Safety Assessment and Strategy using a Risk-Informed Approach for the BWRX-300

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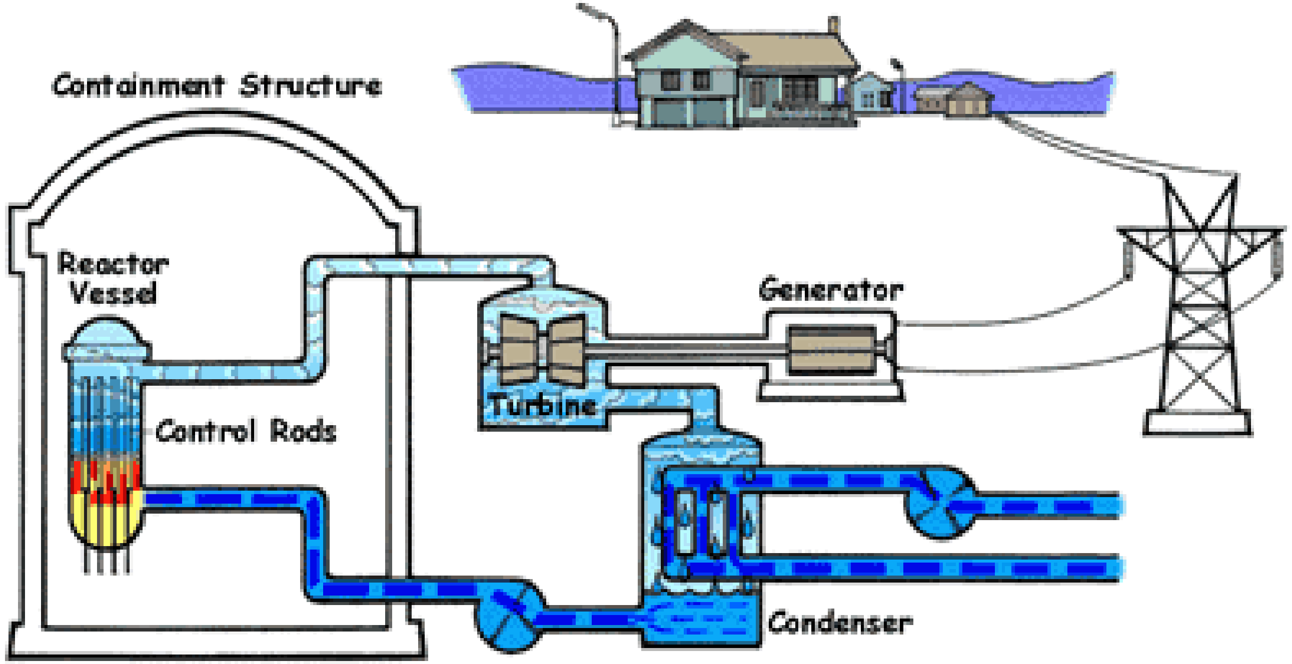
Boiling Water Reactor (BWR) Technology Overview

