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Introduction to Level 2 PSA

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Accident sequences modelled by the PSA

- INITIATING EVENTS
- ↓ SAFETY SYSTEM FAILURE
- ↓ CORE DAMAGE → **LEVEL 1 PSA** — Core damage frequency
- ↓ SEVERE ACCIDENT PROGRESSION
- ↓ CHALLENGE TO CONTAINMENT
- ↓ RELEASE OF RADIOACTIVITY → **LEVEL 2 PSA** — Large (early) release frequency
- ↓ DISPERSION IN THE ENVIRONMENT
- ↓ HEALTH/ FINANCIAL CONSEQUENCES → **LEVEL 3 PSA** — Societal risk

Levels of PSA

Level-1 PSA
- Starts with an initiating event/ internal hazard/ external hazard
- Models the safety systems failures and operator errors that lead to core damage
- Calculates core damage frequency
- Identifies strengths/ weaknesses of safety systems/ emergency procedures

INTERFACE – Plant Damage States (PDSs)

Level-2 PSA
- Starts with the PDSs
- Models phenomena that occur following core damage, challenges to the containment, transport of radioactive material in the containment
- Calculates the frequency/ magnitude of a release of radioactive material
- Identifies strengths/ weaknesses of severe accident mitigation measure/ guidelines

INTERFACE – Release Categories/ Source Term Categories

Level-3 PSA
- Starts with the release categories/ source term categories
- Models the consequences of a release of radioactivity to the environment
- Calculates public health risks and societal risks
- Identified strengths/ weaknesses of off-site emergency plan

