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Application of ALARA Principle in the Radiation Protection Design of HPR1000 Nuclear Power Plant

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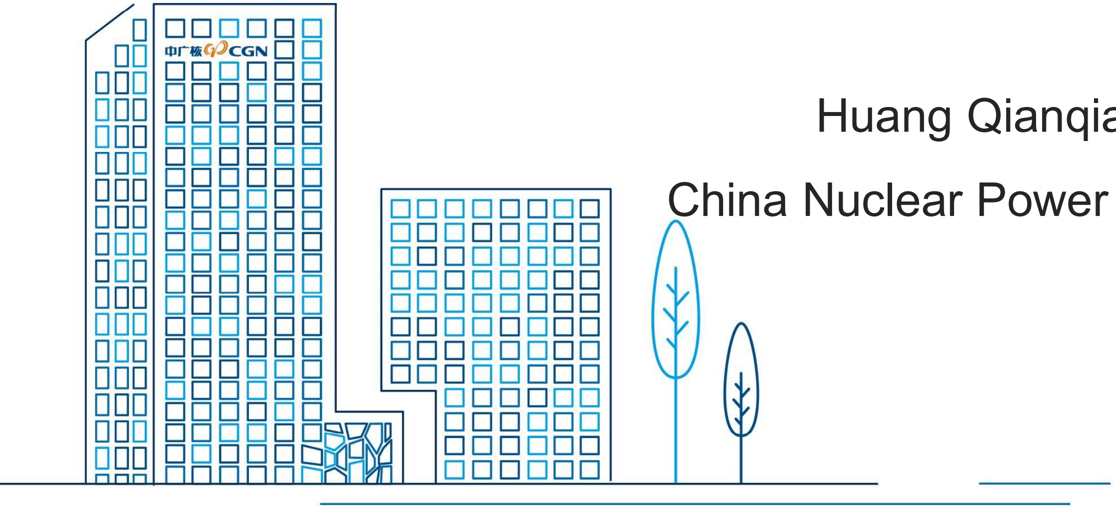


CONTENTS

/1/ Introduction

Radiological exposure is one of the most significant risks that can substantially impact workers and members of the public, and it should be reduced to a level that is As Low As Reasonably Achievable (ALARA).

To better mitigate risks and protect individuals from radiation exposure during normal operation, a methodology for ALARA demonstration in radiological protection was developed during the HPR1000 plant design stage.

The methodology involves steps such as reviewing the design evolution, analyzing compliance with relevant codes and standards, incorporating lessons learned from PWRs' operational experience and nuclear industry practices, and risk-ranking high-dose tasks to identify potential improvements worth implementing. The ERIC-PPE method was applied to determine the feasible design improvements.

Following the ALARA methodology, several improvements compared to CPR1000 were identified and implemented during the HPR1000 design stage, including zinc injection, structural optimization of high-radiation-risk equipment and remote operation. These design improvements reduced occupational exposure to 0.34 man·Sv per unit.

This methodology successfully translates ALARA principles into engineering practice and provides valuable insights for radiation protection design in future nuclear power plants.

/2/ Consideration-*What is ALARA in RP area?*

- ALARA is **not the result of a mathematical formula** → There is no precise legal factor or algorithm for gross disproportion.
- ALARA **is a balance** between risk and sacrifice to reduce it.
- Affordability should not be a priority factor.
- **All the potential options** should be considered, potentially safest first.
- Benefits and disbenefits should be evaluated to ensure that a **proper balance is found**.
- The **higher the risk, the more rigorous** the case should be.
- Presentation and discussion of discarded options are imperative for transparency.
- **Starting point** is the Relevant Good Practice (RGP) and high dose risk activity.

/3/ ALARA methodology-*General Process*

The methodology for ALARA demonstration for radiological protection during normal operation has been developed following the hierarchy of control philosophy and taking into account all factors related to worker dose and public dose from direct radiation to restrict the exposure, such as chemistry control, system design, equipment design, layout scheme, ventilation design, shielding design, etc..

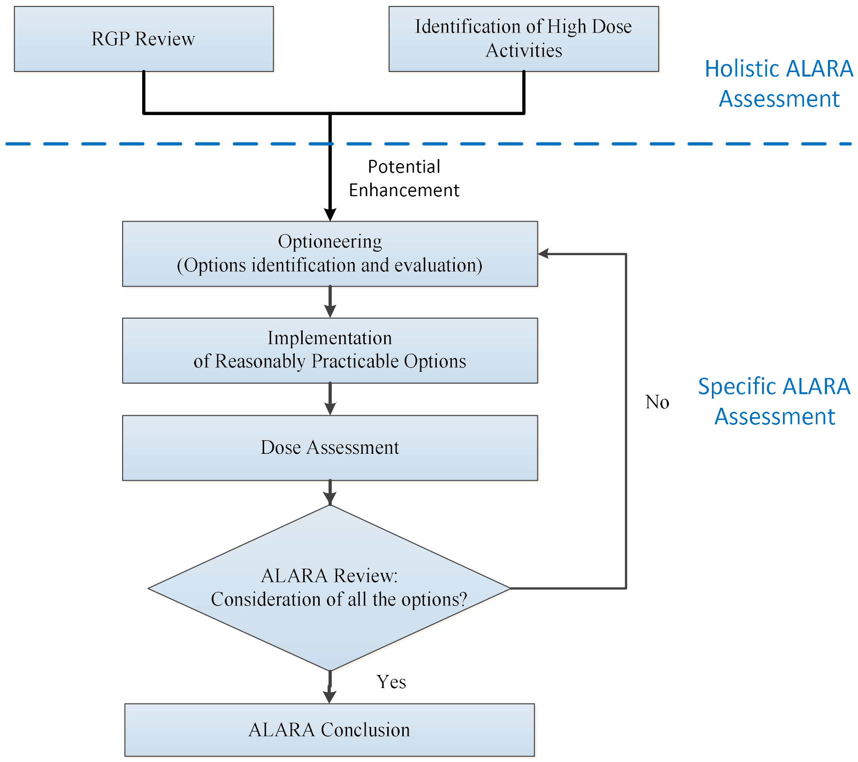
Includes 2 parts:

- Holistic ALARA assessment:

Find gaps and high-risk tasks as the potential enhancement for new plant.

- Specific ALARA assessment:

Systematically apply ALARA assessments on every potential enhancement.