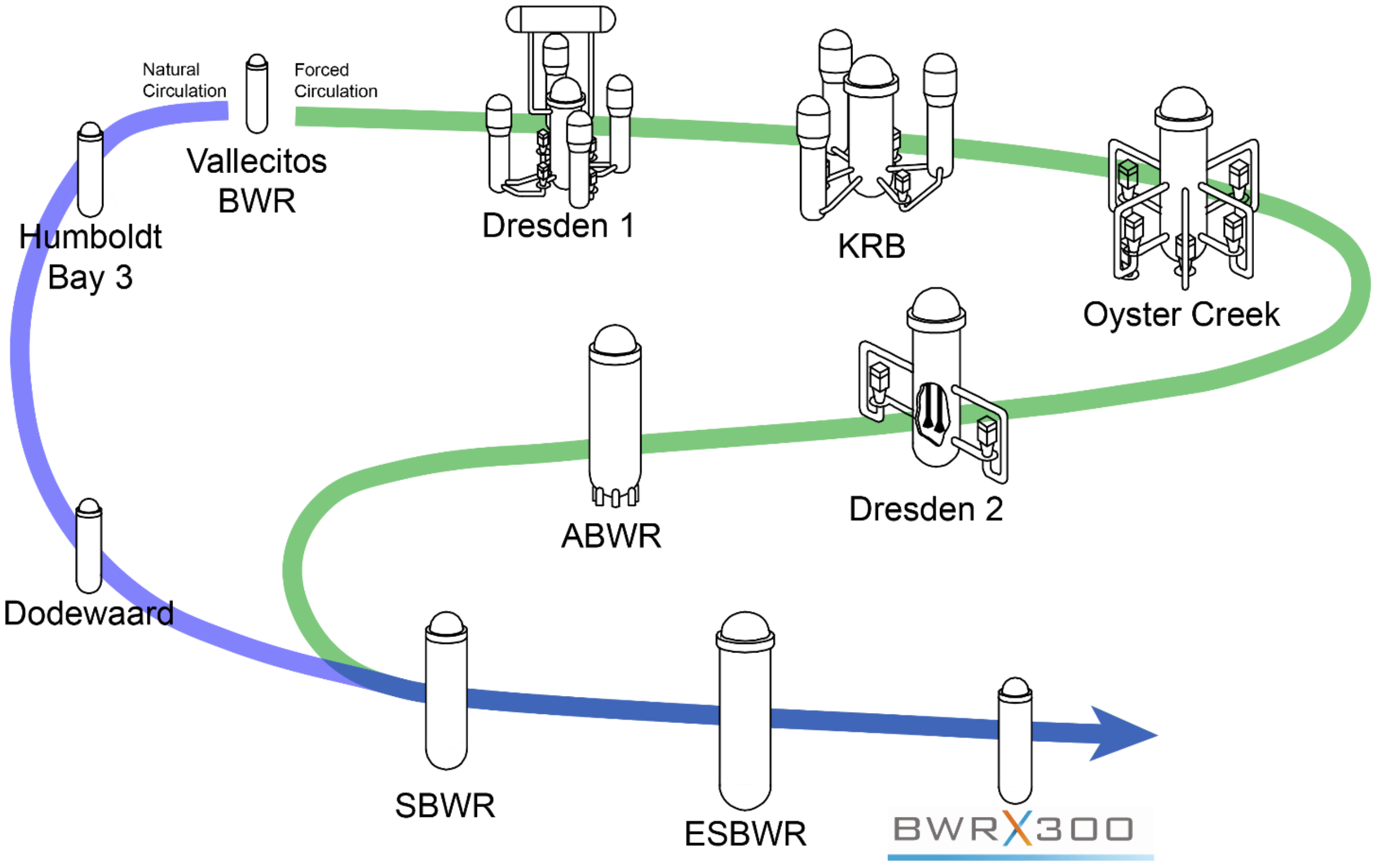
Boiling Water Reactors (BWRs): the simplest way to make steam



INHERENTLY SIMPLE REACTOR DESIGNS

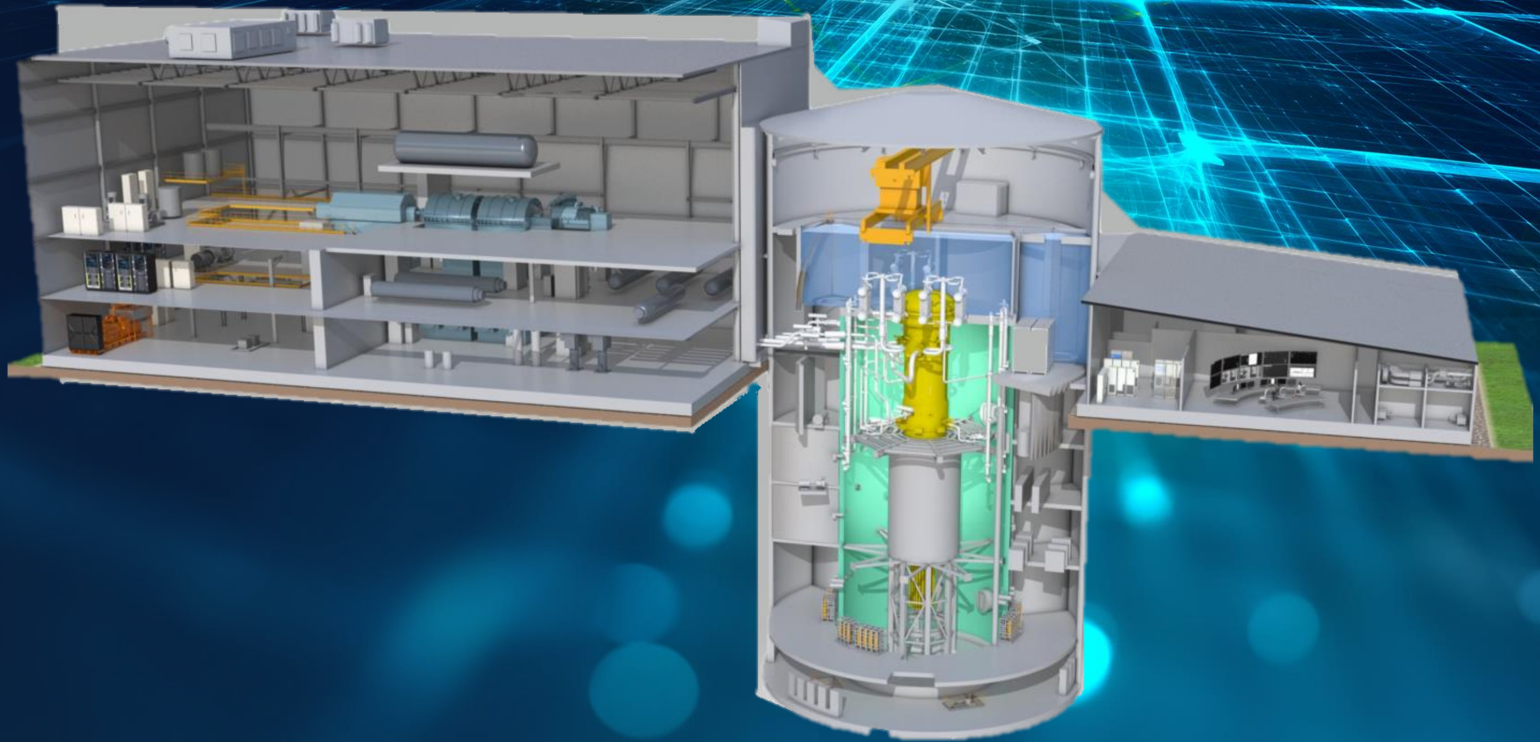
- Direct cycle design with <u>no</u> secondary steam generator and pressurizer
- Traditional balance of plant for electricity generation
- Low enriched (3-5% U-235) oxide fuel in metal cladding
- Water serves as coolant and “moderator” to slow down fast neutrons
- Coolant circulated through core using forced or natural circulation