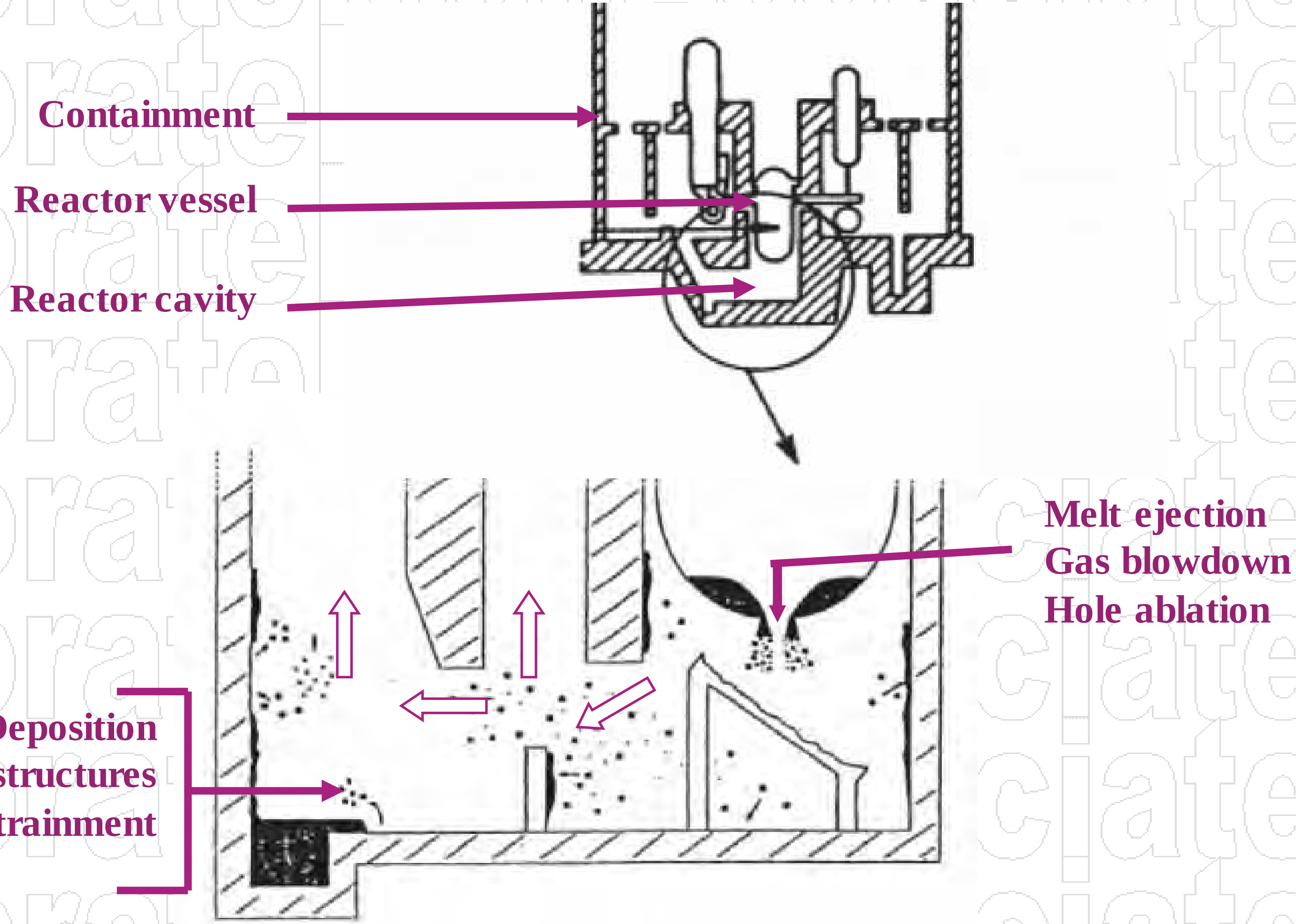
Aims of Level 2 PSA

- Determine how severe accidents progress/ phenomena that could occur
- Identify plant vulnerabilities following severe accidents
- Determine how severe accidents challenge the containment
- Identify major containment failure mechanisms
- Estimate the quantities of radioactive material released to the environment
- Determine the overall large (early) release frequency – LRF/ LERF
- Evaluate the impacts of uncertainties
- Provide a basis for development of Severe Accident Management Guidelines (SAMG)
- Identification od severe accident analysis required to support Level 2 PSA
- Identification/ prioritisation of research activities
- Provide an input into the Level 3 PSA/ development of off-site emergency plans

Severe accident phenomena

- Severe accident phenomena that could occur for a light water reactor:
  - Fuel melting/ relocation
  - Molten fuel-coolant interaction/ steam explosion
  - Hydrogen generation/ combustion
  - High pressure melt ejection/ direct containment heating
  - Molten core-concrete interaction/ basemat melt through
- Plant walk-down to identify features that influence severe accident progression
  - Basement of the containment for spreading/ cooling of molten core material
  - Connection between volumes of the containment for hydrogen mixing
  - Routes from the base of the reactor pressure vessel to the containment atmosphere for high pressure melt ejection/ direct containment heating
- Inputs to the Level 2 PSA
  - Accident sequence leading to core damage from the Level 1 PSA
  - Plant/ systems that can be used to mitigate a severe accident
  - Features of the plant that influence severe accident progression
  - Severe accident analysis
  - Severe Accident Management Guidelines (SAMG)
- Research activities carried out over many years to understand severe accident phenomena/ provide data

