	5.80E-09	3.45E+06	1.57E+03	9.01E-01
P-33	1.66E-09	0.00E+00	1.96E-10	0.00E+00	1.40E-09	1.43E+07	6.49E+03	0.00E+00
S-35	1.04E+01	0.00E+00	1.23E+00	3.02E-02	1.30E-09	1.54E+07	6.99E+03	4.31E-06
Cl-36	1.24E+00	0.00E+00	1.46E-01	3.45E-03	6.90E-09	2.90E+06	1.32E+03	2.62E-06
Cr-51	9.21E-05	3.68E-10	1.09E-05	0.00E+00	3.60E-11	5.56E+08	2.53E+05	0.00E+00
Mn-54	2.05E+06	2.72E+04	2.44E+05	6.04E+03	1.50E-09	1.33E+07	6.06E+03	9.96E-01
Fe-55	1.73E+09	0.00E+00	2.04E+08	5.05E+06	3.70E-10	5.41E+07	2.46E+04	2.06E+02
Fe-59	3.44E-01	9.09E-05	4.07E-02	8.40E-04	3.50E-09	5.71E+06	2.60E+03	3.23E-07
Co-58	4.35E+02	5.57E-02	5.14E+01	1.27E+00	2.00E-09	1.00E+07	4.55E+03	2.80E-04
Co-60	9.76E+08	3.95E+05	1.15E+08	2.86E+06	2.90E-08	6.90E+05	3.13E+02	9.11E+03
Ni-59	2.93E+06	0.00E+00	3.46E+05	8.56E+03	2.20E-10	9.09E+07	4.13E+04	2.07E-01
Ni-63	3.93E+08	0.00E+00	4.65E+07	1.15E+06	5.20E-10	3.85E+07	1.75E+04	6.58E+01
Zn-65	4.00E+03	2.19E+02	4.90E+02	1.21E+01	2.90E-09	6.90E+06	3.13E+03	3.86E-03
Zr-93	3.75E-02	0.00E+00	4.43E-03	0.00E+00	2.90E-08	6.90E+05	3.13E+02	0.00E+00
Zr-95	7.84E-05	6.44E-03	4.92E-04	0.00E+00	5.50E-09	3.64E+06	1.65E+03	0.00E+00
Nb-93m	5.35E+02	0.00E+00	6.32E+01	1.56E+00	1.60E-09	1.25E+07	5.68E+03	2.75E-04
Nb-94	6.90E+03	0.00E+00	8.16E+02	2.02E+01	4.50E-08	4.44E+05	2.02E+02	9.99E-02
Nb-95	5.88E-06	5.67E-08	6.99E-07	0.00E+00	1.60E-09	1.25E+07	5.68E+03	0.00E+00
Mo-93	1.50E+03	0.00E+00	1.77E+02	4.39E+00	2.20E-09	9.09E+06	4.13E+03	1.06E-03
Ag-108m	3.32E+02	0.00E+00	3.93E+01	9.72E-01	3.50E-08	5.71E+05	2.60E+02	3.74E-03
Cd-109	2.30E+03	0.00E+00	2.71E+02	6.72E+00	9.60E-09	2.08E+06	9.47E+02	7.09E-03
Ag-110m	1.07E+03	0.00E+00	1.27E+02	3.14E+00	1.20E-08	1.67E+06	7.58E+02	4.14E-03
Sm-151	9.05E+05	0.00E+00	1.07E+05	2.65E+03	3.70E-09	5.41E+06	2.46E+03	1.08E+00
Eu-152	8.13E+01	0.00E+00	9.61E+00	2.38E-01	3.90E-08	5.13E+05	2.33E+02	1.02E-03