BWR Recirculation system design evolution



- Recirculation system design evolution:
  - Natural circulation
  - External pumps
  - Jet pumps
  - Reactor internal pumps
  - Natural circulation

BWRX-300 Technology Overview



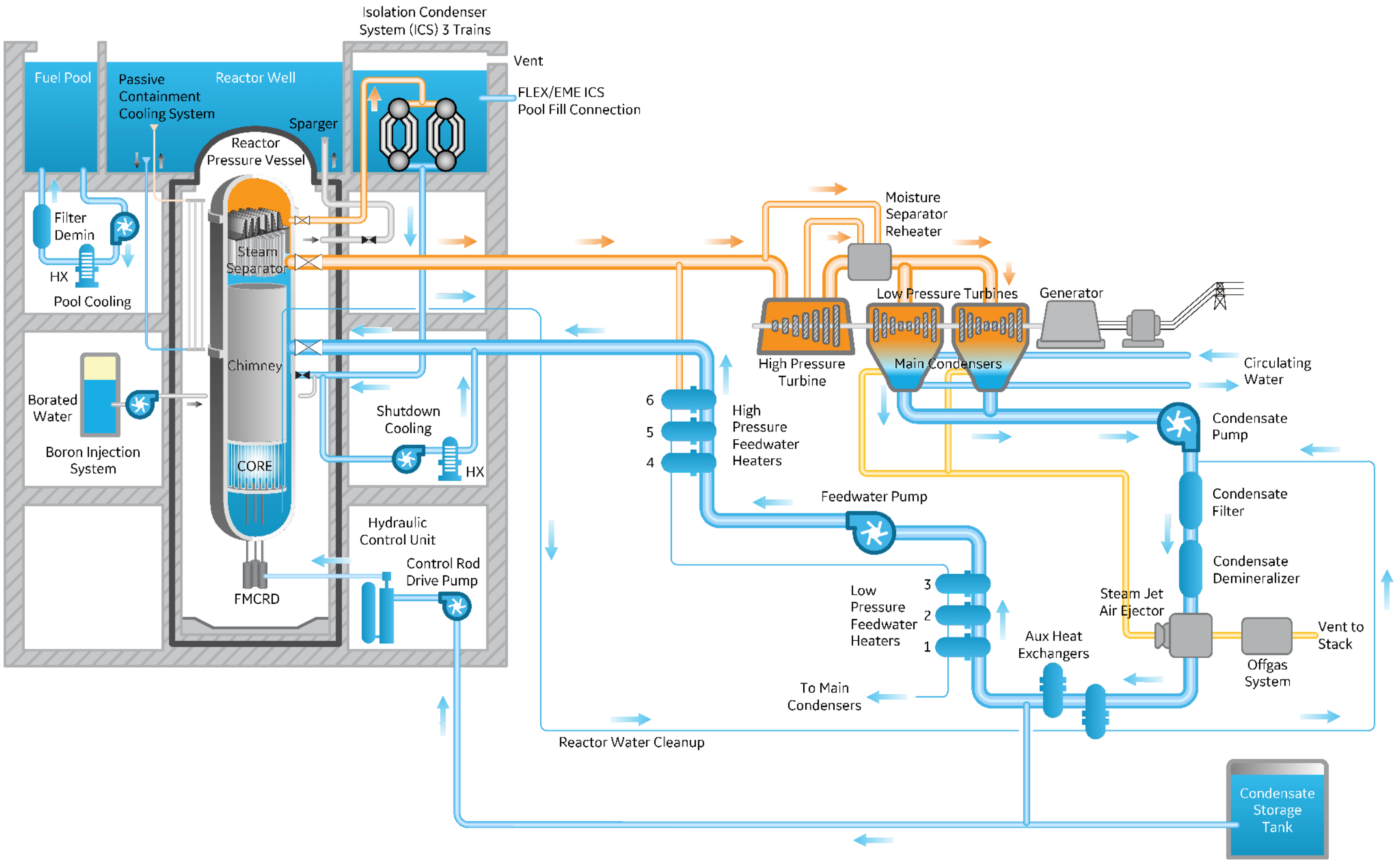
BWRX-300

Breakthrough innovation coupled with a proven design reduces cost and risk.

PROVEN	• 10th generation boiling water reactor (BWR) • Leverages licensed design in the U.S. • Powered by commercially available fuel with qualified manufacturing facilities in the U.S. and Europe (does not need HALEU) • Leverages existing supply chain and off-of-the-shelf components
INNOVATIVE	• Significant capital cost reduction • Less concrete & steel/MW than competitors • Small footprint and simple layout • Underground construction using proven methods from other industries
SIMPLIFIED	• BWR is inherently simple • Fewer components than other SMR technologies leading to less capital and operating cost • Patented innovation drives further simplicity

Ideal for electricity generation and industrial applications, including hydrogen production, desalination and district heating

BWRX-300 steam cycle … normal operation



BWR source: https://www.energy.gov/ne/downloads/infographic-how-does-boiling-water-reactor-work

PWR source: https://www.energy.gov/ne/downloads/infographic-how-does-pressurized-water-reactor-work

Breakthrough innovation – integral isolation valve

Reactor Pressure Vessel with Integral Isolation Valves

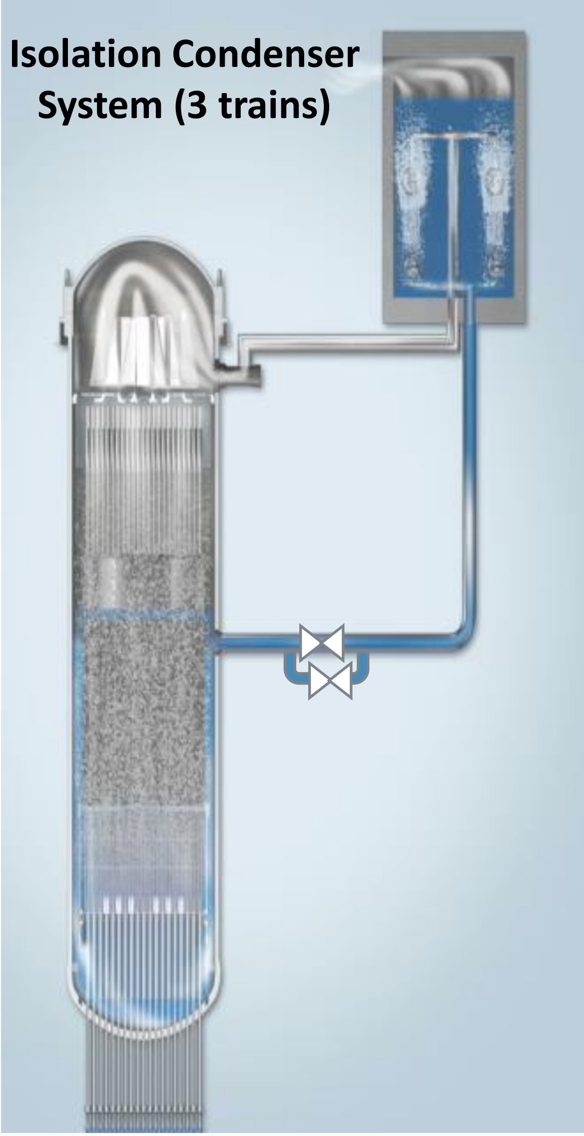
Integral Isolation Valve

- Part of ASME code boundary for vessel
- Double isolation … independent actuators
- Minimizes inventory loss for large breaks … Loss of Coolant Accident (LOCA)
- Patented / NRC approved
- **Integral isolation and cooling strategy by combining with passive safety (natural circulation) Isolation Condenser System (ICS)**