High pressure melt ejection



Level 2 PSA methodology

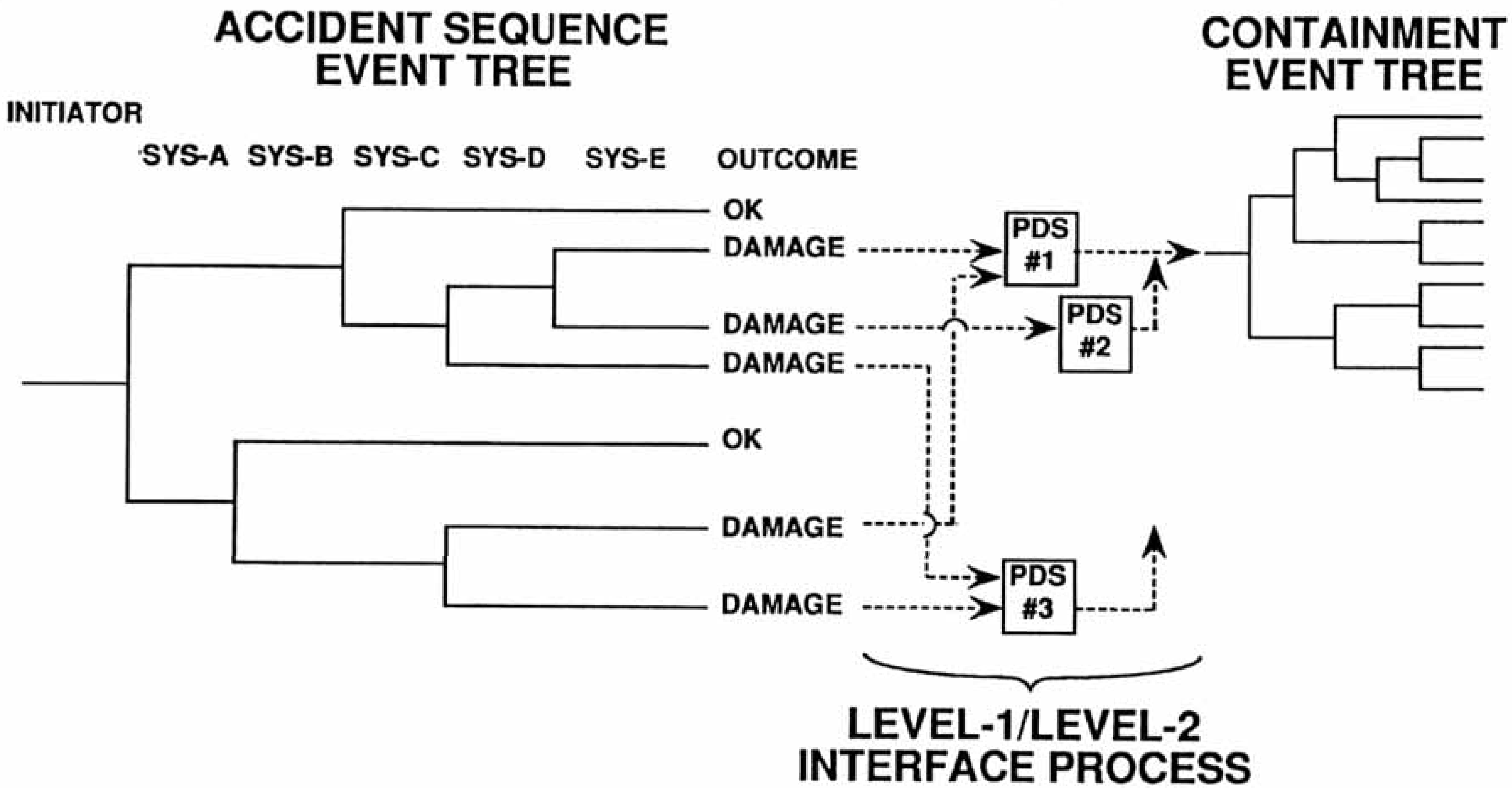
Input from the Level 1 PSA – core damage cut-sets

Plant Damage States	Grouping of core damage cut-sets into PDSs
Plant familiarisation for Level 2 PSA	Plant features that influence severe accident progression
Severe accident modelling	Phenomena/ Containment Event Tree (CET) analysis
Containment performance analysis	Response of containment to severe accidents
Source term analysis	Fission product transport/ release
Quantification	CET probabilities/ quantification
Results	Large (early) release frequency, importance functions
Sensitivities, uncertainties	Sources of uncertainty
Use of the results	Identifications of severe accident vulnerabilities

Plant Damage States

- Core damage sequences/ cut sets from the Level 1 PSA are grouped into Plant Damage States (PDSs)
- PDSs have similar characteristics with respect to:
  - Accident progression/ phenomena that could occur
  - Challenges to the containment
  - Fission product transport in the containment
  - Fission product release routes to the environment
- PDSs form the starting point for the Containment Event Trees (CETs)
- Typical number of PDSs - 10 to 50 based on 10 characteristics
- Additional PDSs may be required for:
  - Low power, shutdown, refuelling states
  - External hazards
  - Other sources of reactivity such as stored fuel

Plant Damage States



Definition of the PDSs

- PDSs are the starting point for the modelling of severe accident progression
- Identify the characteristics of the sequence leading to core damage that influence the way that the severe accident would develop/ challenge the reactor pressure vessel/ lead to a release of radioactive material to the environment
- PDSs usually defined by defining a set of attributes:
  - Type of IE that has occurred - intact circuit, LOCA, …
  - Primary system pressure – high, low
  - Status of the safety systems – decay heat removal, LOCA systems, electrical power, …
  - Status of the containment - intact, isolation failure, SG tube rupture, bypassed, …
  - Status of the containment systems – spray, cooling, H_2 control, filtered vent, …
- All possible PDSs condensed/ grouped into a manageable number

Modelling of PDS characteristics

- Modelled in Level 1 PSA
  - RCS conditions – coolant inventory, pressure
  - Core decay heat removal systems operation
  - Containment systems for design basis accident duty
- Not modelled in Level 1 PSA/ need to be added
  - Severe accident management systems (isolation, fan coolers, sprays)
  - Partial successes of safety systems
  - Non-safety systems - fire spray system
  - Accident management measures (e.g. restoration of safety systems)
- Partial successes
  - ECCS success criterion could be operation of 2o.o.4 trains of HHSI
  - Core damage would occur if 0 or 1 train operates
  - Severe accident progression would be different if 1 train operates from where no trains operate