Nuclide	Cm "peak" Shroud (Bq/g)	Cs (Bq/cm²)	CRi (Bq/min)	ACi (Bq/m³)	CFE (50)w	ALI (Bq)	DAC (Bq/m³)	N.DAC
Eu-154	3.89E+00	0.00E+00	4.60E-01	1.12E-02	5.00E-08	4.00E+05	1.82E+02	6.16E-05
Tb-160	6.87E-02	0.00E+00	8.12E-03	3.43E-05	6.60E-09	3.03E+06	1.38E+03	2.49E-08
Ho-166m	4.35E+00	0.00E+00	5.15E-01	1.26E-02	1.10E-07	1.82E+05	8.26E+01	1.52E-04
Ru-103	0.00E+00	2.86E+02	2.15E+01	5.31E-01	2.80E-09	7.14E+06	3.25E+03	1.64E-04
Ru-106	0.00E+00	6.32E-07	4.74E-08	0.00E+00	6.20E-08	3.23E+05	1.47E+02	0.00E+00
Cs-134	0.00E+00	7.82E+03	5.86E+02	1.45E+01	9.60E-09	2.08E+06	9.47E+02	1.53E-02
Cs-137	0.00E+00	4.18E+04	3.13E+03	7.76E+01	6.70E-09	2.99E+06	1.36E+03	5.72E-02
Ce-141	0.00E+00	5.91E-09	4.43E-10	0.00E+00	3.60E-09	5.56E+06	2.53E+03	0.00E+00
Ce-144	0.00E+00	4.82E+02	3.62E+01	8.95E-01	4.90E-08	4.08E+05	1.86E+02	4.82E-03
TOTAL	3.10E+09	4.73E+05	3.67E+08	9.08E+06				9.38E+03

Table A6.11. AC, DAC, and N.DAC for underwater laser cutting at 5 m depth (RPV, PWR)

Nuclide	Cm "peak" Vessel (Bq/g)	Cs (Bq/cm^2)	CR$_i$ (Bq/min)	AC$_i$ (Bq/m^3)	CFE (50)w	ALI (Bq)	DAC (Bq/m^3)	N.DAC
Nb-95	8.33E-11	5.72E-09	8.89E-10	0.00E+00	1.60E-09	1.25E+07	5.68E+03	0.00E+00
Fe-59	3.39E-04	3.99E-05	2.51E-05	0.00E+00	3.50E-09	5.71E+06	2.60E+03	0.00E+00
Co-58	1.37E-01	2.03E-01	3.90E-02	7.98E-04	2.00E-09	1.00E+07	4.55E+03	1.76E-07
Zr-95	4.00E-06	4.26E-08	2.30E-07	0.00E+00	5.50E-09	3.64E+06	1.65E+03	0.00E+00
Zn-65	4.34E-03	8.77E-01	1.36E-01	3.19E-03	2.90E-09	6.90E+06	3.13E+03	1.02E-06
Mn-54	1.13E+04	1.06E+03	7.95E+02	1.97E+01	1.50E-09	1.33E+07	6.06E+03	3.24E-03
Fe-55	1.35E+06	1.73E+05	1.02E+05	2.53E+03	3.70E-10	5.41E+07	2.46E+04	1.03E-01
Co-60	2.18E+05	1.92E+05	4.19E+04	1.04E+03	2.90E-08	6.90E+05	3.13E+02	3.30E+00
Ni-63	1.71E+04	3.87E+04	6.94E+03	1.72E+02	5.20E-10	3.85E+07	1.75E+04	9.81E-03
Mo-93	5.98E+00	1.27E-01	3.53E-01	8.58E-03	2.20E-09	9.09E+06	4.13E+03	2.08E-06
C-14	8.74E+01	4.93E+01	1.25E+01	3.09E-01	5.80E-09	3.45E+06	1.57E+03	1.97E-04
Nb-94	0.00E+00	1.57E+00	2.43E-01	5.85E-03	4.50E-08	4.44E+05	2.02E+02	2.89E-05
Ni-59	1.47E+02	2.62E+02	4.87E+01	1.20E+00	2.20E-10	9.09E+07	4.13E+04	2.92E-05
Ru-103	0.00E+00	1.97E+02	3.04E+01	7.52E-01	2.80E-09	7.14E+06	3.25E+03	2.32E-04
Ru-106	0.00E+00	4.34E-07	6.71E-08	0.00E+00	6.20E-08	3.23E+05	1.47E+02	0.00E+00
Cs-134	0.00E+00	5.37E+03	8.30E+02	2.05E+01	9.60E-09	2.08E+06	9.47E+02	2.17E-02
Cs-137	0.00E+00	2.87E+04	4.44E+03	1.10E+02	6.70E-09	2.99E+06	1.36E+03	8.09E-02
Ce-141	0.00E+00	4.06E-09	6.28E-10	0.00E+00	3.60E-09	5.56E+06	2.53E+03	0.00E+00
Ce-144	0.00E+00	3.31E+02	5.12E+01	1.27E+00	4.90E-08	4.08E+05	1.86E+02	6.83E-03
TOTAL	1.60E+06	4.40E+05	1.57E+05	3.89E+03				3.53E+00

Table A6.12. AC, DAC, and N.DAC for underwater laser cutting at 5 m depth (RVI, PWR)