Outcomes

- ✓ Defense-in-Depth with redundancy and diversity … 3 x 100% trains
- ✓ Removes decay heat and maintains pressure while maintaining water inventory
- ✓ Inherently safe with no operator action or AC power for accidents … 7 days minimum
- ✓ Enables dramatic design simplification and elimination of unnecessary systems

Isolation Condenser System (3 trains)



Utilizing proven technology

BWRX300

PROVEN COMPONENTS, PRIOR TESTING, AND OPERATIONAL HISTORY GREATLY ACCELERATE DEPLOYMENT

Dryer
Same features as ABWR* and ESBWR …
Same as upgrades for existing fleet …
Size nearly identical to KKM**

Steam separators:
Same as ABWR* and ESBWR …
Similar to others in the BWR fleet

GNF2 fuel:
>25,000 bundles delivered …
Utilized by ~70% of BWR fleet

Control rod blades:
Same as ABWR* …
Longer than ESBWR …
Almost identical to latest design for BWR fleet

Reactor pressure vessel:
Same material and fabrication processes as ABWR*, ESBWR and many of the BWR fleet …
Diameter almost identical to KKM**

Chimney:
Uses ESBWR and Dodewaard*** technology … Simplified

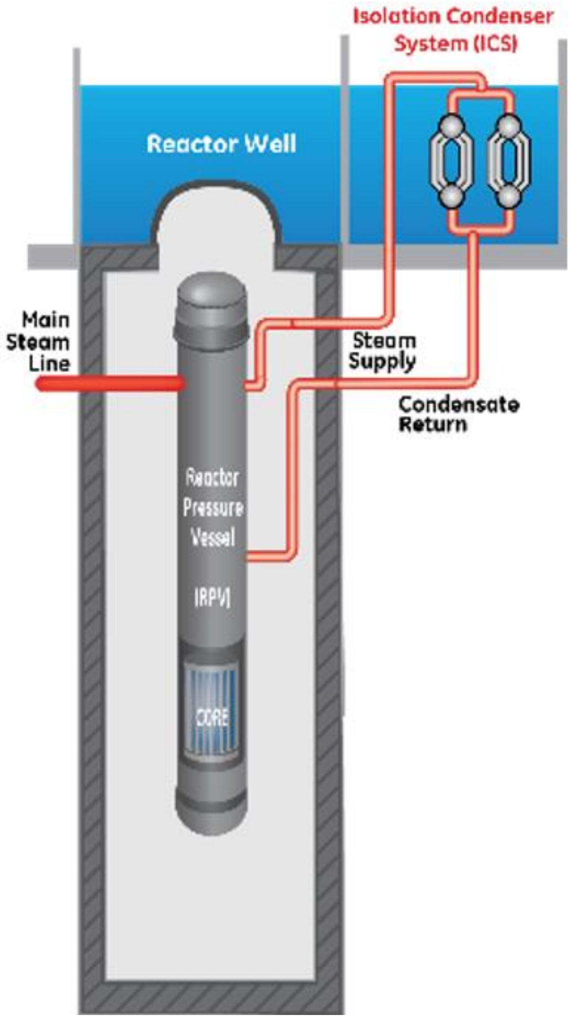
Nuclear Instrumentation:
Fixed in-core Wide Range Neutron Monitors and Local Power Range Monitors

Fine motion control rod drives:
Same as ABWR* and ESBWR

* ABWR fleet has combined 22+ years of operating experience | ** Kernkraftwerk Mühleberg (KKM): 355 MWe BWR/4 in operation since 1972 | *** Dodewaard: 58MWe natural circulation BWR, 1969 ~ 1997