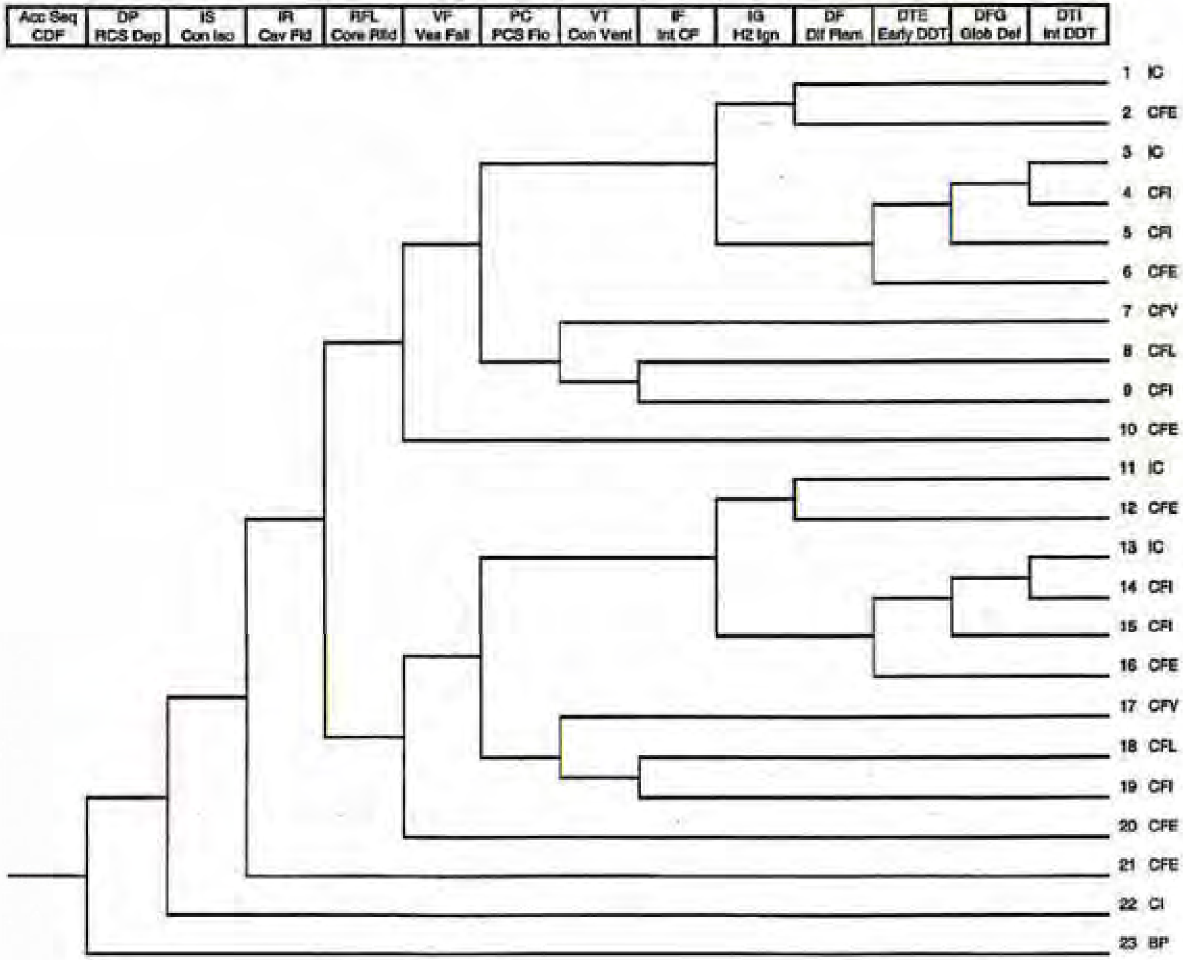
Severe accident progression

- Logical model developed of how severe accidents progress
- Model all the physical/ chemical processes that could occur and the operator actions to mitigate the consequences of the severe accident
- Usually based on event trees
  - Containment Event Trees (CETs) – relatively small number of nodes
  - Accident Progression Event Trees (APETs) – relatively large number of nodes
- Reflect the phases of severe accident progression
  - In-vessel processes following onset of core damage
  - Challenges to the reactor pressure vessel
  - Ex-vessel processes immediately after vessel breach
  - Long term processes in the containment

