



Nuclear Safety
(Week 8/Day 1)

Introduction to Nuclear Safety

Gulf Nuclear Energy Infrastructure Institute – 2013 Fundamentals Course

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Week 8:

- **Nuclear Safety**

Week 8 Learning Objectives:

- Understand the role of nuclear safety in a responsible nuclear energy program and how it relates to security and safety
- Recognize nuclear safety as a systems concept with basic requirements, design variables, and analysis for both technical and operations objectives
- Understand the concept of defense-in-depth (DID)
- Understand the relationship between Design Basis Accidents and reactor safety systems
- Understand Probabilistic Risk Assessment, fault trees, and event trees

Nuclear Safety (Week 8/Day 1)

Lecture #1: Introduction to Nuclear Safety

Primary Day 1 Learning Objective:

- Understand the role of nuclear safety in a responsible nuclear energy program and how it relates to security and safety

Take away from this lecture:

- Introduction to the different components of nuclear safety and how they relate to a responsible nuclear energy program

- Introduction to Nuclear Safety:
 - Safety Culture
 - Safety Enabling Tools
- Safety Culture
 - 3S Culture – Refresher
 - Nuclear Security Culture - Definitions
- Safety Enabling Tools
 - Objectives of Nuclear Safety
 - List of Safety Systems and Their Functions
 - Concept of Defense- in-Depth
 - Safety Analysis
 - Inventory and Location of Radioactive Material in the Nuclear Power Plant
 - Modeling Dispersion of Radioactivity Releases

- There are two major aspects to Nuclear Safety:
 - Safety Culture
 - Safety Enabling Tools
- Safety Culture is an integrated part of the 3S we have covered throughout the curriculum
 - Will provide the definitions of safety culture according to IAEA and other internationally recognized organizations
- Safety Enabling Tools (Technical Design - Week 11)
 - Provide an overview of the objectives of nuclear safety per IAEA's standards
 - List the reactor plant safety systems and provide an overview of their functions
 - Describe the concept of Defense- in-Depth in the design of reactor power plants
 - List the main safety analysis methods and their application
 - List the inventory and location of radioactive material in the nuclear power plant – as the source term for dispersion modeling
 - Explain the purpose for modeling the dispersion of radioactivity releases
- Safety Enabling Tool (Operational Aspects – Week 12)

*Nuclear Safety Philosophy – NRC**

- US NRC's nuclear safety goals and requirements (for nuclear reactors)

“...even in the unlikely event of a release of radioactive materials to the environment, there is reasonable assurance that actions can be taken to protect the population around nuclear power plants.”

**NRC= US Nuclear Regulatory Commission*

See: <http://www.nrc.gov/reading-rm/doc-collections/fact-sheets/emer-plan-prep.html>

Nuclear Safety

Operating conditions, prevention of accidents/mitigation of consequences, resulting in the protection of workers, the public, and the environment from undue radiological hazards.



Nuclear Safeguards

Prevention and detection, through the use of material control and accountancy, of theft or diversion of special nuclear material from civilian facilities.

Nuclear Security

Prevention and detection of, and response to sabotage, unauthorized access, or other malicious acts involving nuclear material, other radioactive substances or their associated facilities.

IAEA Defines Safety Culture as

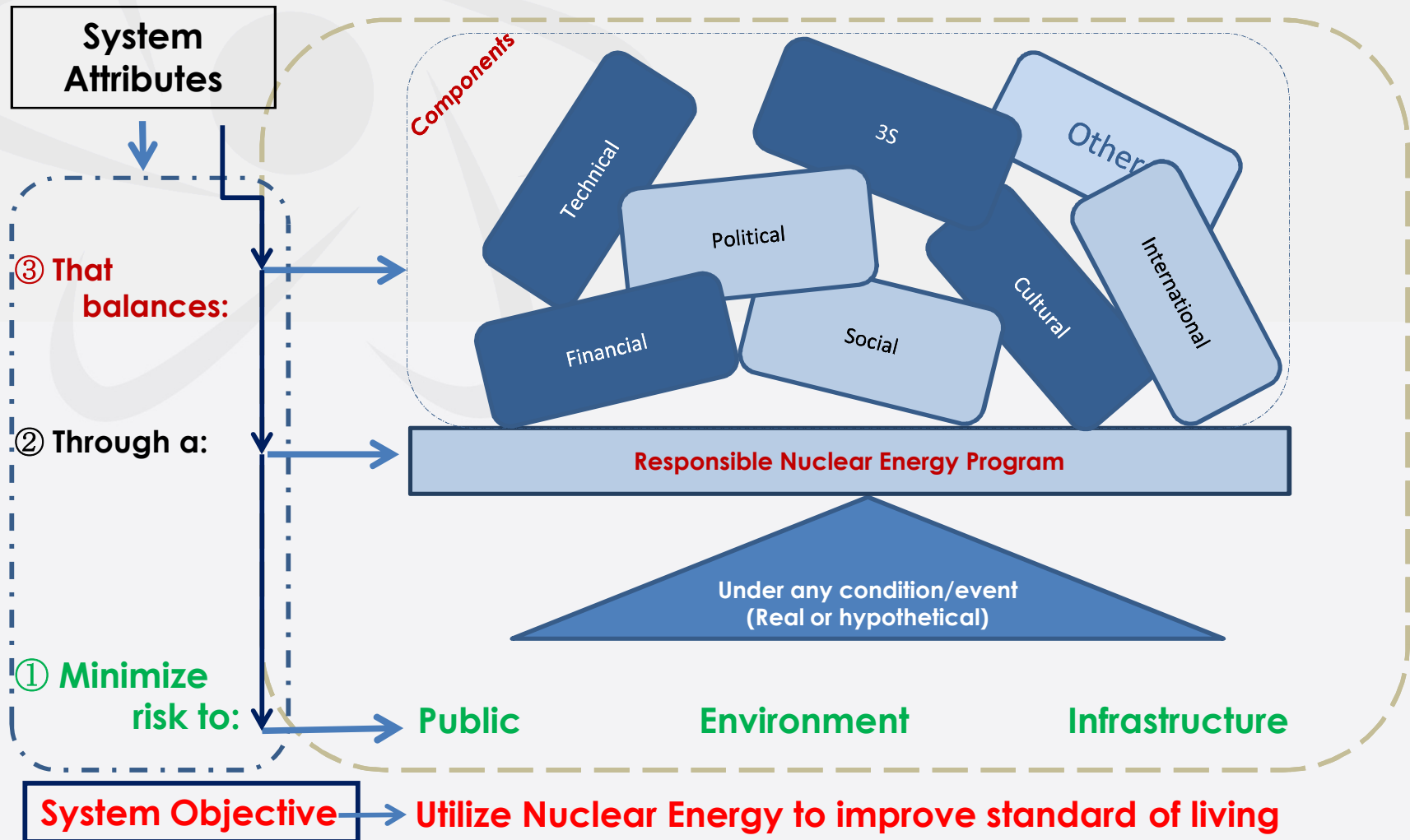
“...that assembly of characteristics and attitudes in organizations and individuals which establishes that, as an overriding priority, protection and safety issues receive the attention warranted by their significance.”