Process of ALARA Demonstration for Radiological Protection

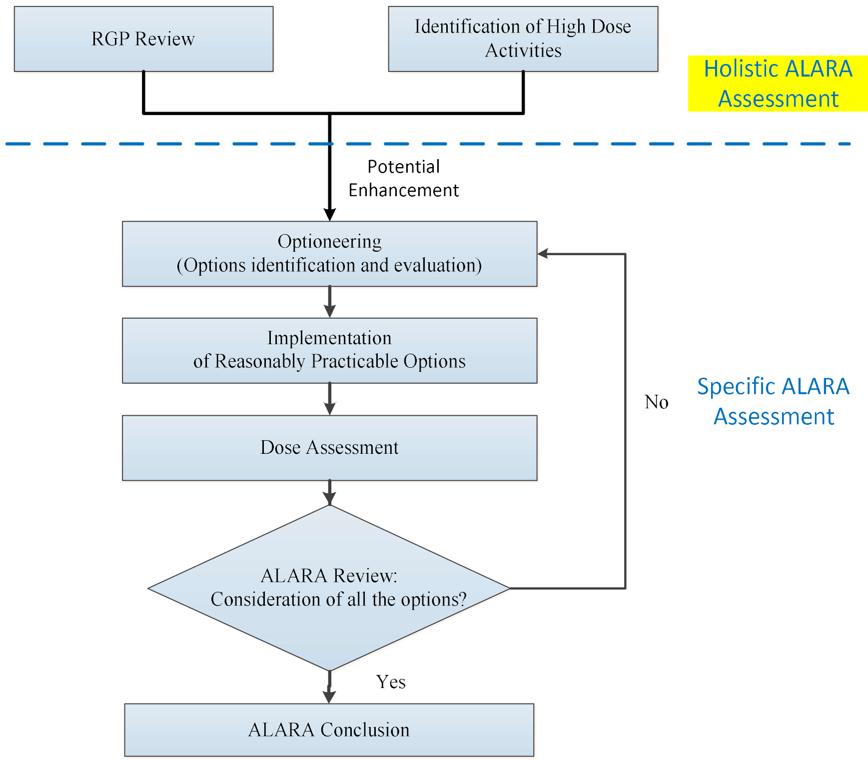
/4/ ALARA methodology-*Holistic ALARA Assessment*

Baseline： The HPR1000 is a 3rd-generation PWR, which is developed based on OPEX feedbacks from CGN fleets including CPR1000 and M310, considering also the advanced design features of EPR and AP1000.

At the beginning of HPR1000 design, the potential enhancements have been identified by:

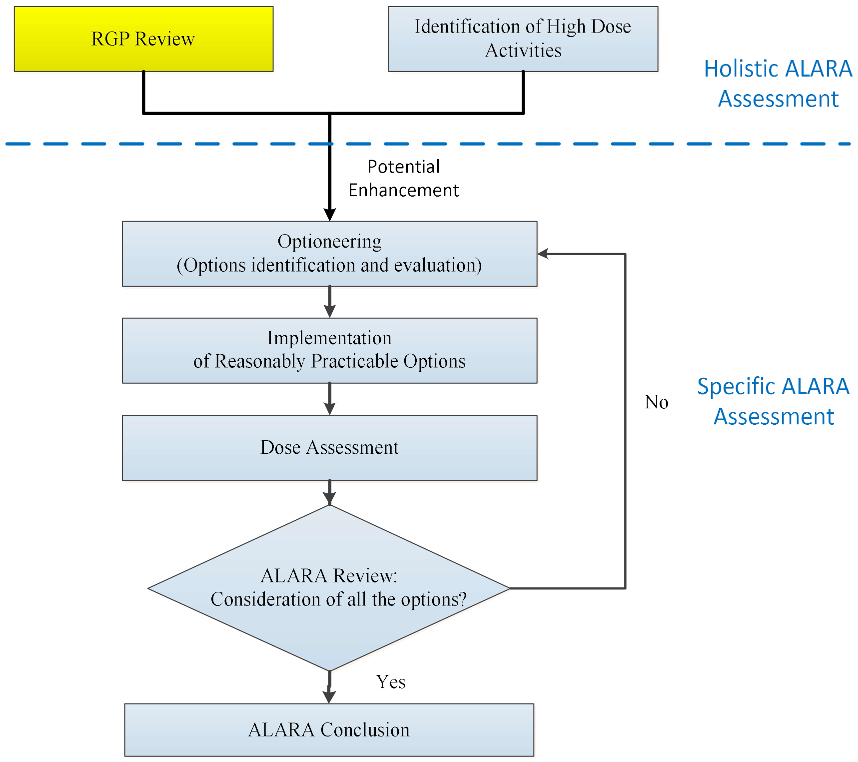
1） RGPs

2） Identified high dose risk activities



/4.1/ *Holistic ALARA Assessment-The Use of RGP*

- In most cases, demonstrating ALARA is not done through explicit comparison of costs and benefits, but by applying established **relevant good practice (RGP)**
- **RGP includes** standards, advanced and verified technologies for dose risk control, and the operational experience related to dose risk.
- **RGP is a starting point** in any ALARA demonstration:
  - Focus on appropriate engineering, operations and management of dose safety.
  - Adopt hierarchy of control measures.



/4.2/ Holistic ALARA Assessment - Source of RGP

- **Codes/Standards/Regulation,etc.**

  IAEA Safety Standards:GSR Part 3, SSR-2/1, NS-G-1.13,etc.

  ICRP publications: ICRP Publication 60 and Publication 103

  Local Government Policies: HAF 102, HAD 102/12, HAD 103/04, GB18871, etc.

  etc.

- **International PWR experience feedbacks and nuclear industry practice:**

  Lessons learnt from previous PWR plants' regulatory process.

  Approved advanced PWR design features: EPR and AP1000.

  International OPEX sharing from authority website: Nuclear Institute, Organization for Economic Co-operation and Development (OECD), Information System on Occupational Exposure (ISOE) etc.

  CGN OPEX feedbacks.

/4.3/ *Holistic ALARA Assessment* - RGPs

Application of mature improvements: in the development process of PWR, some advanced technologies for safety have been continuously improved.

The RGPs related to dose restriction include mainly the following categories:
a) Material selection;
b) Surface finishes;
c) Engineering controls;
d) Chemistry regimes;
e) Maintenance regimes;
f) Operational regimes, etc.