Containment/ accident progression event trees

- Two approaches
  - Small CET - 10 to 30 nodes (referred to as CETs)
  - Large CET - 50 to 120 nodes (referred to as APETs)
- CET/ APET nodes
  - Occurrence of phenomena
    - Does hydrogen combustion occur in this time frame?
  - Operation of severe accident mitigation failure
    - Does the containment spray operate?
  - Containment response
    - Does containment failure occur in this time frame?
  - Multiple branching
    - Different modes of containment failure
    - Containment intact, small/ enhanced leakage, gross failure
- Need to take account of inter-dependencies in severe accident phenomena

Containment event trees



Analysis required to support the Level 2 PSA

- **Core and debris behaviour**
  - **Core melting, exit from pressure vessel, inside containment**
- **Thermal-hydraulic analysis**
  - **Pressure/ temperature conditions inside the containment**
- **Radiological analysis**
  - **Release of fission products from fuel**
  - **Transport through the containment, deposition, re-suspension**
  - **Release to the environment**
- **Containment performance**
  - **Failure of containment due to loads imposed on it by the severe accident phenomena**
  - **Fragility as a function of pressure/ temperature**
- **Severe accident analysis codes**
  - **integral codes - MAAP (Modular Accident Analysis Programme), MELCOR, THALES, ASTEC**
  - **single effects codes**