References:

1. INTERNATIONAL ATOMIC ENERGY AGENCY, *The Management System for Facilities and Activities*, IAEA Safety Standards Series No. GS-R-3, IAEA, Vienna (2006).
2. INTERNATIONAL ATOMIC ENERGY AGENCY, *Application of the Management System for Facilities and Activities*, IAEA Safety Standards Series No. GS-G-3.1, IAEA, Vienna (2006).

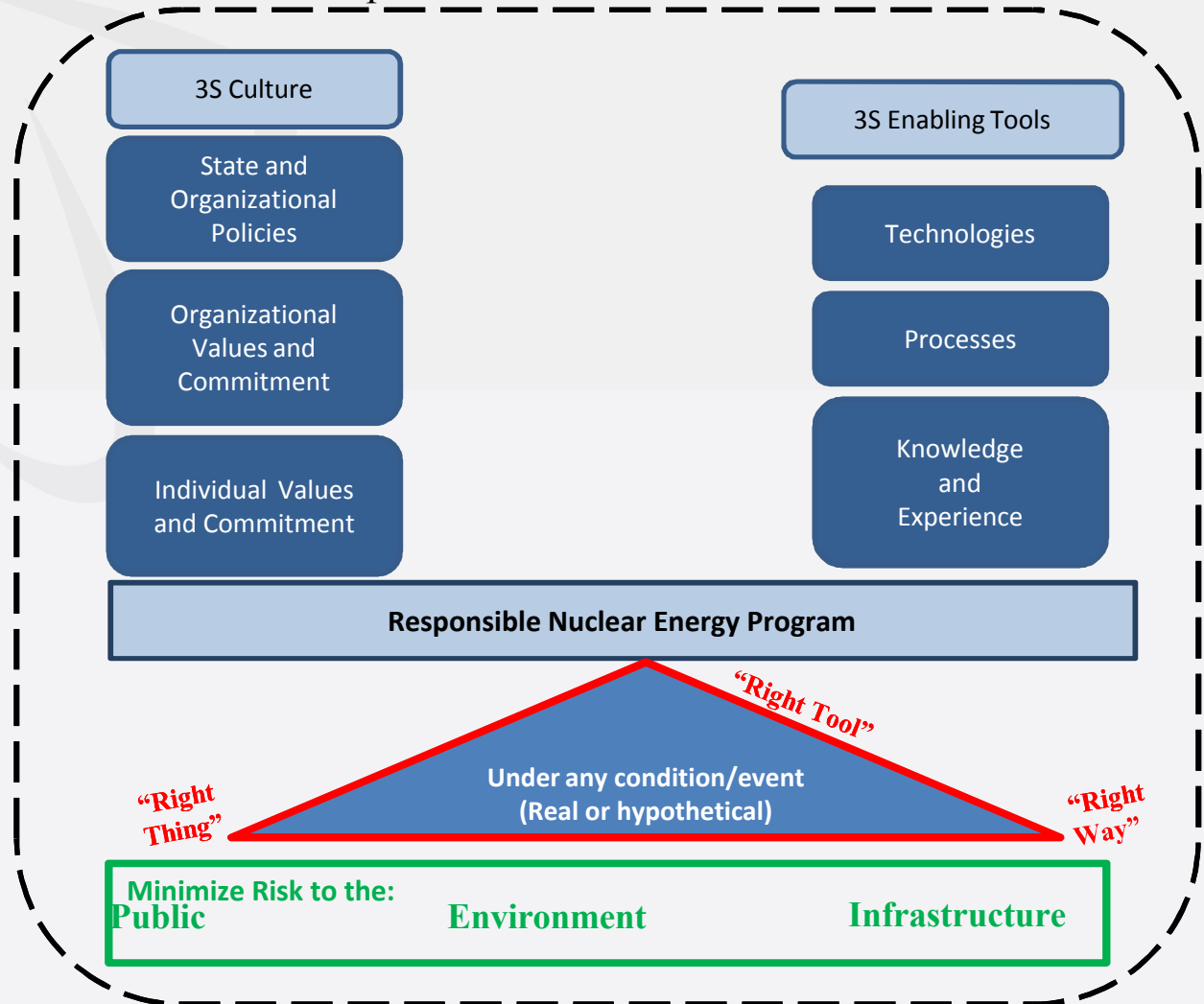
Recall our RNEP Model

SYSTEM: Responsible Nuclear Energy Program



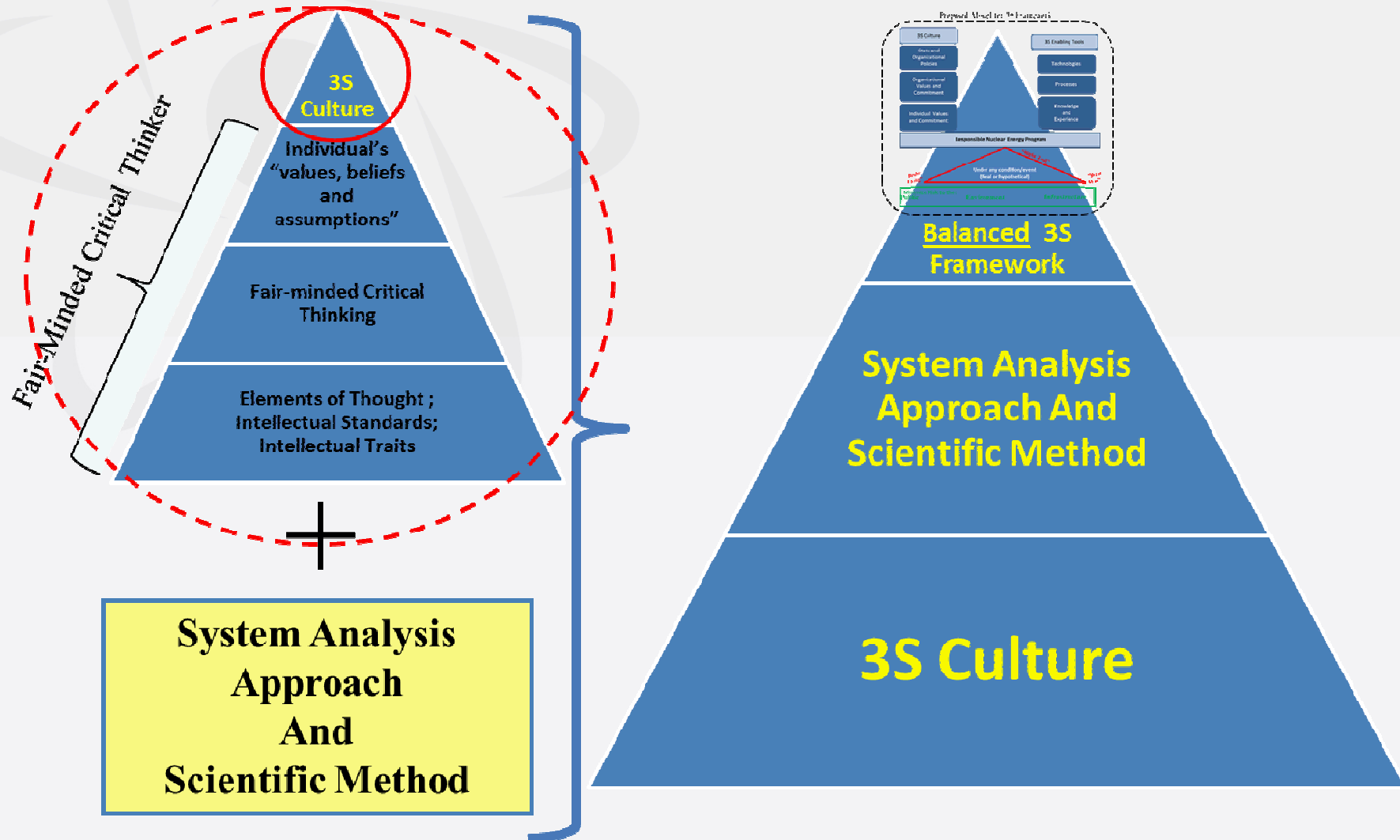
- Recall our 3S Framework Model
- Apply the model to Safety – replace “3S” with “Nuclear Safety”; so we have
 - 1) Safety Culture;
 - 2) Safety Enabling Tools
- We learn about both of these in Week 11 and Week 12 of GNEII