/4.3/ Holistic ALARA Assessment - RGPs

<u>The applicable RGPs list related to dose restriction in HPR1000</u>

Item	Experience feedbacks	HPR1000 Design
Reactor chemistry	Use of enriched boric acid.	UK HPR1000 adopts 7.2 as the pH control value and use boric acid with 35at% B-10 enrichment for pH control.
	Adoption of a constant high pH control of 7.2 chemistry regime with Boron-Lithium coordination.	
Layout design	Collective layout of interrelated radioactive components. Inside radioactive buildings, the area has been divided into functional blocks.	The layout design inside radioactive buildings considers the collective layout principle, which means to divide the building into blocks by functions and arrange the components and pipelines with similar function and upstream and downstream relation together.
	Inclusion of an area entirely dedicated to storing the RPV head in the reactor building.	A specific room for RPV head storage is considered to be set above the platform on +22.5m level and the corresponding shielding is considered to restrict the radiological exposure to the workers on platform.
	Measures to limit "hot spots" in the design: reduce the use of socket welds at pipe connections.	The seal weld technique is considered to be adopted in place of socket weld at pipe connections.
	Installation of permanent platforms around the SG for maintenance.	Permanent platform on +4.9m and +7.37m around the SG is considered to be set to better help SG inspection and maintenance.
	Use of distance separation (with operation position set behind the shield) for valve inspection and maintenance.	The valves located in high radiation rooms are equipped with remote operation mode, ensuring operators perform the operations from a low radiation room without entering the compartment.

/4.3/ *Holistic ALARA Assessment* - RGPs

The applicable RGPs list related to dose restriction in HPR1000

Item	Experience feedbacks	HPR1000 Design
Component design	Reduction of the use of antimony and chromium in the primary pumps especially on surface contacting the primary coolant.	Antimony and silver are forbidden for those parts of primary pumps having direct contact with primary coolant. Limitations on chromium are also raised according to RCC-M F5100.
	Reduction of the residual cobalt content in the stainless steels making up the primary circuit and the usage of Stellite TM-based hard facing materials (steam generator).	The use of Stellite TM and cobalt content are reduced as much as possible and acceptable for primary circuit.
	Use of Alloy 690 (steam generator).	UK HPR1000 adopts Alloy 690 instead of Alloy 600, which has better corrosion resistance.
	Improvement of valve leaktightness: if the fluid is highly radioactive, bellow-sealed globe valves are specified.	Bellow-sealed globe valves are considered to be set for the high radioactive pipelines to reduce the leakage.
	Use of fast assembly-disassembly thermal insulation around the main pipelines, SGs, the pressuriser, the welds and sensitive tap points	Fast assembly-disassembly thermal insulation are considered for the RPV top cover, SGs, the pressuriser, the welds and sensitive tap points to simplify the installation and removal of the insulation during inspection.
	Improvement of chemical and volume control system (RCV) filtration grade	Filters with high precision filtration (0.45μm) are adopted for RCV.

/4.3/ *Holistic ALARA Assessment - RGPs*

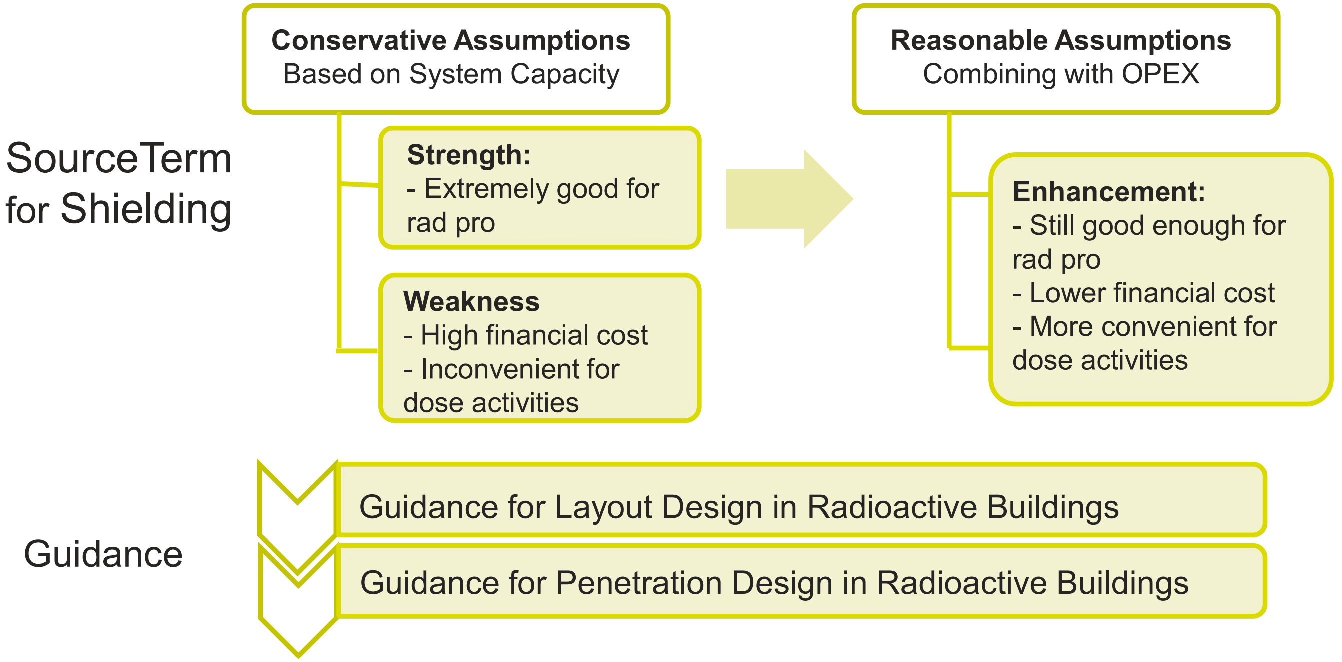
The applicable RGPs list related to dose restriction in HPR1000

Item	Experience feedbacks	UK HPR1000 Design
Radiation shielding	Setting of labyrinths and shield doors	Labyrinths and shield doors are considered for high radiation rooms. Labyrinths are more preferred for UK HPR1000 since it is more convenient and has lower cost.
	Wall penetrations shields	Wall penetration shields are carefully considered in UK HPR1000 design and detailed analysis has been carried out to establish guidance for penetration shielding design in terms of radiation protection.
	Changeroom design	The changeroom design of UK HPR1000 serves for the same purpose (access control) as UK practice. However, the design scheme of UK HPR1000 is a little different from UK practice. Further analysis will be carried out.
	Source term analysis methods	UK HPR1000 adopts a theory-OPEX combined method for source term, considering the production and transport mechanisms of the radionuclides, which is consistent with the international practice.
	Dose rate calculation methods	UK HPR1000 adopts Point-Kernel and Monte Carlo methods for dose rate evaluation, which is consistent with the international practice.