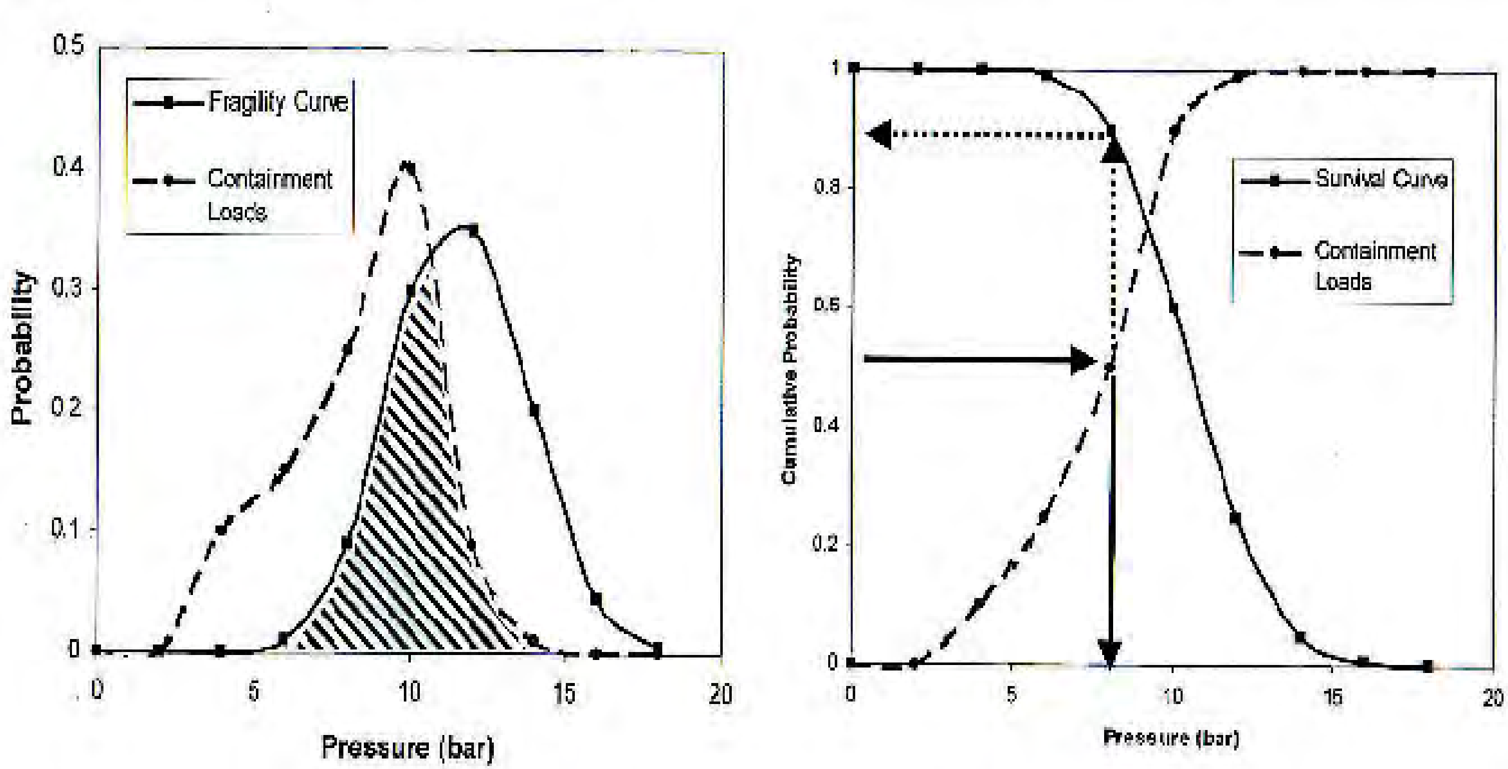
Containment failure modes

- Failure modes modelled in the Level 1 PSA
  - Failure of containment isolation
  - Direct containment bypass - SG tube rupture, interfacing systems LOCA, …
- Failure modes due to the severe accident
  - Rapid overpressurisation - steam explosion/ Hydrogen combustion/ direct containment heating
  - Missiles
  - Slow overpressurisation - build up of heat/ incondensable gases
  - Effects of molten core - penetration/ liner failure/ base-mat melt through

Containment performance analysis

- Structural analysis carried out for the containment
  - Plant specific analysis
  - Identify realistic failure criteria, failure locations, leak areas
  - Non-linear finite element analysis
- Derive best estimate failure criteria
  - To replace the conservative design criteria/ threshold model used in deterministic analysis
  - Failure of doors, seals, penetrations, liner tear, …
  - Leak before break is more likely failure mode
  - Determine the conditional probability of failure for the severe accident scenario
- Severe accident analysis carried out to define the loads on the containment
  - Quasi-static loads - pressure-temperature build up over a period of time
  - Impulse loads – due to steam explosion, high pressure melt ejection, Hydrogen combustion
  - Direct contact with molten core material

Containment performance analysis



Quantification of the CET/ APET

- Aim is to determine the frequency of the CET/ APET branches
  - Requires PDS frequencies and CET/ APET branch probabilities
- PDS frequencies
  - Obtained from core damage cut-set grouping
- CET/ APET branch probabilities
  - Failure of safety systems (e.g. containment spray system) quantified using fault trees
  - Structural failures of the containment quantified as part of the containment structural analysis
  - Occurrence of physical phenomena represented by split fractions that relate to the analyst's "degree of belief" that a particular phenomenon will occur

CET/ APET probabilities

- Stochastic probabilities
  - Probabilities that random failures will occur
  - Failure of containment isolation, failure of operator to carry out action
- Epistemic uncertainties
  - Arise from a lack of knowledge on the phenomena that occur during a severe accident
  - Probability that HPME/ DCT will occur; probability that hydrogen combustion will occur; probability of base-mat melt through
  - Three types:
    - Parameter uncertainty
    - Model uncertainty
    - Completeness uncertainty

Derivation of CET probabilities

- Expert judgement
  - Degree of belief translated into numerical value
- Convolution of two probability density functions
  - Containment pressure load & ultimate pressure capacity
- Decomposition
  - Hydrogen combustion broken down into generation/ mixing/ concentration/ ignition/ combustion

- CET probabilities are conditional probabilities
  - Depend on the sequence of events that has occurred
  - Need to take account of interdependencies