Proposed Model for 3S Framework



Safety Culture Per Our Model:

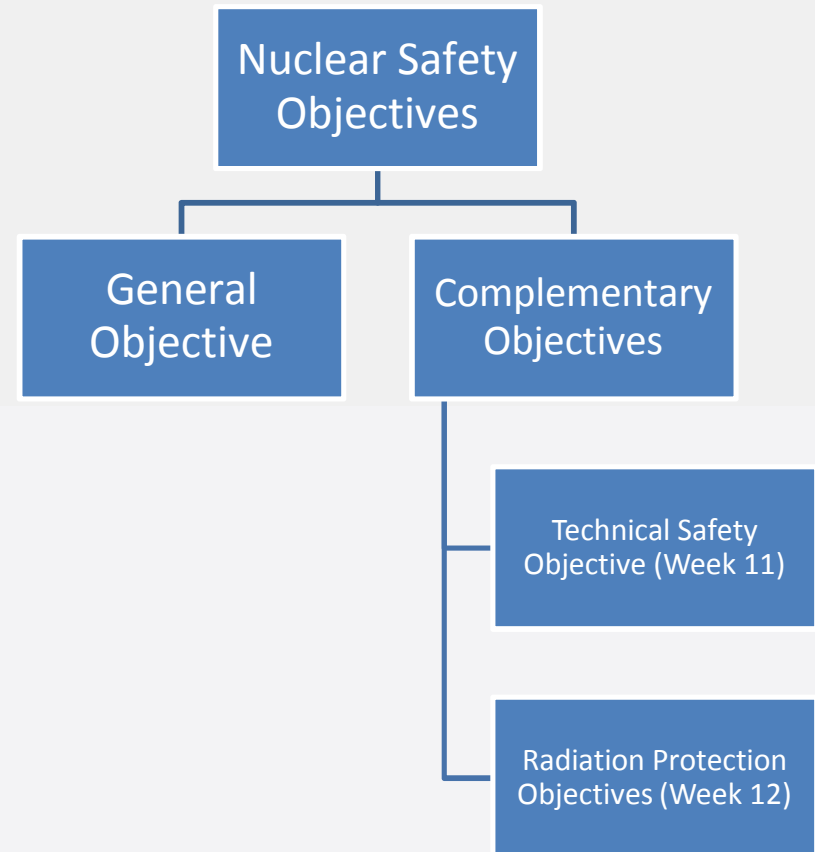
Recall our Model for Creating a Balanced Integrated 3S Framework



Safety Enabling Tools:

Objectives of Nuclear Safety

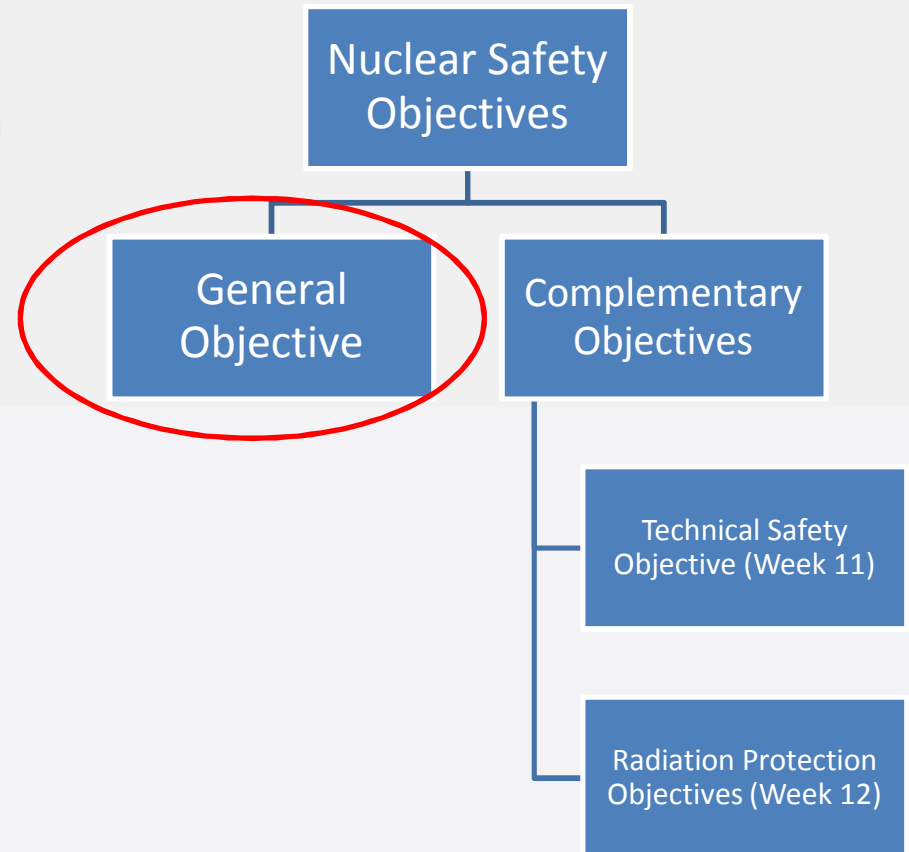
- Three safety objectives:
 - One General (in nature) Objective
 - Two Complementary Objectives; dealing with
 - Technical aspects of safety
 - Radiation protection