/4.3/ *Holistic ALARA Assessment - RGPs*

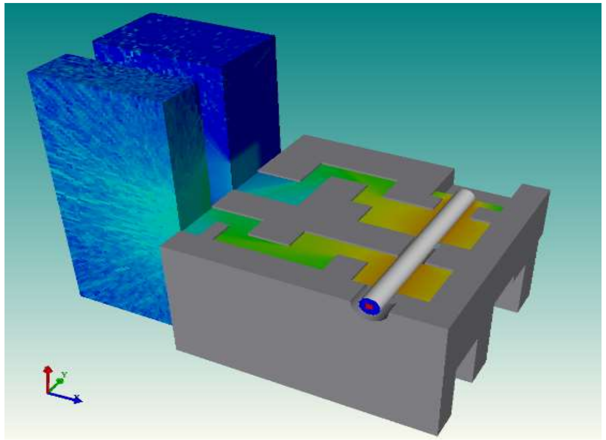
Optimisation of RP design methodology: The radiation protection design methodology has also been continuously improved during the design evolution, including the source term methodology, radiation shielding design, and design considerations/principles for other areas from the radiation protection point of view.

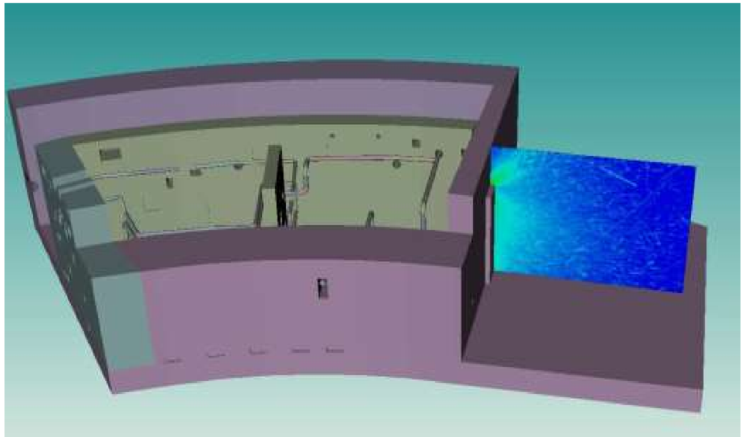
Examples:

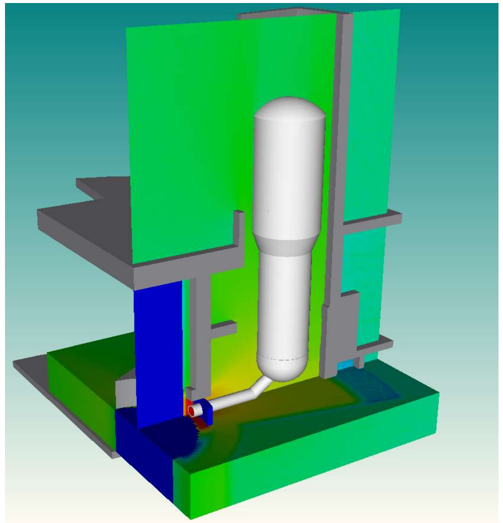


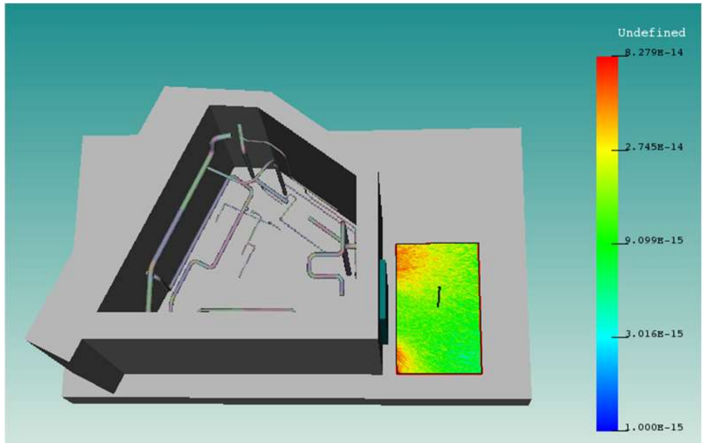
/4.3/ *Holistic ALARA Assessment* - *RGPs*