Source term/ release categories

Input from CETs

↓

CET ENDPOINTS
Severe accident sequences

Many thousand

↓ GROUPING

SOURCE TERM CATEGORIES
Similar release

↓ GROUPING

Severe accident sequences that lead to similar release to the environment

RELEASE CATEGORIES
Similar offsite consequences

Source term categories that lead to similar offsite consequences

↓

Output to Level 3 PSA

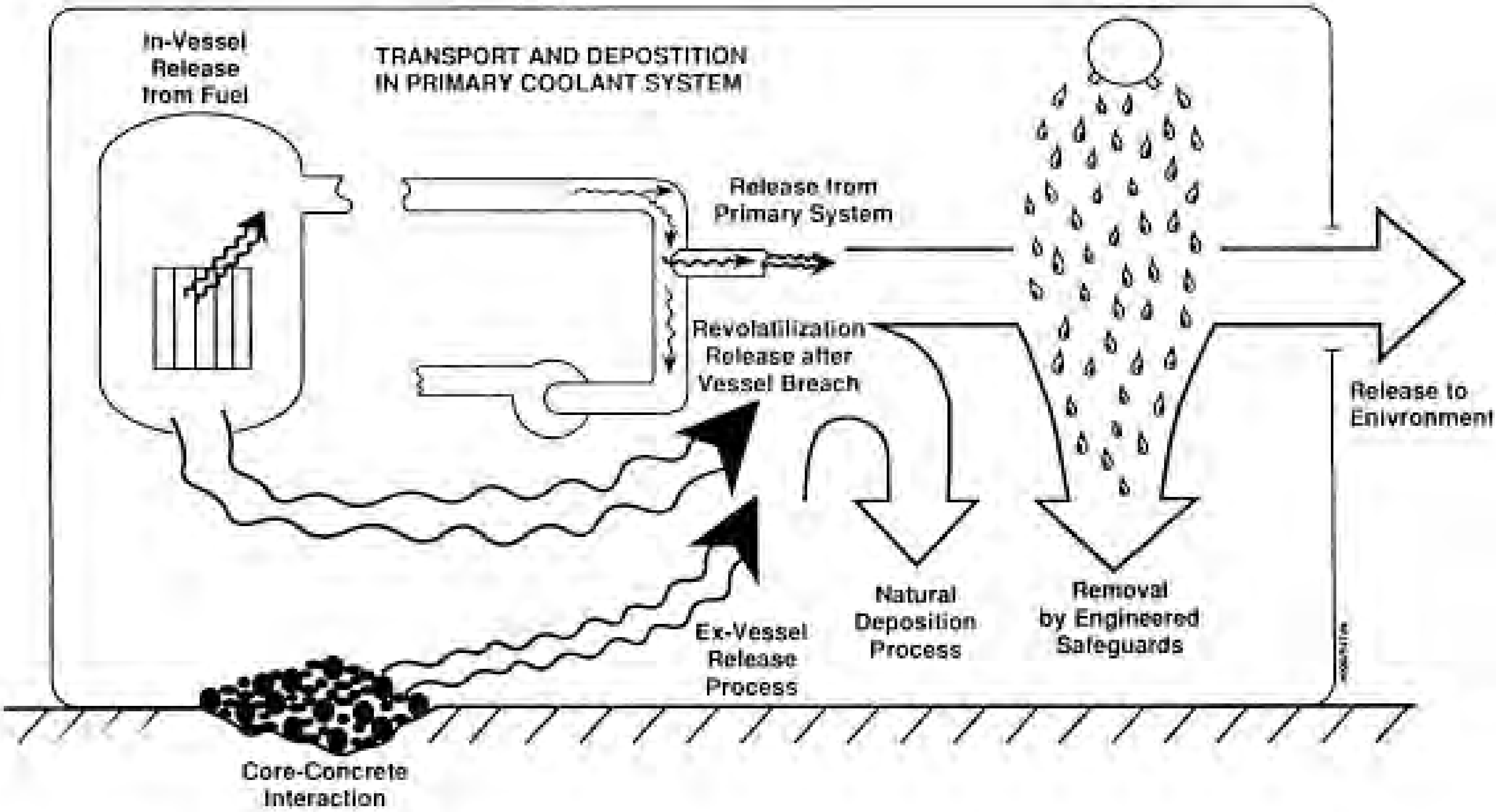
Source term/ release categories

- **Source Term Categories**
  - Similar characteristics for fission product release from the fuel, transport through containment to environment

- **Release Categories**
  - Similar characteristics for release of radioactive material from the plant

- **Characteristics**
  - Mode of ex-vessel releases
  - Fission product removal mechanisms
  - Containment leakage rate
  - Timing of release - warning/ start/ duration

Source term/ release categories



Results of Level 2 PSA

- Results of the Level 2 PSA
  - Source terms frequencies
  - Large release frequency (LRF)/ large early release frequency (LERF)
  - Release category frequencies
- Use of the results of the Level 2 PSA
  - Identify weaknesses in protection for severe accidents
  - Identify accident management measures
  - Identify need for additional protection systems
    - Hydrogen recombiners/ igniters
    - Core catcher/ spreading area/ core cooling
    - Filtered containment vent
  - Severe accident recovery procedures
    - Symptom based procedures
  - Training

Uncertainties, sensitivities

- Level 2 PSA addresses some uncertainties directly
  - CET branch points relate to the analyst's degree of belief
- Uncertainties usually addressed by sensitivity studies
  - Sensitivity studies carried out for the important assumptions in the CETs