Safety Enabling Tools:

Objectives of Nuclear Safety

- General (in nature) Objective
 - *To protect individuals, society and the environment from harm by establishing and maintaining, in nuclear installations, effective defenses against radiological hazards.*
- *Our model for Responsible Nuclear Energy Program (RNEP) is consistent with this objective*



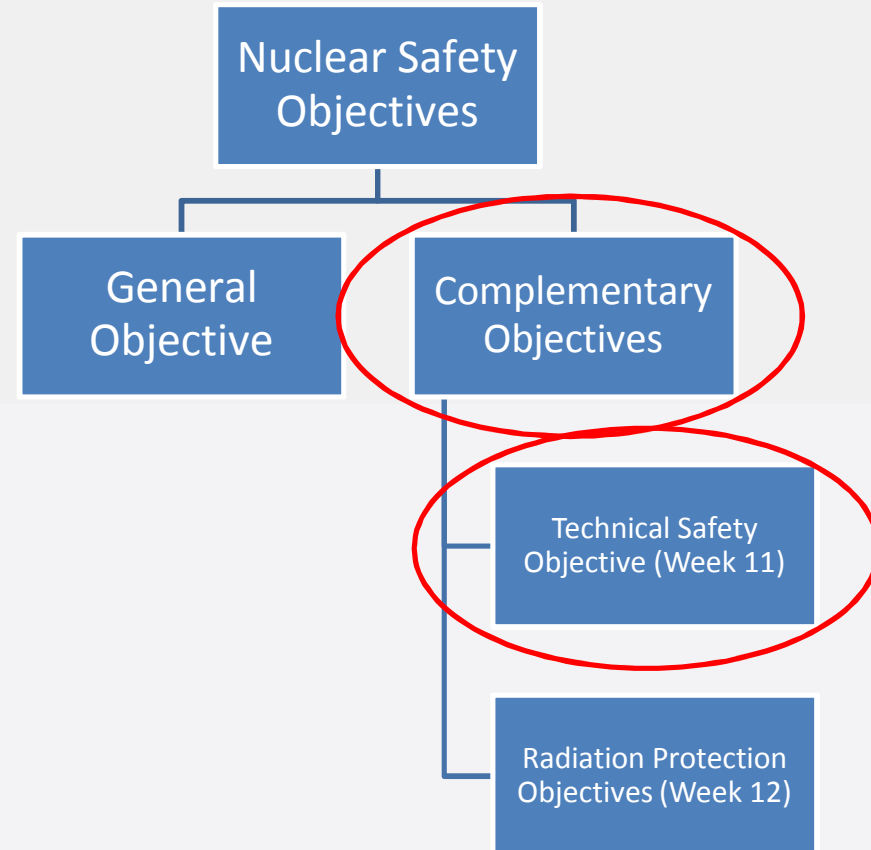
References: IAEA Safety of nuclear power plants: Design, NS-R-1, 31 October 2000.
INTERNATIONAL ATOMIC ENERGY AGENCY, The Safety of Nuclear Installations, Safety Series No. 110, IAEA, Vienna (1993).

Safety Enabling Tools:

Objectives of Nuclear Safety

Technical Safety Objective: (Week 11)

“To take all reasonably practicable measures to prevent accidents in nuclear installations and to mitigate their consequences should they occur; to ensure with a high level of confidence that, for all possible accidents taken into account in the design of the installation, including those of very low probability, any radiological consequences would be minor and below prescribed limits; and to ensure that the likelihood of accidents with serious radiological consequences is extremely low.”



References: IAEA Safety of nuclear power plants: Design, NS-R-1, 31 October 2000.
INTERNATIONAL ATOMIC ENERGY AGENCY, The Safety of Nuclear Installations, Safety Series No. 110, IAEA, Vienna (1993).

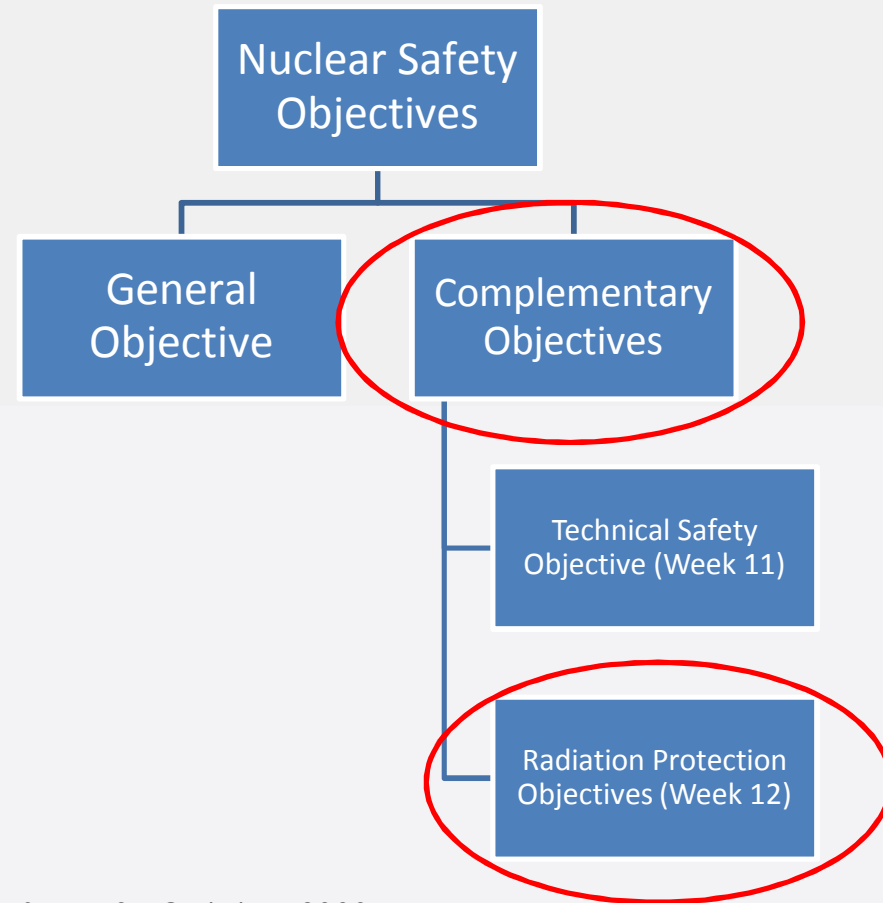
Safety Enabling Tools:

Objectives of Nuclear Safety

Radiation Protection Objective: (Week 12)

“To ensure that in all operational states radiation exposure within the installation or due to any planned release of radioactive material from the installation is kept below prescribed limits and as low as reasonably achievable, and to ensure mitigation of the radiological consequences of any accidents.”