Nuclide	Cm "peak" Shroud (Bq/g)	Cs (Bq/cm^2)	CR$_i$ (Bq/min)	AC$_i$ (Bq/m^3)	CFE (50)w	ALI (Bq)	DAC (Bq/m^3)	N.DAC
Nb-95	9.80E-05	5.72E-09	5.47E-06	0.00E+00	1.60E-09	1.25E+07	5.68E+03	0.00E+00
Fe-59	5.78E-01	3.99E-05	3.22E-02	6.31E-04	3.50E-09	5.71E+06	2.60E+03	2.43E-07
Co-58	3.10E+03	2.03E-01	1.73E+02	4.29E+00	2.00E-09	1.00E+07	4.55E+03	9.43E-04
Zr-95	6.12E-04	4.26E-08	3.41E-05	0.00E+00	5.50E-09	3.64E+06	1.65E+03	0.00E+00
Zn-65	1.49E+04	8.77E-01	8.30E+02	2.05E+01	2.90E-09	6.90E+06	3.13E+03	6.55E-03
Mn-54	1.64E+07	1.06E+03	9.14E+05	2.26E+04	1.50E-09	1.33E+07	6.06E+03	3.73E+00
Fe-55	2.44E+09	1.73E+05	1.36E+08	3.36E+06	3.70E-10	5.41E+07	2.46E+04	1.37E+02
Co-60	2.79E+09	1.92E+05	1.56E+08	3.85E+06	2.90E-08	6.90E+05	3.13E+02	1.23E+04
Ni-63	5.39E+08	3.87E+04	3.01E+07	7.44E+05	5.20E-10	3.85E+07	1.75E+04	4.26E+01
Mo-93	1.66E+03	1.27E-01	9.24E+01	2.29E+00	2.20E-09	9.09E+06	4.13E+03	5.53E-04
C-14	6.90E+05	4.93E+01	3.85E+04	9.53E+02	5.80E-09	3.45E+06	1.57E+03	6.08E-01
Nb-94	2.49E+04	1.57E+00	1.39E+03	3.43E+01	4.50E-08	4.44E+05	2.02E+02	1.70E-01
Ni-59	3.41E+06	2.62E+02	1.90E+05	4.70E+03	2.20E-10	9.09E+07	4.13E+04	1.14E-01
Ru-103	0.00E+00	1.97E+02	2.60E+00	6.41E-02	2.80E-09	7.14E+06	3.25E+03	1.97E-05
Ru-106	0.00E+00	4.34E-07	5.73E-09	0.00E+00	6.20E-08	3.23E+05	1.47E+02	0.00E+00
Cs-134	0.00E+00	5.37E+03	7.09E+01	1.75E+00	9.60E-09	2.08E+06	9.47E+02	1.85E-03
Cs-137	0.00E+00	2.87E+04	3.79E+02	9.37E+00	6.70E-09	2.99E+06	1.36E+03	6.91E-03
Ce-141	0.00E+00	4.06E-09	5.36E-11	0.00E+00	3.60E-09	5.56E+06	2.53E+03	0.00E+00
Ce-144	0.00E+00	3.31E+02	4.37E+00	1.08E-01	4.90E-08	4.08E+05	1.86E+02	5.82E-04
TOTAL	5.79E+09	4.40E+05	3.23E+08	7.99E+06				1.25E+04

Table A6.13. AC, DAC, and N.DAC for underwater laser cutting at 5 m depth (RPV, BWR)