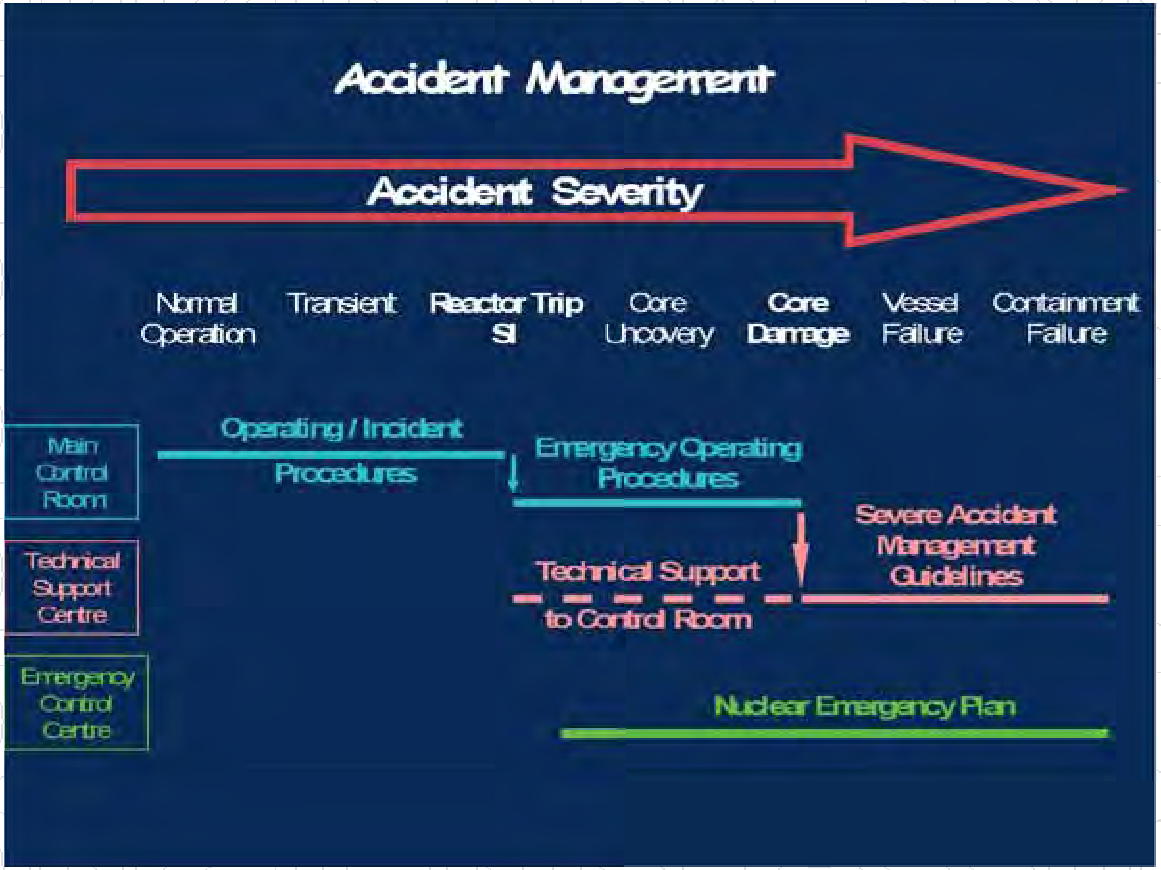
Severe Accident Management

- **Provision of hardware**
  - **Hydrogen control system with a high capacity for severe accidents**
  - **Filtered containment venting system to prevent containment overpressure failure**
  - **Core catcher/ cooling of molten core material outside the core**

Severe Accident Management Procedures

- Preventative procedures
  - Limit core damage
  - Prevent containment bypass
- Mitigate the consequences of a severe accident
  - Prevent reactor vessel failure – depressurisation of the primary circuit by opening pressuriser relief valves
  - Add water to containment for cooling of molten core material outside the reactor pressure vessel
  - Control the transport of radioactive material - use of the fire sprinkler system
- Severe Accident Management Guidelines (SAMG)
  - Generic SAMG developed by vendor owners groups

Severe Accident Management Guidelines



Level 2 PSA - conclusions

- Level 2 PSAs have now been carried out for many nuclear power plant worldwide
- Consistent framework developed for carrying out the analysis
- Development of Containment Event Trees supported by accident analysis (MAAP, MELCOR)
- Used to identify the specific plant vulnerabilities to severe accidents
- Severe Accident Management Guidelines have been developed for many plants
- Severe accident management systems have been back-fitted to many existing plants and included in new designs

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