- *Must Protect:*
 - Workers (Personnel)
 - Environment
 - Public



References: IAEA Safety of nuclear power plants: Design, NS-R-1, 31 October 2000.
INTERNATIONAL ATOMIC ENERGY AGENCY, The Safety of Nuclear Installations, Safety Series No. 110, IAEA, Vienna (1993).

Safety Enabling Tools:

Safety Systems and Their Functions



- Included in the design, construction, and operation of the nuclear power plant (NPP)
- Can be a part of requirements both for operation of the reactor AND also for meeting the safety objectives – all three objectives
- Have Three main objectives:
 - Quick Shutdown of Chain Reaction (Reactor) – Control Rods; Insertion of Neutron “poison”
 - Emergency cooling of the reactor after shutdown – Remove the “decay” heat; Emergency Core Cooling Systems (ECCS - Both Passive and Active)
 - Containment of radioactive products after their accidental release from the reactor – Combination of special buildings and engineered systems (“double containment,” Isolation valves; negative pressure between “primary containment” and “secondary containment”; cooling and water spray systems;..)
- Designed to cope with a set of accidental events (design basis accidents or DBA)

Safety Enabling Tools:

Concept of Defense- in-Depth (DID) in Nuclear Safety



- DID concept in nuclear safety consists of providing multiple independent protections against the occurrence of accidents and their progression, in such a way that, should one of them fail, at least another is present whose failure is independent from the operation of the first.
- “Independence” of barriers is only an objective
 - Not always possible in reality in every conceivable accident sequence.

Reference: Nuclear Safety by Gianni Petrangeli, First Edition 2006; Required textbook for Weeks 11 and 12.
IAEA TECDOC Implementation of Defence (Defense) in Depth for next generation light water reactors, No. 986, 21 November 1997.

IAEA TECDOC Defence in Depth in nuclear safety, No. 10, 26 September 1996.

IAEA INSAG Basic safety principles for nuclear power plants, 75-INSAG-3 Rev. 1, No. 12, 7 December 1999.

Safety Enabling Tools:

Concept of Defense- in-Depth (DID) in Nuclear Safety

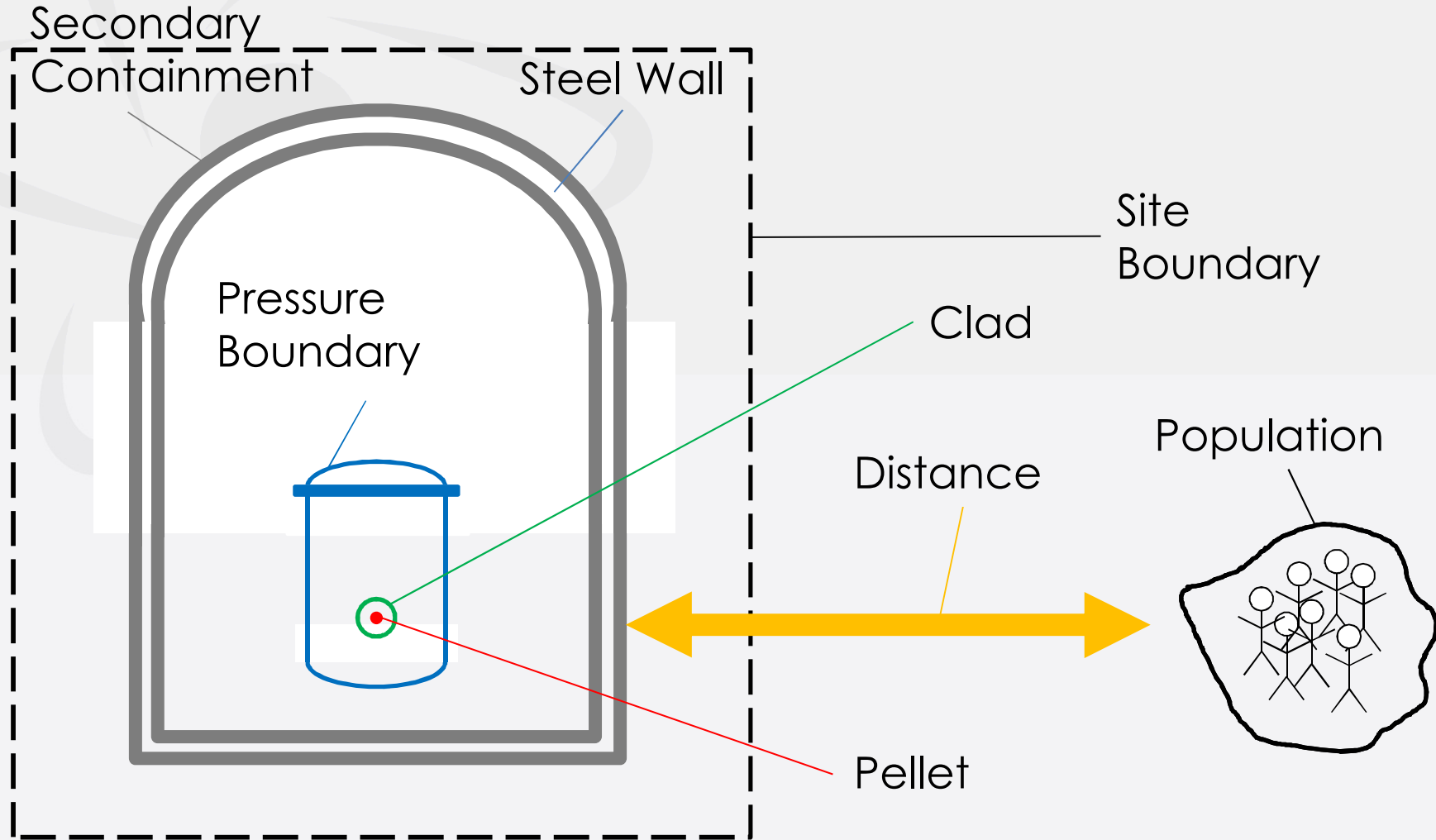


- DID is to be understood as a general defense principle,
 - Implemented to the maximum technically feasible degree
 - Provide a ‘graded’ protection against a vast variety of transients, abnormal events and accidents, including the malfunction of components, human errors in the plant and events initiated outside it.
- Per most recent IAEA document*, the DID is based on four principal barriers against the external release of radioactive products (fuel matrix, fuel cladding, reactor cooling circuit pressure boundary, and containment system), and on five defense levels in order to best use these barriers.

* IAEA TECDOC Implementation of Defence (Defense) in Depth for next generation light water reactors, No. 986, 21 November 1997.