Nuclide	Cm "peak" Vessel (Bq/g)	Cs (Bq/cm²)	CRi (Bq/min)	ACi (Bq/m³)	CFE (50)w	ALI (Bq)	DAC (Bq/m³)	N.DAC
C-14	3.21E+01	0.00E+00	1.79E+00	4.42E-02	5.80E-09	3.45E+06	1.57E+03	2.82E-05
P-32	4.27E-24	0.00E+00	2.38E-25	0.00E+00	3.20E-09	6.25E+06	2.84E+03	0.00E+00
S-35	3.41E-03	0.00E+00	1.90E-04	0.00E+00	1.30E-09	1.54E+07	6.99E+03	0.00E+00
Cr-51	1.15E-10	3.68E-10	5.33E-11	0.00E+00	3.60E-11	5.56E+08	2.53E+05	0.00E+00
Mn-54	2.63E+03	2.72E+04	3.61E+03	8.92E+01	1.50E-09	1.33E+07	6.06E+03	1.47E-02
Fe-55	6.47E+05	0.00E+00	3.61E+04	8.93E+02	3.70E-10	5.41E+07	2.46E+04	3.64E-02
Fe-59	1.22E-04	9.09E-05	1.84E-05	0.00E+00	3.50E-09	5.71E+06	2.60E+03	0.00E+00
Co-58	3.18E-02	5.57E-02	8.87E-03	5.27E-05	2.00E-09	1.00E+07	4.55E+03	1.16E-08
Co-60	1.94E+04	3.95E+05	5.14E+04	1.27E+03	2.90E-08	6.90E+05	3.13E+02	4.06E+00
Ni-59	6.93E+01	0.00E+00	3.86E+00	9.54E-02	2.20E-10	9.09E+07	4.13E+04	2.31E-06
Ni-63	8.01E+03	0.00E+00	4.47E+02	1.11E+01	5.20E-10	3.85E+07	1.75E+04	6.33E-04
Zn-65	2.40E-04	2.19E+02	2.79E+01	6.89E-01	2.90E-09	6.90E+06	3.13E+03	2.20E-04
Zr-95	9.28E-07	6.44E-03	8.20E-04	0.00E+00	5.50E-09	3.64E+06	1.65E+03	0.00E+00
Nb-93m	1.59E+00	0.00E+00	8.88E-02	2.03E-03	1.60E-09	1.25E+07	5.68E+03	3.57E-07
Nb-94	3.94E-03	0.00E+00	2.20E-04	0.00E+00	4.50E-08	4.44E+05	2.02E+02	0.00E+00
Nb-95	1.90E-11	5.67E-08	7.23E-09	0.00E+00	1.60E-09	1.25E+07	5.68E+03	0.00E+00
Mo-93	4.45E+00	0.00E+00	2.48E-01	5.98E-03	2.20E-09	9.09E+06	4.13E+03	1.45E-06
Ru-103	0.00E+00	2.86E+02	3.65E+01	9.02E-01	2.80E-09	7.14E+06	3.25E+03	2.78E-04
Ru-106	0.00E+00	6.32E-07	8.05E-08	0.00E+00	6.20E-08	3.23E+05	1.47E+02	0.00E+00
Cs-134	0.00E+00	7.82E+03	9.96E+02	2.46E+01	9.60E-09	2.08E+06	9.47E+02	2.60E-02
Cs-137	0.00E+00	4.18E+04	5.32E+03	1.32E+02	6.70E-09	2.99E+06	1.36E+03	9.71E-02
Ce-141	0.00E+00	5.91E-09	7.53E-10	0.00E+00	3.60E-09	5.56E+06	2.53E+03	0.00E+00
Ce-144	0.00E+00	4.82E+02	6.14E+01	1.52E+00	4.90E-08	4.08E+05	1.86E+02	8.19E-03
TOTAL	6.77E+05	4.73E+05	9.80E+04	2.43E+03				4.24E+00

Table A6.14. AC, DAC, and N.DAC for underwater laser cutting at 5 m depth (RVI, BWR)