Isolation Condenser System (ICS) Functions

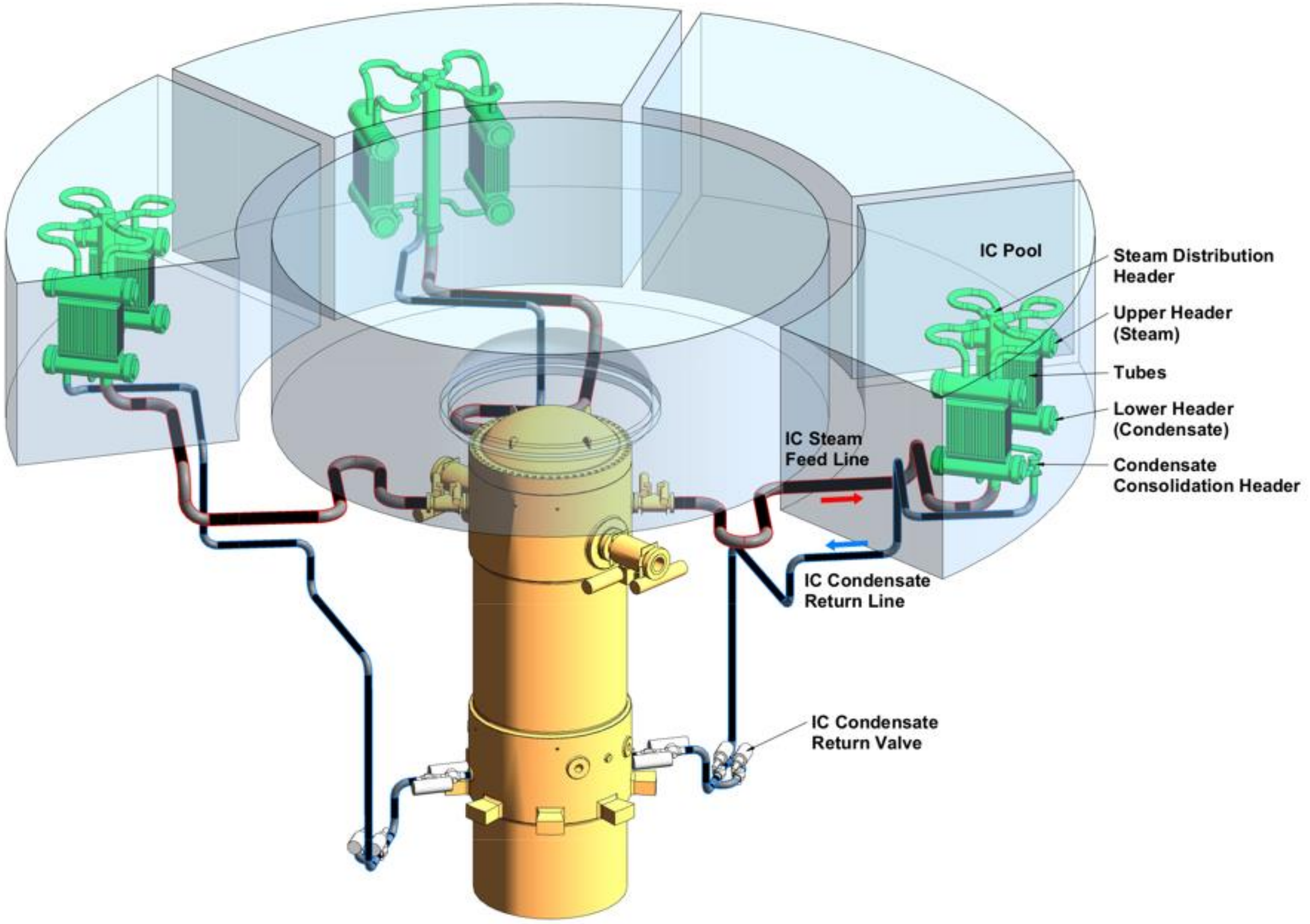
- ICS in conjunction with reactor scram provides inventory retention and decay heat removal for a minimum of seven days without requiring operation actions
- ICS in conjunction with reactor scram provides reactor pressure boundary overpressure protection when system is isolated
- ICS provides isolation capability to maintain Primary Containment integrity



Three Independent 100% Capacity ICS loops

Each ICS loop includes:

- Separate cooling water pool below refuel floor
- Separate condenser/heat exchanger located in the ICS pools
- Separate steam supply and condensate return lines with dual RPV integral isolation valves
- Separate / independent system initiation valves
- Each loop can remove 100% of decay heat approximately one minute after Reactor shutdown (33 MWth)



ICS is the BWRX-300 Emergency Core Cooling System

- Full-scale prototype testing of ICS condensers performed to demonstrate capability
- Minimal changes planned for final design
  - Incorporate changes to support higher design pressure of RPV
  - Incorporate catalytic recombiner to eliminate need for venting of noncondensibles