Safety Enabling Tools:

Concept of Defense-in-Depth (DID) in Nuclear Safety



Safety Enabling Tools:

Concept of Defense- in-Depth (DID) in Nuclear Safety



- Per most recent IAEA document*, the DID is based on five defense levels in order to best use the barriers.

Defense level	Objective	Essential means
Level 1	Prevention of abnormal operation and of malfunctions.	Conservative design and high quality of construction and of operation.
Level 2	Control of abnormal operation and detection of malfunctions.	Control, limitation and protection systems and other surveillance characteristics.
Level 3	Control of accidents included in the design basis.	Engineered safety systems and accident procedures.
Level 4	Control of the severe accident conditions of the plant, including the prevention of accident progression and mitigation of consequences.	Additional measures and accident management.
Level 5	Mitigation of the radiological consequences of significant releases of radioactive products.	External site emergency plan.

Nuclear Safety; By Gianni Petrangeli, Copyright Gianni Petrangeli © 2006, Publisher: Elsevier Science and Technology Books, Inc. (The required textbook for this Module of GNEII.)

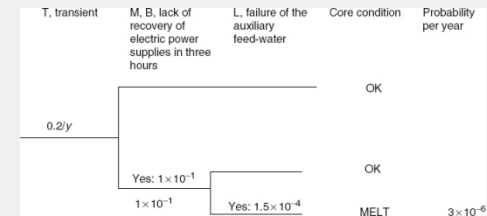
* IAEA TECDOC Implementation of Defence (Defense) in Depth for next generation light water reactors, No. 986, 21 November 1997.

Safety Enabling Tools:

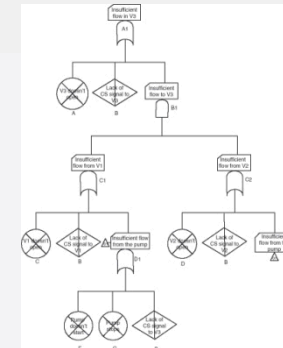
Safety Analysis (Objective, Deterministic, Probabilistic, Event Trees, and Fault Trees)

- Objective of Safety Analysis:

- Help define and to confirm, through adequate analysis tools, the safety basis for the parts of the plant which are important for safety
- To ensure that the general design of the plant is capable of complying with the dose limits in force and with the radioactive releases specified for any plant conditions



Event Tree



Fault Tree

IAEA Safety Assessment and verification for Nuclear Power Plants, NS-G-1.2, 28 January 2002. Nuclear Safety; By Gianni Petrangeli, Copyright Gianni Petrangeli © 2006, Publisher: Elsevier Science and Technology Books, Inc. (The required textbook for this Module of GNEII.)

Safety Enabling Tools:

Safety Analysis (Objective, Deterministic, Probabilistic, Event Trees, and Fault Trees)



- Safety Analysis Used in Licensing:
 - Should proceed in parallel with the design – to continue to comply with dose limits and with the radioactive releases
 - Must be kept up to date during the life of the plant in order to account for the progress of knowledge and in case of plant or site modifications

IAEA Safety Assessment and verification for Nuclear Power Plants, NS-G-1.2, 28 January 2002. Nuclear Safety; By Gianni Petrangeli, Copyright Gianni Petrangeli © 2006, Publisher: Elsevier Science and Technology Books, Inc. (The required textbook for this Module of GNEII.)

Safety Enabling Tools:

Safety Analysis (Objective, Deterministic, Probabilistic, Event Trees, and Fault Trees)



- Deterministic Safety Analysis Approach:
 - Studies the behavior of the plant in operational states and under specific accident conditions or for compliance with the chosen criteria.
 - Usually use conservative assumptions on input data, intermediate parameters for the analyses and on the behavior of plant systems (single failure, etc.).
 - Severe accidents are also part of the deterministic analyses;
 - However, because of their very low probability, the conservative assumptions used for DBAs are not used for severe accident analysis. A 'best estimate' treatment of the phenomena is preferred in such cases.

IAEA Safety Assessment and verification for Nuclear Power Plants, NS-G-1.2, 28 January 2002. Nuclear Safety; By Gianni Petrangeli, Copyright Gianni Petrangeli © 2006, Publisher: Elsevier Science and Technology Books, Inc. (The required textbook for this Module of GNEII.)

Safety Enabling Tools:

Safety Analysis (Objective, Deterministic, Probabilistic, Event Trees, and Fault Trees)



- Probabilistic Safety Analysis (PSA):
 - Has become common practice for new plants and for existing ones
 - International requirements include that safety analysis reports include a summary of the PSA study of the plant
 - Is a complete and well-structured method for identifying accident scenarios and to obtain numerical risk estimates.
 - Its use to demonstrate the compliance with numerical safety criteria is not advisable because of the uncertainties in methods, in data and, therefore, in their results – there is still a debate.

IAEA Safety Assessment and verification for Nuclear Power Plants, NS-G-1.2, 28 January 2002. Nuclear Safety; By Gianni Petrangeli, Copyright Gianni Petrangeli © 2006, Publisher: Elsevier Science and Technology Books, Inc. (The required textbook for this Module of GNEII.)

Safety Enabling Tools:

Safety Analysis (Objective, Deterministic, Probabilistic, Event Trees, and Fault Trees)



- Probabilistic Safety Analysis (PSA):
 - Positive aspects of PSA:
 - It forces the analyst to examine the complete set of possible sequences of events which may happen on a plant, without excluding any of them before-hand (as is done in the deterministic method);
 - It affords a general vision of the plant from the safety point of view, highlighting specific weak points and, therefore, in particular during the design phase, allowing a well-balanced plant to be conceived;
 - The method gives an idea of the global risk and is useful for comparative considerations between different plants and, therefore, it contributes to the creation of an homogeneous reactor overview from the point of view of risk.

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Safety Enabling Tools:

Safety Analysis (Objective, Deterministic, Probabilistic, Event Trees, and Fault Trees)



- Probabilistic Safety Analysis (PSA):
 - Commonly PSA detects weak points of the plant where the normal design process had not been able to reveal weaknesses. This, in particular, happens for support systems of primary safety systems, for example the space cooling systems for rooms where the safety injection pumps are located
 - Probabilistic analyses are applicable to Levels 1, 2 or 3 (IAEA, 1992, 1995, 1996), because they examine the events up to core damage, up to the evaluation of radioactivity releases from the plant, or up to the external radiological consequences
 - The present trend for the support of plant safety decisions, including those concerning operation, involves both safety analyses: the deterministic and the probabilistic.

IAEA Safety Assessment and verification for Nuclear Power Plants, NS-G-1.2, 28 January 2002. Nuclear Safety; By Gianni Petrangeli, Copyright Gianni Petrangeli © 2006, Publisher: Elsevier Science and Technology Books, Inc. (The required textbook for this Module of GNEII.)