Nuclide	Cm "peak" Shroud (Bq/g)	Cs (Bq/cm²)	CRi (Bq/min)	ACi (Bq/m³)	CFE (50)w	ALI (Bq)	DAC (Bq/m³)	N.DAC
H-3	1.76E+00	0.00E+00	9.81E-02	2.26E-03	2.60E-10	7.69E+07	3.50E+04	6.46E-08
Be-10	1.21E-02	0.00E+00	6.76E-04	0.00E+00	3.20E-08	6.25E+05	2.84E+02	0.00E+00
C-14	4.83E+05	0.00E+00	2.70E+04	6.67E+02	5.80E-09	3.45E+06	1.57E+03	4.26E-01
P-33	1.66E-09	0.00E+00	9.25E-11	0.00E+00	1.40E-09	1.43E+07	6.49E+03	0.00E+00
S-35	1.04E+01	0.00E+00	5.79E-01	1.42E-02	1.30E-09	1.54E+07	6.99E+03	2.02E-06
Cl-36	1.24E+00	0.00E+00	6.91E-02	1.54E-03	6.90E-09	2.90E+06	1.32E+03	1.17E-06
Cr-51	9.21E-05	3.68E-10	5.14E-06	0.00E+00	3.60E-11	5.56E+08	2.53E+05	0.00E+00
Mn-54	2.05E+06	2.72E+04	1.15E+05	2.85E+03	1.50E-09	1.33E+07	6.06E+03	4.70E-01
Fe-55	1.73E+09	0.00E+00	9.64E+07	2.39E+06	3.70E-10	5.41E+07	2.46E+04	9.71E+01
Fe-59	3.44E-01	9.09E-05	1.92E-02	3.08E-04	3.50E-09	5.71E+06	2.60E+03	1.19E-07
Co-58	4.35E+02	5.57E-02	2.43E+01	6.00E-01	2.00E-09	1.00E+07	4.55E+03	1.32E-04
Co-60	9.76E+08	3.95E+05	5.45E+07	1.35E+06	2.90E-08	6.90E+05	3.13E+02	4.30E+03
Ni-59	2.93E+06	0.00E+00	1.63E+05	4.04E+03	2.20E-10	9.09E+07	4.13E+04	9.78E-02
Ni-63	3.93E+08	0.00E+00	2.19E+07	5.43E+05	5.20E-10	3.85E+07	1.75E+04	3.10E+01
Zn-65	4.00E+03	2.19E+02	2.31E+02	5.72E+00	2.90E-09	6.90E+06	3.13E+03	1.82E-03
Zr-93	3.75E-02	0.00E+00	2.09E-03	0.00E+00	2.90E-08	6.90E+05	3.13E+02	0.00E+00
Zr-95	7.84E-05	6.44E-03	2.32E-04	0.00E+00	5.50E-09	3.64E+06	1.65E+03	0.00E+00
Nb-93m	5.35E+02	0.00E+00	2.98E+01	7.38E-01	1.60E-09	1.25E+07	5.68E+03	1.30E-04
Nb-94	6.90E+03	0.00E+00	3.85E+02	9.53E+00	4.50E-08	4.44E+05	2.02E+02	4.72E-02
Nb-95	5.88E-06	5.67E-08	3.30E-07	0.00E+00	1.60E-09	1.25E+07	5.68E+03	0.00E+00
Mo-93	1.50E+03	0.00E+00	8.37E+01	2.07E+00	2.20E-09	9.09E+06	4.13E+03	5.01E-04
Ag-108m	3.32E+02	0.00E+00	1.85E+01	4.59E-01	3.50E-08	5.71E+05	2.60E+02	1.77E-03
Cd-109	2.30E+03	0.00E+00	1.28E+02	3.17E+00	9.60E-09	2.08E+06	9.47E+02	3.35E-03
Ag-110m	1.07E+03	0.00E+00	5.99E+01	1.48E+00	1.20E-08	1.67E+06	7.58E+02	1.95E-03
Sm-151	9.05E+05	0.00E+00	5.05E+04	1.25E+03	3.70E-09	5.41E+06	2.46E+03	5.08E-01

Nuclide	Cm "peak" Shroud (Bq/g)	Cs (Bq/cm²)	CRi (Bq/min)	ACi (Bq/m³)	CFE (50)w	ALI (Bq)	DAC (Bq/m³)	N.DAC
Eu-152	8.13E+01	0.00E+00	4.54E+00	1.12E-01	3.90E-08	5.13E+05	2.33E+02	4.81E-04
Eu-154	3.89E+00	0.00E+00	2.17E-01	5.20E-03	5.00E-08	4.00E+05	1.82E+02	2.86E-05
Tb-160	6.87E-02	0.00E+00	3.83E-03	0.00E+00	6.60E-09	3.03E+06	1.38E+03	0.00E+00
Ho-166m	4.35E+00	0.00E+00	2.43E-01	5.85E-03	1.10E-07	1.82E+05	8.26E+01	7.07E-05
Ru-103	0.00E+00	2.86E+02	1.01E+01	2.51E-01	2.80E-09	7.14E+06	3.25E+03	7.72E-05
Ru-106	0.00E+00	6.32E-07	2.24E-08	0.00E+00	6.20E-08	3.23E+05	1.47E+02	0.00E+00
Cs-134	0.00E+00	7.82E+03	2.77E+02	6.85E+00	9.60E-09	2.08E+06	9.47E+02	7.23E-03
Cs-137	0.00E+00	4.18E+04	1.48E+03	3.66E+01	6.70E-09	2.99E+06	1.36E+03	2.70E-02
Ce-141	0.00E+00	5.91E-09	2.09E-10	0.00E+00	3.60E-09	5.56E+06	2.53E+03	0.00E+00
Ce-144	0.00E+00	4.82E+02	1.71E+01	4.22E-01	4.90E-08	4.08E+05	1.86E+02	2.28E-03
TOTAL	3.10E+09	4.73E+05	1.73E+08	4.29E+06				4.43E+03