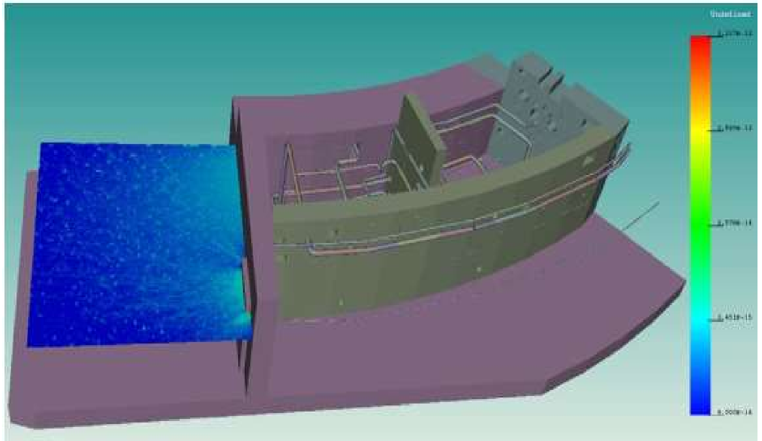
Refined Shielding Design

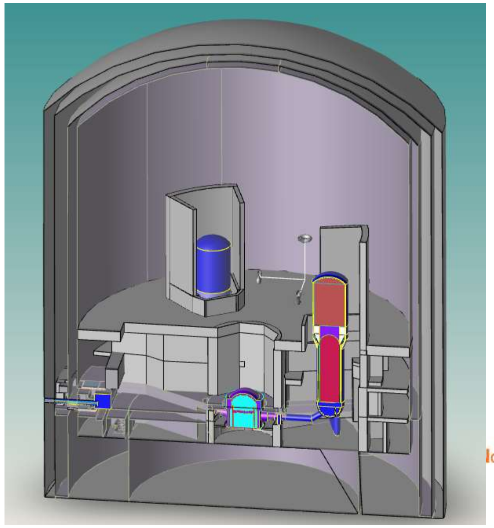








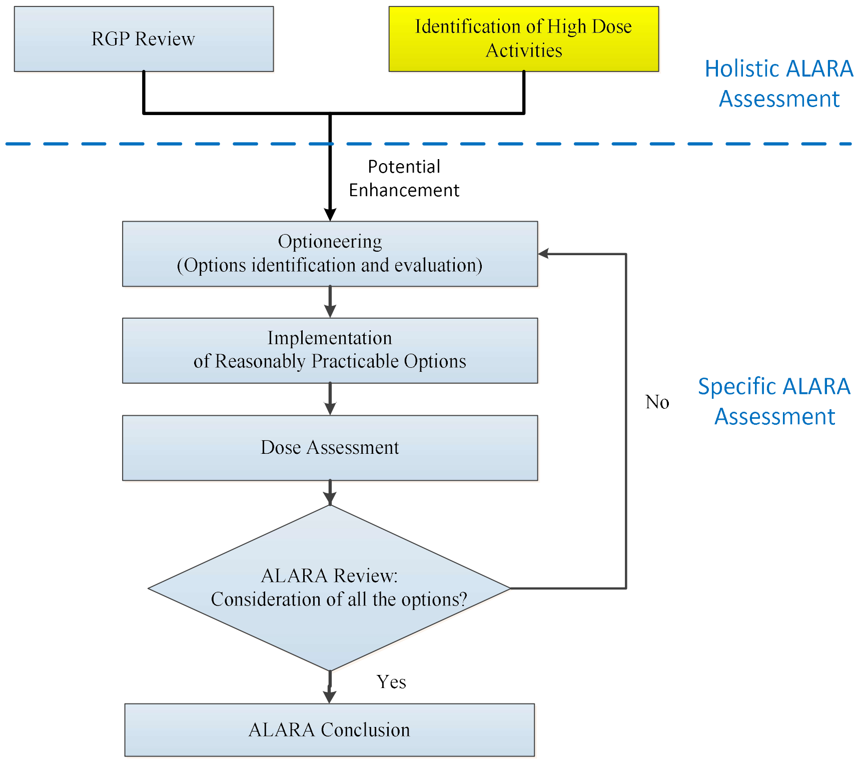




/4.4/ *Holistic ALARA Assessment* - *High-Dose Risk Activities Identification*

High-dose tasks are given higher priority.

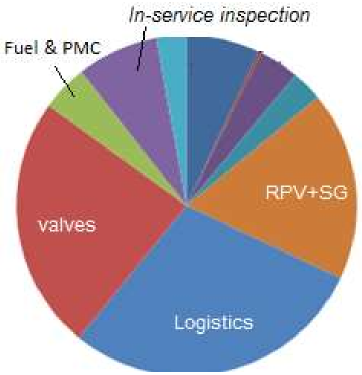
- *The single activity with high individual dose*
- *The most exposed group activities that contribute significantly to collective dose*



/4.4/ Holistic ALARA Assessment - High-Dose Risk Activities Identification

Identified high-dose activities:

- *Works involved reactor pressure vessel;*
- *Works involved steam generator;*
- *Works involved valve inspection and maintenance;*
- *In-service inspection;*
- *Waste processing;*
- *On-site service.*



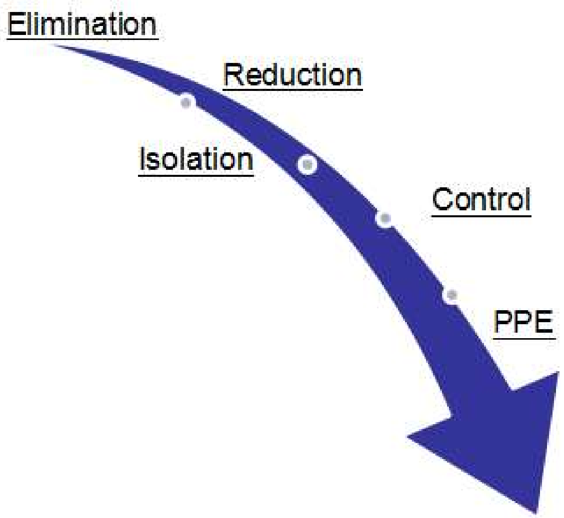
tasks	Man-hours (h)	Worker dose (mSv)	Proportion	Collective dose TOP10	Average personal dose mSv/h TOP10
SG/开关手眼孔	229.83	8.18	0.80%	4.78	0.0356
RCV/其它设备/换热器维检	287.75	9.26	0.90%	5.41	0.0322
RCP/其它设备/管道检修	429.67	11.04	1.08%	6.45	0.0257
RCV/其它设备/容控箱维检	107.47	2.66	0.26%	1.55	0.0248
SG/二次侧检查	533.53	12.49	1.22%	7.30	0.0234
在役检查/支撑和支架	323.75	7.47	0.73%	4.36	0.0231
RRA/换热器维检	139.79	3.18	0.31%	1.86	0.0227
SG/冲洗和干燥	812.13	18.32	1.78%	10.71	0.0226
通用服务/保温	3281.35	70.95	6.91%	41.46	0.0216
废物处理/放射性废物处理/工作准备	9.8	0.21	0.02%	0.12	0.0214
RCV/阀相关维检	3439.35	71.54	6.97%	41.81	0.0208
RCP/阀门相关工作	3113.17	44.79	4.36%	26.17	0.0144
其它系统/阀相关维检	8843.13	86.66	8.44%	50.64	0.0098
压力容器开关盖	6299.91	48.62	4.74%	28.41	0.0077
例行检测	15271.23	84.07	8.19%	49.13	0.0055
杂项	16017.75	38.44	3.74%	22.46	0.0024
其它工作	36994.08	65.84	6.41%	38.47	0.0018
系统运行和测试	36662.51	63.01	6.14%	36.82	0.0017
通用服务	36981.79	31.77	3.09%	18.57	0.0009