IAEA Requirements under Specific Safety Requirements SSR-2/1

IAEA SSR-2/1: Safety of Nuclear Power Plants: Design

- Requirements 1 to 3: Management of Safety In Design
- Requirements 4 to 12: Principal Technical Requirements including Fundamental Safety Functions (4), DID, and Safety Assessment (10)
- Requirements 13 to 42: General Plant Design including Postulated Initiating Events (16), Design Basis Accidents (19), Design Extension Conditions (20), Safety Classification (22), and Reliability of items important to Safety (23)

- Under Requirement 16 (PIEs):
  - The postulated initiating events shall be identified on the basis of engineering judgement and a combination of deterministic assessment and probabilistic assessment. A justification of the extent of usage of deterministic safety analysis and probabilistic safety analysis shall be provided to show that foreseeable events have been considered.

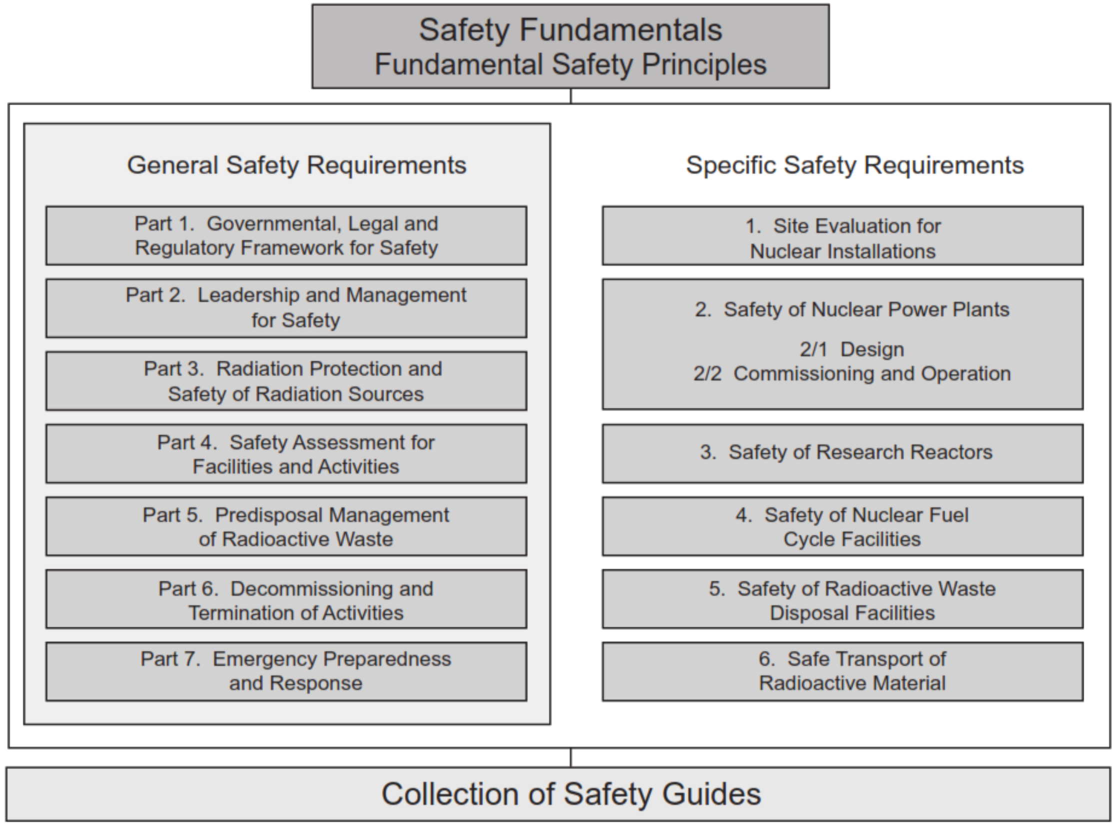


FIG. 1. The long term structure of the IAEA Safety Standards Series.

Risk-Informed Safety Analysis

IAEA SSR-2/1 discusses the use of the PSA to support the DSA in a number of key areas:

1) Ensure the Safety Requirements are met throughout the lifetime of the plant.
2) Establishment of postulated initiating events (PIEs) including combinations of events
3) Evaluation of Design Extension Conditions (DECs)
4) Support classification of SSCs
5) Establish that a balanced design is achieved.

Additionally, the PSA can support:

6) Evaluation of practical elimination for PIEs
7) Sufficient Defense-in-Depth is established
8) Independence of DID layers is sufficient (DID levels are independent as practicable).