ANNEX VII - RISK MATRIX

Normal segmentation conditions

			Unoptimized Conditions				Safety Measures and Controls
Situation	Associated Activities	Potential Causes	Probability (1)	Dose to Workers	Dose to Public	Environment	Design options
External Exposure Normal conditions	All activities	Activities in radiation and contaminated areas.	All along the process	Very high if no measures are taken due to highly activated materials	Low	N/A	Remote Operation, robust design, easy installation & decontamination. Shielding, dosimeters, and other Radiation Protection (RP) procedures and controls. Area Radiation Monitoring. Water Level Monitoring. Building off-gas system monitoring and filtration. Training.
Internal Exposure Normal conditions	Segmentation activities	Airborne releases during RPV/RVI cutting. Sublimation of ruthenium to gaseous form (in-air cutting).	All along the process	Very high if no measures are taken due to high releases from activated materials during segmentation		N/A	Remote Operation. Dust/aerosols collection system. Contamination Control Confinement (Airlock). Area Radiation Monitoring. Building off-gas system monitoring and filtration.
Effluents and secondary waste Normal conditions	Segmentation activities	Airborne releases, dross generation, and water contamination during RPV/RVI cutting.	All along the process	N/A	N/A	Low	Protection of cavity floor. Effluents Monitoring. Auxiliary water filtration systems.
Waste management Normal conditions	Radioactive waste handling and fluxes	Cutting pattern choice	All along the process	Low	N/A	N/A	Minimize waste generation. Shielding. Online removal of waste. Optimization of waste location considering personnel walking paths.
Hazardous materials exposure Normal conditions	Segmentation activities	Potential generation of hazardous chemical compounds during cutting operations, such as ozone, carbon oxides, nickel carbonyl, nitrogen oxide and toluene. Hexavalent chromium generation during stainless steel cutting.	All along the process	N/A	N/A	Toxicity	Dust/aerosols collection system. Contamination Control Confinement (Airlock). Area Radiation Monitoring.
Maintenance operation Normal conditions	Maintenance (nozzle replacement, support equipment - platform-...)	Maintenance activities, repairs, and replacements.	All along the process	Low	N/A	N/A	Robust design, easy and scarce maintenance. RP procedures and controls. Protective personal equipment.

Potential Deviations and accidental situations

Risk	Scenario	Associated Activities	Potential Causes	Unmitigated Conditions: Probability (1)	Unmitigated Conditions: Dose to Workers	Unmitigated Conditions: Dose to Public	Unmitigated Conditions: Other	Safety Measures and Controls: Prevention	Safety Measures and Controls: Detection	Safety Measures and Controls: Mitigation	Mitigated Conditions: Dose to Workers	Mitigated Conditions: Dose to Public
Non-planned External Exposure	N/A	In-air segmentation activities	Inadvertent entry in high radiation or contaminated areas, or inappropriate removal of shielding. Failures during waste handling.	Medium to High	Medium	Very Low	N/A	Shielding. RP procedures and controls.	Ambient gamma dose rate control. Surveillance and monitoring of work premises.	Evacuation of the workers from the facility. Building off-gas system monitoring and filtration.	Very low	Very low
Non-planned External Exposure	N/A	Underwater segmentation activities	Inadvertent entry in high radiation or contaminated areas, inappropriate removal of shielding or water shielding loss (leak or by excessive elevation of highly activated pieces). Failures during waste handling.	Medium to High	High	Low	N/A	Planning and double verification during relocation of highly activated pieces. RP procedures and controls. Human error minimization techniques and training.	Surveillance and monitoring of work premises.	Evacuation of the workers from the facility. Building off-gas system monitoring and filtration.	Medium	Very low
Non-planned internal Exposure	IE.1	In-air segmentation activities	Rupture of the contamination control confinement (airlock) or filtration malfunction (IE.1), pressure increase in airlock due to laser air supply. Non-planned exposure during maintenance in contact with contaminated equipment. Waste handling.	Medium to High	Medium	Low	Environment	HEPA filters periodic controls. Atmospheric airborne contamination control. Radiation Protection procedures and controls.	Surveillance and monitoring of work premises.	Evacuation of the workers from the facility. Protective personal equipment. Building off-gas system monitoring and filtration.	Medium	Low
Non-planned Internal Exposure	IE.1	Underwater segmentation activities	Rupture of the contamination control confinement (airlock) or filtration malfunction (IE.1), pressure increase in airlock due to laser air supply. Non-planned exposure during maintenance in contact with contaminated equipment. Waste handling.	Medium to High	Medium	Low	Environment	HEPA filters periodic controls. Atmospheric airborne contamination control. Radiation Protection procedures and controls.	Surveillance and monitoring of water contamination.	Evacuation of the workers from the facility. Protective personal equipment. Building off-gas system monitoring and filtration.	Low to medium	Very low