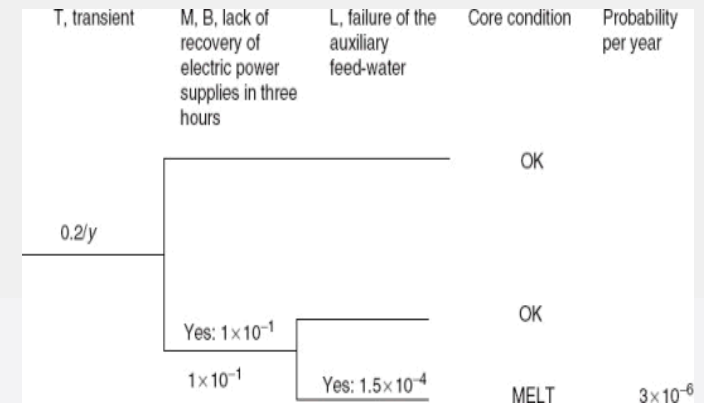
Safety Enabling Tools:

Safety Analysis (Objective, Deterministic, Probabilistic, Event Trees, and Fault Trees)



- **Event Tree:**

- Are branched graphs which, starting from the initiating event considered, show (in their most common use) the various possible sequences of plant situations (with corresponding estimated probability) consequent to the good operation or malfunction of safety systems designed to stop the accident or to mitigate its consequences.
- Gives the picture of the various final plant situations, each one with the pertinent overall probability.



Event Tree

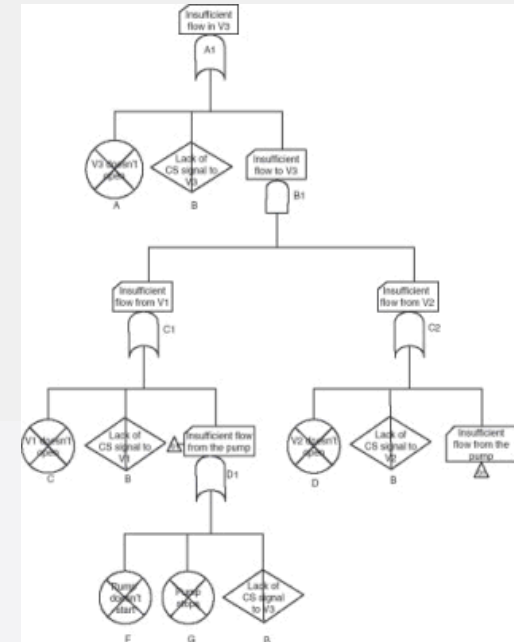
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Safety Enabling Tools:

Safety Analysis (Objective, Deterministic, Probabilistic, Event Trees, and Fault Trees)

- **Fault Tree:**

- Unlike the event trees, proceed backward from the final event (i.e. the fault of the component or system) to the various causes which may have originated it, with the corresponding probabilities.
- Generally use Boolean algebra (the algebra of binary systems: 1s and 0s) - leads to the maximum simplification of the fault tree.
- More on PSA in later lectures.



Fault Tree

IAEA Safety Assessment and verification for Nuclear Power Plants, NS-G-1.2, 28 January 2002. Nuclear Safety; By Gianni Petrangeli, Copyright Gianni Petrangeli © 2006, Publisher: Elsevier Science and Technology Books, Inc. (The required textbook for this Module of GNEII.)

Safety Enabling Tools:

Inventory and Location of Radioactive Material in the Nuclear Power Plant



- Location of Radioactive Material:
 - Almost all are contained in fuel located in:
 - The reactor itself
 - In used fuel which is still stored at the plant
 - In the spent fuel pool
 - Less frequently, in dry containers for temporary storage

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Safety Enabling Tools:

Inventory and Location of Radioactive Material in the Nuclear Power Plant



Partial List of Radionuclide inventory in a 1000 MWe PWR in equilibrium conditions (for certain operation time and condition)

Nuclide	Half-life (days)	Radioactivity	
		(Bq × 10 ¹⁸)	(MCi)
⁸⁵ Kr	3950	2.072	56
^{85m} Kr	0.183	0.888	24
⁸⁷ Kr	0.0528	1.739	47
⁸⁸ Kr	0.117	2.516	68
¹³³ Xe	5.28	6.29	170
¹³⁵ Xe	0.384	1.258	34
¹³¹ I	8.05	3.145	85
¹³² I	0.0958	4.44	120
¹³³ I	0.875	6.29	170
¹³⁴ I	0.0366	7.03	190
¹³⁵ I	0.28	5.55	150
¹³⁴ Cs	750	0.2775	7.5
¹³⁶ Cs	13	0.111	3
¹³⁷ Cs	11 000	0.1739	4.7

Nuclide	Half-life (days)	Radioactivity	
		(Bq × 10 ¹⁸)	(MCi)
⁸⁶ Rb	18.7	0.00096	0.026
¹²⁷ Te	0.391	0.2183	5.9
^{127m} Te	109	0.0407	1.1
¹²⁹ Te	0.048	1.147	31
^{129m} Te	0.34	0.1961	5.3
^{131m} Te	1.25	0.481	13
¹³² Te	3.25	4.44	120
¹²⁷ Sb	3.88	0.2257	6.1
¹²⁹ Sb	0.179	1.221	33
⁸⁹ Sr	52.1	3.478	94
⁹⁰ Sr	11 030	0.1369	3.7
⁹¹ Sr	0.403	4.07	110
¹⁴⁰ Ba	12.8	5.92	160

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Safety Enabling Tools:

Inventory and Location of Radioactive Material in the Nuclear Power Plant



Partial List of Radionuclide inventory in a 1000 MWe PWR in equilibrium conditions (for certain operation time and condition)

Nuclide	Half-life (days)	Radioactivity	
		(Bq × 10 ¹⁸)	(MCi)
⁵⁸ Co	71	0.02886	0.78
⁶⁰ Co	1920	0.01073	0.29
⁹⁹ Mo	2.8	5.92	160
^{99m} Tc	0.25	5.18	140
¹⁰³ Ru	39.5	4.07	110
¹⁰⁵ Ru	0.185	2.664	72
¹⁰⁶ Ru	366	0.925	25
¹⁰⁵ Ru	1.5	1.813	49
⁹⁰ Y	2.67	0.1443	3.9
⁹¹ Y	59	4.44	120
⁹⁵ Zr	65.2	5.55	150
⁹⁷ Zr	0.71	5.55	150
⁹⁵ Nb	35	5.55	150
¹⁴⁰ La	1.67	5.92	160

Nuclide	Half-life (days)	Radioactivity	
		(Bq × 10 ¹⁸)	(MCi)
¹⁴¹ Ce	32.3	5.55	150
¹⁴³ Ce	1.38	4.81	130
¹⁴⁴ Ce	284	3.145	85
¹⁴³ Pr	13.7	4.81	130
¹⁴⁷ Nd	11.1	2.22	60
²³⁹ Np	2.35	60.68	1640
32	500	0.002109	0.057
²³⁹ Pu	8.9 × 10 ⁶	0.000777	0.021
²⁴⁰ Pu	2.4 × 10 ⁶	0.000777	0.021
²⁴¹ Pu	5350	0.1258	3.4
²⁴¹ Am	1.5 × 10 ⁵	0.0000629	0.0017
TOTAL		Total activity (EBq) 193	Total activity (MCi) 5202

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Safety Enabling Tools:

Modeling Dispersion of Radioactivity Releases



- Objectives Dispersion Modeling:
- Three steps in the evaluation of the consequences of accidents:
 - Evaluation of the releases (the 'source term; amount, chemical–physical form, trend with time).
 - Evaluation of the dispersion of releases in the environment.
 - Evaluation of the health consequences.