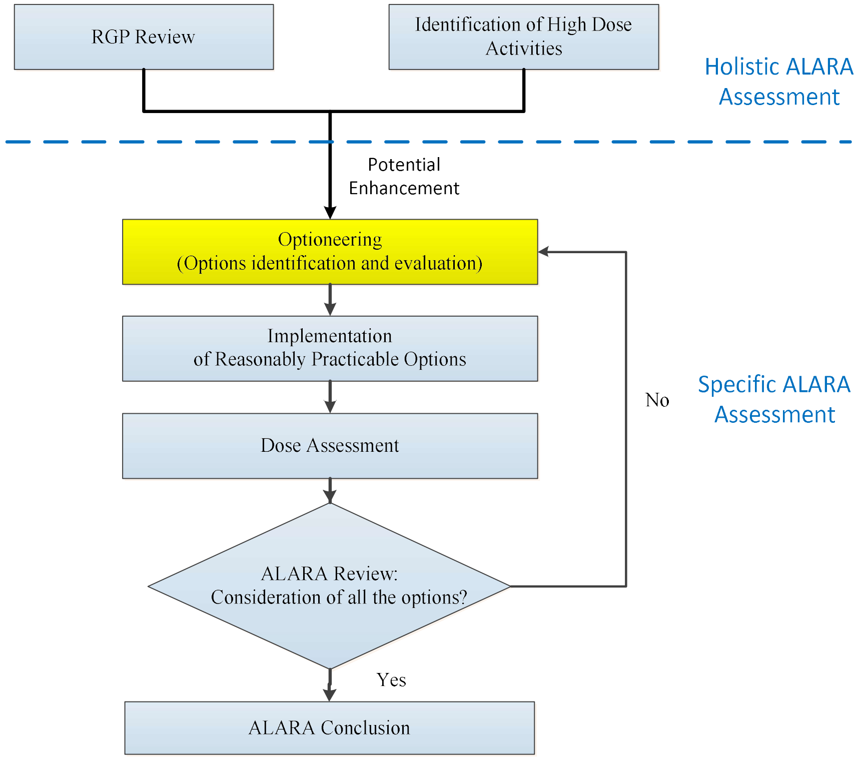
/5.1/ Specific ALARA Assessment *- Optioneering*

Options Identification

Hierarchy of control philosophy (ERIC/PPE) has been applied to identify the potential options.

RGPs are considered as the most important sources of options while applying the ERIC/PPE methodology to identify the options.





/5.1/ Specific ALARA Assessment *- Optioneering*

➢ Elimination:

Eliminate the radiation sources or exposed activities to avoid the radiological risk.

- Remove the radiation source around the area of activities;
- Replace the manual tasks by fully automatic tasks; or
- Replace the near-distance operation by remote operation.

➢ Reduction:

Reduce the source term or the frequency and duration of the dose activities.

- Optimise the material selection, surface finishes, primary coolant chemistry control and decontamination to reduce the source term;
- Optimise the process design, system design and equipment design to be more convenient and robust to reduce the frequency and duration of the operation and maintenance.

➢ Isolation:

Isolate the radiation sources or contaminations from workers.

- Perform radiation zoning to isolate the high radiation areas from low radiation areas;
- Adopt appropriate shielding or containment to isolate the sources from workers.

➢ Control:

Implement administrative control to avoid unauthorised entrance or spread of contamination.

- Temporary access control to avoid unauthorised entrance;
- Ventilation control to avoid spread of contamination;
- Monitoring and alarm on radiation and contamination level to avoid excessive doses.

➢ Personal Protective Equipment (PPE):

Use appropriate PPE for radiological protection.

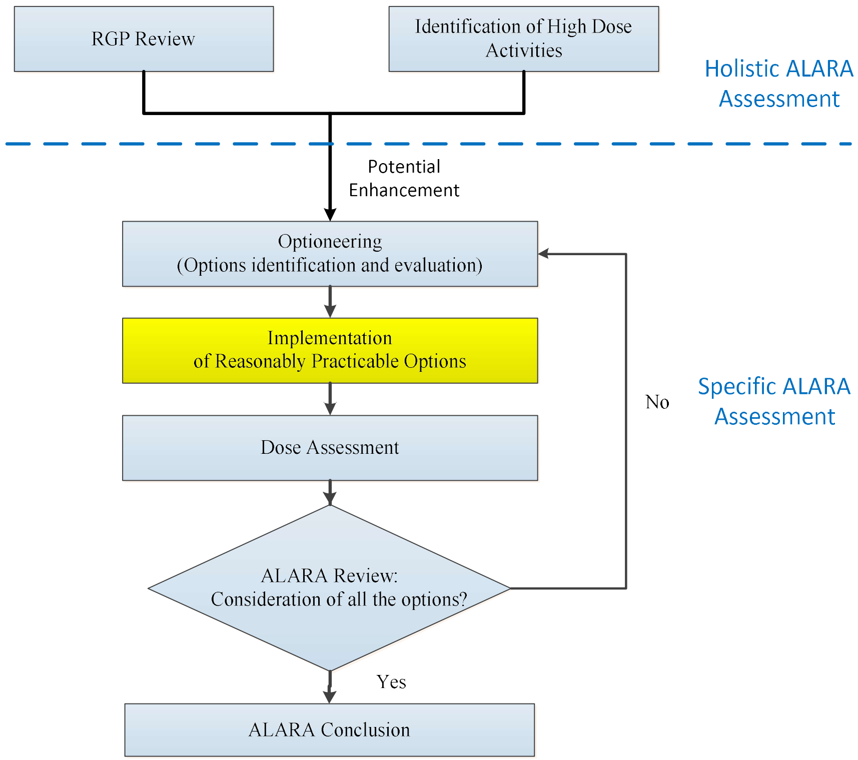
/5.2/ Specific ALARA Assessment *- Decision-making*

Option Evaluation

The identified options are then evaluated by **multi-disciplines analysis,** such as nuclear safety analysis, radiological protection impact analysis, environmental impact analysis, etc.

The comments and feedbacks from operating orgnization are also important.

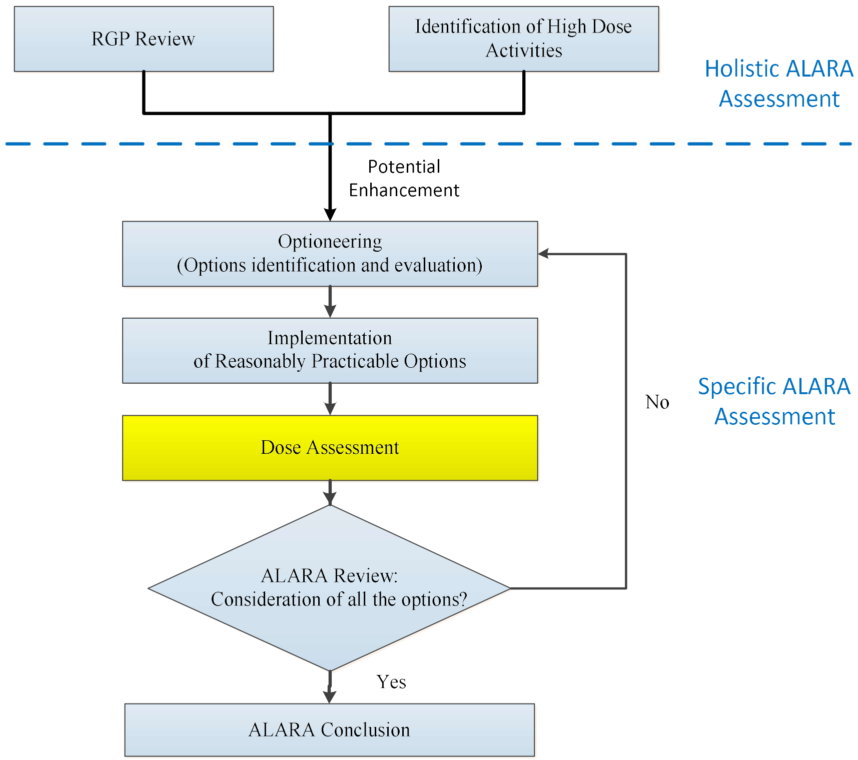
Ensure that the reasonably practicable options, which balance all the relevant factors and impacts, have been found to support the decision-making process.