				Unmitigated Conditions				Safety Measures and Controls			Mitigated Conditions	
Risk	Scenario	Associated Activities	Potential Causes	Probability (1)	Dose to Workers	Dose to Public	Other	Prevention	Detection	Mitigation	Dose to Workers	Dose to Public
Fire /Explosion	IE.2	All activities (including maintenance), especially during segmentation.	Laser source, coupler and head, laser beam and its residual power. I.e. generation of hot spots in the fibre, burning of materials (for instance, due to human error), electrical cables, etc. Air supply system. Flammable hydraulic fluids of robotic arm. Hydrogen generation for underwater cutting (brought to negligible levels).	Medium	High	Low to Medium	Personnel or Equipment Damage	Control of fire loads close to the laser source, coupler and head. Use of fire retardant materials in collection systems and cables. Optical fibre path studied, labelled and/or physically protected. Laser cutting system with provisions for avoiding unintentional cuts: stop time, prohibited cutting areas in the software, double check of operator, etc. HSE procedures and controls. Fire break zoning of premises. Automatic shutdown in case of ventilation loss (avoiding H2 local build-up)	Electrical cable in the fibre. Automatic detection systems.	Emergency and fire plan. Fire mitigation systems within the building. Building off-gas system monitoring and filtration.	Low	Very low
Hazardous materials exposure (e.g. Lead, Asbestos, Beryllium, Chromium, etc.)	N/A	In-air segmentation activities.	Laser beam residual power impacting hazardous materials (e.g. lead shielding, etc.), human error.	N/A	N/A	N/A	Toxicity	Laser cutting system with provisions for avoiding unintentional cuts.	N/A	Personal protective equipment	N/A	N/A
Electrical hazards	N/A	All activities involving electrical components.	Use of three phase 400V and other electrical connections.	N/A	N/A	N/A	Personnel injury or Equipment Damage	Human error minimization techniques and training. HSE procedures and controls.	N/A	N/A	N/A	N/A

				Unmitigated Conditions				Safety Measures and Controls			Mitigated Conditions	
Risk	Scenario	Associated Activities	Potential Causes	Probability (1)	Dose to Workers	Dose to Public	Other	Prevention	Detection	Mitigation	Dose to Workers	Dose to Public
Loss of control of the laser beam and residual power	N/A	Segmentation activities.	Use of laser source, coupler and head, equipment malfunction or human error.	N/A	N/A	N/A	Personnel injury or Equipment Damage	Laser cutting system with provisions for avoiding unintentional cuts. Closed laser environment or shielding. Human error minimization techniques and training. HSE procedures and controls.	N/A	N/A	N/A	N/A
Drop of heavy loads	IE.3	Installation of the laser cutting system, handling of contaminated cut pieces.	Handling equipment malfunction or human error.	Medium (2)	Low	Low	Personnel injury or Equipment Damage	Fail-safe design of handling equipment, which shall be certified and with a scale. HSE procedures and controls. Human error minimization techniques and training.	N/A	Building off-gas system monitoring and filtration. Protective equipment of the liner of the pool (for underwater cutting)	Very low	Negligible
Other industrial hazards	N/A	All activities.	Working at heights, high noise areas, use of dangerous equipment (i.e. powered tools), pinch points and sharp objects, kinetic energy, compressed air (used for the laser head), etc.	N/A	N/A	N/A	Personnel injury or Equipment Damage	HSE procedures and controls. Human error minimization techniques and training.	N/A	N/A	N/A	N/A

(1) Although the analysis is performed in a deterministic manner, the estimated frequency of occurrence (adjusted from NUREG/CR-0130 and NUREG/CR-0672), is indicated. As per the references, the frequency is listed as “High” if the occurrence of a release of similar or greater magnitude per year is greater than 10^{-2}, as “Medium” if between 10^{-2} and 10^{-5}, and as “Low” if less than 10^{-5}.

(2) Frequency based on expert judgement. For explosion risk, information from WP2 was considered.