Safety Enabling Tools:

Modeling Dispersion of Radioactivity Releases



- Objectives Dispersion Modeling
 - Gaseous releases
 - Most relevant for the evaluation of the immediate accident consequences
 - For the preparation of short-term emergency plans
 - Solid and liquid releases
 - Less of concern for off-site environmental impact
 - Important for on-site impact (workers and structure contamination)
 - Hence, Dispersion Modeling focuses on Gaseous Releases

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Safety Enabling Tools:

Modeling Dispersion of Radioactivity Releases



- Dispersion Modeling:
 - Dispersion of a light cloud in the environment occurs by diffusion, generally in a turbulent regime
 - Dispersion of a heavy cloud occurs firstly by fall and by gravitational spread
 - At a certain distance from the source, the heavy cloud is also dispersed by diffusion
 - Two parameters have an overwhelming influence on the atmospheric dispersion:
 - The wind speed;
 - The vertical thermal gradient (i.e. the change of the temperature with height).

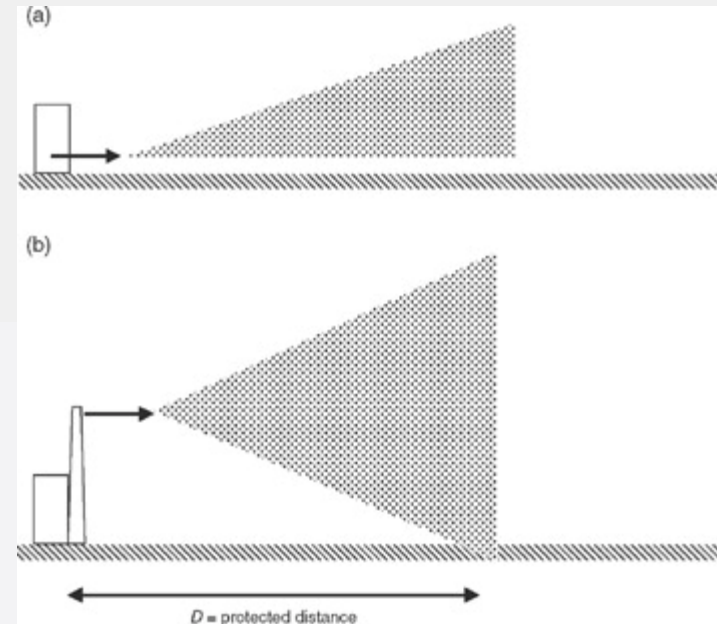
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Safety Enabling Tools:

Modeling Dispersion of Radioactivity Releases

- Dispersion Modeling:
 - Gaussian theory of diffusion is most commonly used
 - A function of:
 - Wind speed
 - Standard deviation of the Gaussian distribution
 - Height of release
 - Position of a point in space with reference to the release point
- Will be covered in details later

Diffusion plume for (a) ground and (b) elevated release from a chimney



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Safety Enabling Tools:

Design Basis Accident (DBA)



- DBAs are those accidents chosen by the deterministic method or with the help of probabilistic considerations
- Some of the following considerations are of interest for DBAs
- Some Important Data for Accident Analysis
 - Initial conditions
 - Doppler coefficient
 - Coefficient of moderator temperature and of the voids
 - Reactivity of the boron content (content of boron in the cooling water)
 - Reactivity of the control rods
 - Reactivity of fission products (xenon and samarium)

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Safety Enabling Tools:

Design Basis Accident



- Additional considerations include:
 - Spurious opening of a pressurizer safety valve
 - Instantaneous power loss to all the primary pumps
 - Main steam line break
 - Sudden expulsion of a control rod from the core
 - Break of the largest pipe of the primary system (large Loss of Cooling Accident (LOCA))
 - Fuel handling accident
 - Area accidents

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Safety Enabling Tools:

Beyond Design Basis Accident



- BDBAs are neither DBAs nor Severe accidents
- They have a low probability of occurrence
- Their margins of safety are rather smaller than those adopted for DBAs
- They are dealt with using specific prevention and mitigation measures
- Important examples are:
 - Transients without scram (ATWS – anticipated transients without scram); and
 - Total loss of external and internal electric power supplies (station blackout).

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Safety Enabling Tools:

Site Safety Plan



- A Final Note:

As we study the Nuclear Safety during Weeks 11 and 12, we should think about the need for a Site Safety Plan – that would include the plan for the site 3S integrated plan into other site safety program.

- Nuclear Safety by Gianni Petrangeli, First Edition 2006; Required textbook for Weeks 11 and 12.
- INTERNATIONAL ATOMIC ENERGY AGENCY, The Management System for Facilities and Activities, IAEA Safety Standards Series No. GS-R-3, IAEA, Vienna (2006).
- INTERNATIONAL ATOMIC ENERGY AGENCY, Application of the Management System for Facilities and Activities, IAEA Safety Standards Series No. GS-G-3.1, IAEA, Vienna (2006).
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- IAEA INSAG Basic safety principles for nuclear power plants, 75-INSAG-3 Rev. 1, No. 12, 7 December 1999.

- What are the objectives of Nuclear Safety?
- What are two major aspects of Nuclear Safety?
- Based on the 3S Framework presented in the GNEII curriculum, list the elements of Safety Culture.
- Based on the 3S Framework presented in the GNEII curriculum, list the elements of Safety Enabling Tools.
- What are the definitions of safety culture according to IAEA guidelines?
- List the reactor plant safety systems and provide an overview of their functions.
- Describe the concept of Defense-in-Depth in the design of reactor power plants.

- List the main safety analysis methods and their application.
- List the inventory and location of radioactive material in the nuclear power plant – as the source term for dispersion modeling.
- Explain the purpose for modeling the dispersion of radioactivity releases.
- List the most important parameters that impact the dispersion of gaseous releases.
- How are DBAs chosen?
- What are (provide a list) some the important data needed for accident analysis?
- What are the Beyond Design Basis Accidents (BDBAs)? How are they different from the DBAs or Severe accidents?
- Give two examples of BDBAs.