/5.3/ Specific ALARA Assessment *- Dose Assessment*

After implementation of the reasonably practicable options, the dose assessment for workers and members of the public from direct radiation during normal operation can be carried out.

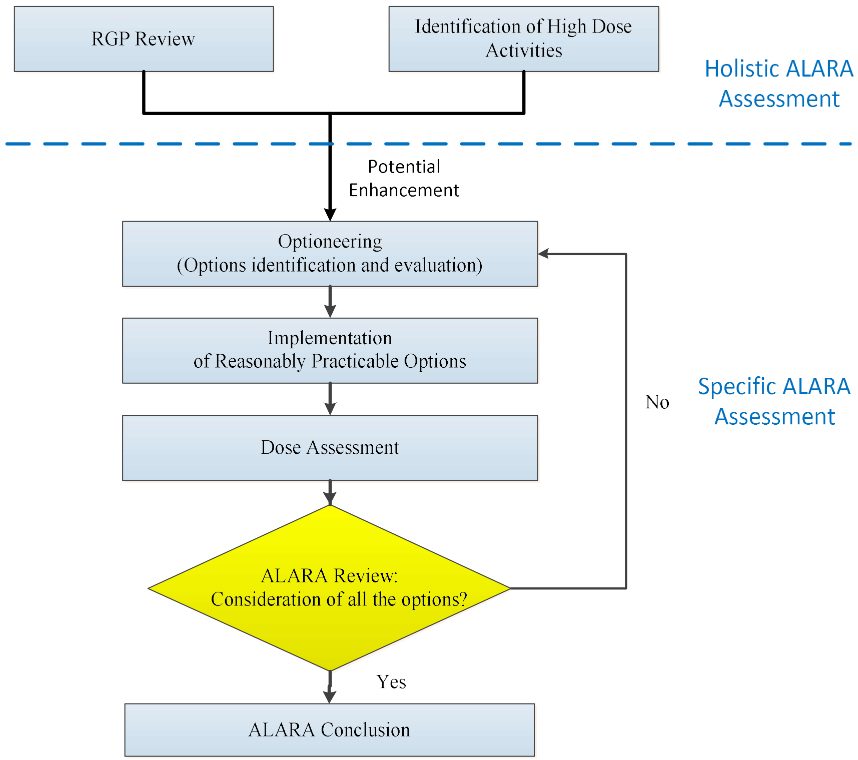
The collective dose for workers has been reduced to 0.34 man·Sv/unit in HPR1000(UK).



/5.3/ Specific ALARA Assessment *- ALARA Review*

The ALARA process will finally be reviewed to check whether all the reasonably practicable options have been considered without any omission. If not, the ALARA process will be repeated to further reduce the doses.

If all the reasonably practicable options have already been considered, an ALARA conclusion can be drawn for this stage of the design.

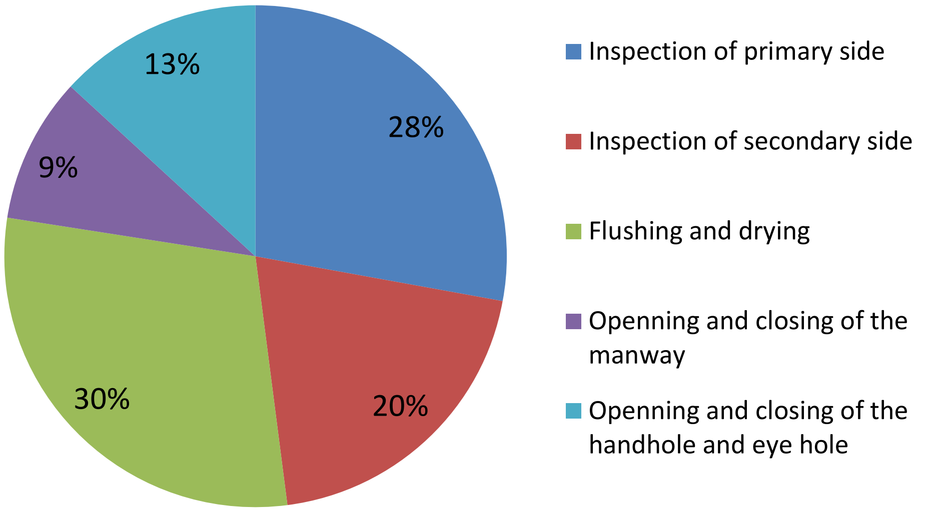


/6.1/ Example for ALARA Demonstration of Radiological Protection

SG inspection and maintenance

Task	Activities	Collective Doses (man.mSv/yr/unit)	Percentages
Works involving steam generator (SG inspection and maintenance)	Inspection of primary side	10.60	28%
	Inspection of secondary side	7.65	20%
	Flushing and drying	11.22	30%
	Opening and closing of the manway	3.57	9%
	Opening and closing of the handhole and eye hole	5.01	13%

Percentage in SG Inspection & Maintenance



/6.1/ Example for ALARA Demonstration of Radiological Protection

Hierarchy of control	thinking	options	Reasonable practicable options?
Elimination	-Eliminate the radioactive source?	Impossible to eliminate SG since SG is an essential equipment for PWR.	No
	-Eliminate the dose activity?	Impossible to eliminate the inspection and maintenance for SG because they are always necessary to guarantee that the SG works in expected performance.	No
Reduction	-Reduce the source term?	•Reactor chemistry Improvement on pH control and adoption of higher enriched boric acid maybe possible.	Yes
		•Material selection Reduction of the use of cobalt-based alloy, e.g. Stellite TM. Use of the alloy with better resistance to corrosion, e.g. Alloy 690 instead of 800.	Yes
		•Decontamination Higher decontamination efficiency by RCV filters and demineraliser. Decontamination of SG before inspection and maintenance.	Yes
	-Reduce the duration?	•Use of sludge trap to reduce frequency of flushing and drying of SG •Use of fast assembly/disassembly tools •Use of Fast assembly/disassembly insulation •Improvement of inspection techniques •Installation of permanent platform for inspection and maintenance •More training on mock-up, etc.	Yes
Isolation	•Radiation zoning and contamination zoning •Radiation shielding		Yes
Control	•Access control to avoid unauthorized entrance •Contamination control to avoid entrance of extra radioactive contamination		Yes
Personal Protective Equipment (PPE)	•Use appropriate PPE if necessary		Yes

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/6.1/ Example for ALARA Demonstration of Radiological Protection

Based on part of the optimisation mentioned in the former slides, the collective dose for SG inspection and maintenance has been reduced.