ANNEX VIII - RECOMMENDATIONS PROVIDED BY IRSN DURING THE REVIEW PROCESS

Recommendations which have been considered in the Generic safety assessment (final version)

1. In the final version of the Generic safety assessment, the interfaces between LD-SAFE safety assessment and the target facility safety assessment should be detailed, especially for the existing systems or activities that are expected to be reused by the LD-SAFE equipment, such as power, fluids, ventilation, radiation or fire detection systems, handling devices, radioactive waste management... To do so, Tecnatom should provide clarification in GSA § 1.2 and/or § 6.3 that End User shall be responsible for the verification of matching LD-SAFE technical pre-requisites in his facility.

2. The final version of the Generic safety assessment should provide basic description and, ideally, first elements of design requirement the static confinement device should match, for the case of in-air cutting in the reactor cavity.

3. The final version of the Generic safety assessment should underline that compliance with dose limits established by the IAEA (e.g. 20 mSv per year average on five consecutive years and of 50 mSv in any single year) does not necessarily matches ALARA principle, so dose constraints should be set accordingly by the End User.

4. The final version of the Generic safety assessment should clarify the calculated overall filtration coefficients of filtration systems for discharges into the atmosphere, taking into account building filtration, any intermediate local process filtration if any and, for underwater cutting, water scrubbing effect. More generally, the calculation of the reduction factors “DTcc”, “DTcs” and “DTcc+cs” should be clarified.

5. The final version of the Generic safety assessment should demonstrate that the hydrogen-related risks are controlled and should take into account:

6. the production of H2 during the cutting process, as shown in laboratories (and to be verified in the demonstrator),

7. the ventilation system that participates in the absence of local build-up of H2,

8. the loss of ventilation which should lead to automatic stop of the laser cutting, supported with alarms for potential manual stop.

9. The final version of the Generic safety assessment should assess the risk induced by the robotic arm used as an actuator for piloting the laser cutting head. In particular, the risk matrix section should consider the risk of fire due to presence of flammable hydraulic fluids.

10. The final version of the Generic safety assessment should present an exhaustive list of the relevant parameters to be monitored by the Instrumentation and Control of the laser cutting process. For each of these important parameters, the final version of the Generic safety assessment should introduce the concept of operational domain.

11. The final version of the Generic safety assessment should justify that there are no other relevant accidental scenarios for workers.

12. The final version of the Generic safety assessment should justify, at least for the "IE.3 – drop of load" scenario, the volume retained for the dilution of airborne radioactive material being disseminated during an accidental scenario or revise the calculation of the consequences.

13. The final version of the Generic safety assessment should justify the retained value of the containment volumes (1000 m3 for in-air cutting and 50 m3 for underwater cutting), with regard to the volume of 485 m3 used besides. For calculating the activity that would be released during the "IE.1 - loss of local confinement" accident, the use of a 100 mg/m3 fixed value instead of values considered for confinement design should also be justified.

14. The final version of the Generic safety assessment should provide basic guidelines for the protection of workers in order to reduce the unmitigated consequences to the workers for the two scenarios with the largest consequences for workers (IE.1 and IE.2).

Recommendations to consider within the industrial demonstrator

1. Estimation of atmospheric concentrations should be consolidated by some measures during the implementation of the industrial demonstrator.

2. Tests with the industrial demonstrator should aim to consolidate the quantification of hydrogen production during underwater laser cutting.

3. Tests with the industrial demonstrator should aim to consolidate the operational domain of relevant parameters of the laser cutting process.

Recommendations for the End User

1. The End User will have to ensure compatibility between the existing systems of its facility with the requirements of the future LD-SAFE equipment, especially for utility power and fluids.

2. The End User will have to ensure hypotheses for dose calculations are matching the decommissioning project hypotheses on the corresponding facility or to make specific provisions if necessary.

3. The end user will have to ensure that provided scenarios in the GSA are relevant towards special operations such as planned maintenance.

4. The End User should take benefit from the possibility to cut complex geometry with the laser head to optimize the amount of waste categories by ensuring that the operators are trained to the laser cutting technique. Working procedures could be developed by the End User to determine how workers could take benefit from the laser cutting process to optimize the segmentation plan of the reactor vessel and internals with the aim of optimizing waste categories.

5. The End User must ensure that provided hypotheses for accidental situations for workers in the Generic safety assessment are relevant for its own facility and decommissioning project.

6. The End User should take advantage of the possible deportation of the supporting systems of the laser cutting head to prevent the controlled areas of the facility from an event related to a dysfunction of the supporting systems.

7. The End User must ensure his off-site emergency plan won't require any modification because of LD-SAFE equipment operation. Otherwise, the End User should reassess the accidental situations postulated in the safety assessment of his facility, and to revise the emergency plan accordingly.