Task	Activities	Collective Doses (man.mSv/yr/unit)	impacts	Optimised Collective Doses (man.mSv/yr/unit)
Works involving steam generator (SG inspection and maintenance)	Inspection of primary side	10.60	**-10.00%**	9.54
	Inspection of secondary side	7.65	**-10.07%**	6.88
	Flushing and drying	11.22	**-50.00%**	5.61
	Opening and closing of the manway	3.57	**-10.08%**	3.21
	Opening and closing of the handhole and eye hole	5.01	**-9.98%**	4.51

/6.2/ ALARP Demonstration Framework for Radiation Protection (Normal Operations)

Tier 1 Documents	Tier 2 Documents				
	Categories			Titles of Documents	Topic Area
ALARP Demonstration Report of RP	General Source Term Optimisation	Reactor Chemistry	pH	Topic Report of pH Control in the Primary Circuit of UK HPR1000	Reactor Chemistry
			Hydrogen	Topic Report on Hydrogen Concentration Control in the Primary Circuit	Reactor Chemistry
			Impurity	Topic Report on Impurity Control for the Operation	Reactor Chemistry
			Zinc Injection	Topic Report on Zinc Injection in the Primary Circuit of UK HPR1000	Reactor Chemistry
			Chemistry Control	Topic Report on Startup and Shutdown Chemistry	Reactor Chemistry
				Topic Report on Power Operation Chemistry	Reactor Chemistry
				Generic Water Chemistry Specification (LCO)	Reactor Chemistry
		Material Selection	Cobalt Content	Topic Report on Application of Cobalt Based Alloy in SSCs	Reactor Chemistry
				Application Analysis of Cobalt based Alloy in Valves	Reactor Chemistry
				ALARP Assessments for Applications of Cobalt Based Alloy in Reactor Coolant Pump	Reactor Chemistry
			Main Components	Material Selection Report of SG	Structure Integrity
				Material Selection Report of MCL	Structure Integrity
				Material selection report of RVI	Structure Integrity
				Material Selection Report of PZR	Structure Integrity
				Material Selection Report of RPV	Structure Integrity
	EMIT	EMIT Task Arrangement		EMIT Consistency Analysis	Cross Cutting
				EMIT Strategy Implementation Report	Cross Cutting
	Top 6 High Dose Risk Activities	Works involving valve inspection and maintenance		Design Considerations to Minimise the Worker Dose for Valve Inspection and Maintenance	Radiological Protection
				Layout Design Considerations to Minimise the Worker Dose	Radiological Protection
		On-site service	Setting of Scaffolding	Layout Design Considerations to Minimise the Worker Dose	Radiological Protection
			Assembly/ Disassembly Thermal insulation	Optioneering report of the upstream material	Fault Studies
			Setting of Temporary Shielding	Layout Design Considerations to Minimise the Worker Dose	Radiological Protection
		Works involving reactor pressure vessel	RPV Head Assembly Lifting	Minimisation of the Occupational Exposure for Reactor Pressure Vessel Head Assembly Lifting	Radiological Protection
			Fuel Handling	ALARP Demonstration Report of the PMC [FHSS] SSCs	Mechanical Engineering
				ALARP Assessment of the BFX Cranes Arrangements	Mechanical Engineering
				ALARP Assessment of the Spent Fuel Delivery Process	Mechanical Engineering
			ICIA Replacement	Management Proposal of Waste Non-Fuel Core Components	Radwaste Management
				Process Risks/Hazards Analysis for ICIAs Retrieval and Processing Operations	Radwaste Management
		Works involving steam generator	Steam Generator Inspection and Maintenance	Design Considerations to Minimise the Worker Dose for Steam Generator Inspection and Maintenance	Structure Integrity
		In-service inspection	Welding inspection	ALARP Assessment Report for MCL Forgings	Structure Integrity
				ALARP Assessment Report of RPV flange nozzle shell and closure head	Structure Integrity
				ALARP Assessment Report of Reactor Coolant Pump Casing	Structure Integrity
				ALARP Assessment for the PZR Forging	Structure Integrity
				The ALARP Assessment Report of SG Forgings	Structure Integrity
				Design for Inspectability Requirements and Guidance of HIC Components	Structure Integrity
				Design for Inspectability Requirements and Guidance of Non-HIC Components	Structure Integrity
				Layout Design Considerations to Minimise the Worker Dose	Radiological Protection
		Waste processing	Waste Processing Techniques	Optioneering Report for Operational Solid Waste Processing Techniques	Radwaste Management
			ILW Spent Resin and Filter Cartridge Management	Optimisation in Occupational Exposure of ILW Spent Resin and Filter Cartridge Management	Radiological Protection
	Radiological Protection	Guideline		Radiation Protection Guidelines	Radiological Protection
				Radiation Protection Specification on Layout Design	Radiological Protection
				Radiation Protection Design Principles of Opening	Radiological Protection
				Guidelines on Determination and Setting of Remote Drive for Valves	Radiological Protection
		Shielding		Radiation Shielding Topic Report	Radiological Protection
		Zoning		Radiation and Contamination Zoning Topic Report	Radiological Protection
		Monitoring		Radiation and Contamination Monitoring Topic Report	Radiological Protection
		Access Control		Optioneering Report of Contamination and Access Control Method	Radiological Protection
Worker Dose Evaluation	Collective Dose Evaluation	Starting point		Establishment of the Starting Point for the Collective Dose Evaluation of the UK HPR1000	Radiological Protection
		Design Improvements		Evaluation of the Impacts on Collective Dose from the Design Improvements	Radiological Protection

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Thanks!