Under SSR-2/1, an all-modes PSA is required. A risk-informed Safety Analysis can implement some or all the above (plus other items), with several of the requirements involving “SHALL” statements such as items 1, 2, and 3. SSC Classification allows for classifying SSCs using probabilistic methods, where appropriate.

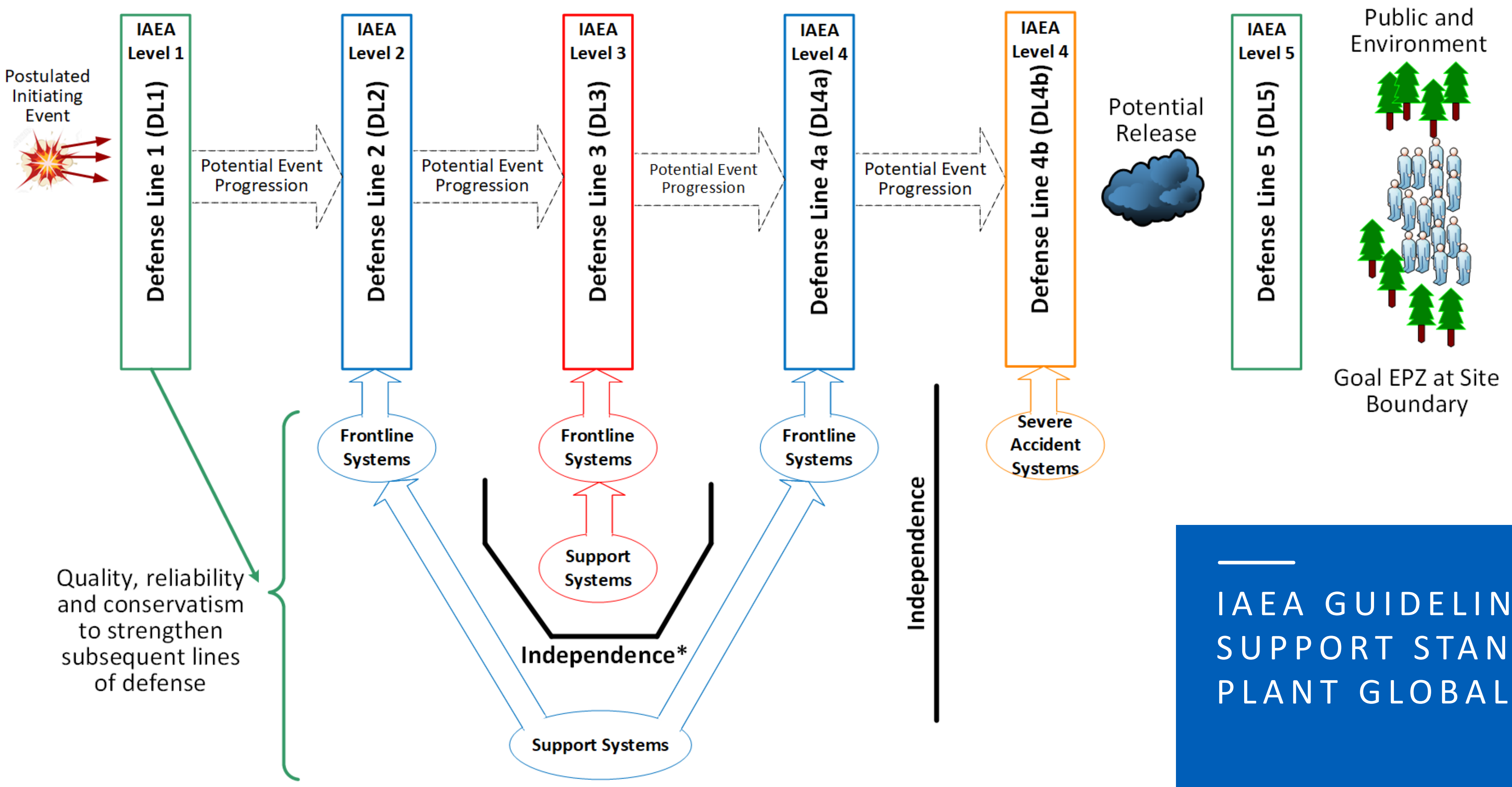
BWRX-300 Risk-Informed Design and Safety Strategy

Examples of Risk-Informed Design

GEH has developed a full-scope all-modes PSA for the BWRX-300.
Design Improvements and/or cost savings primarily informed by PSA or with significant input from PSA:

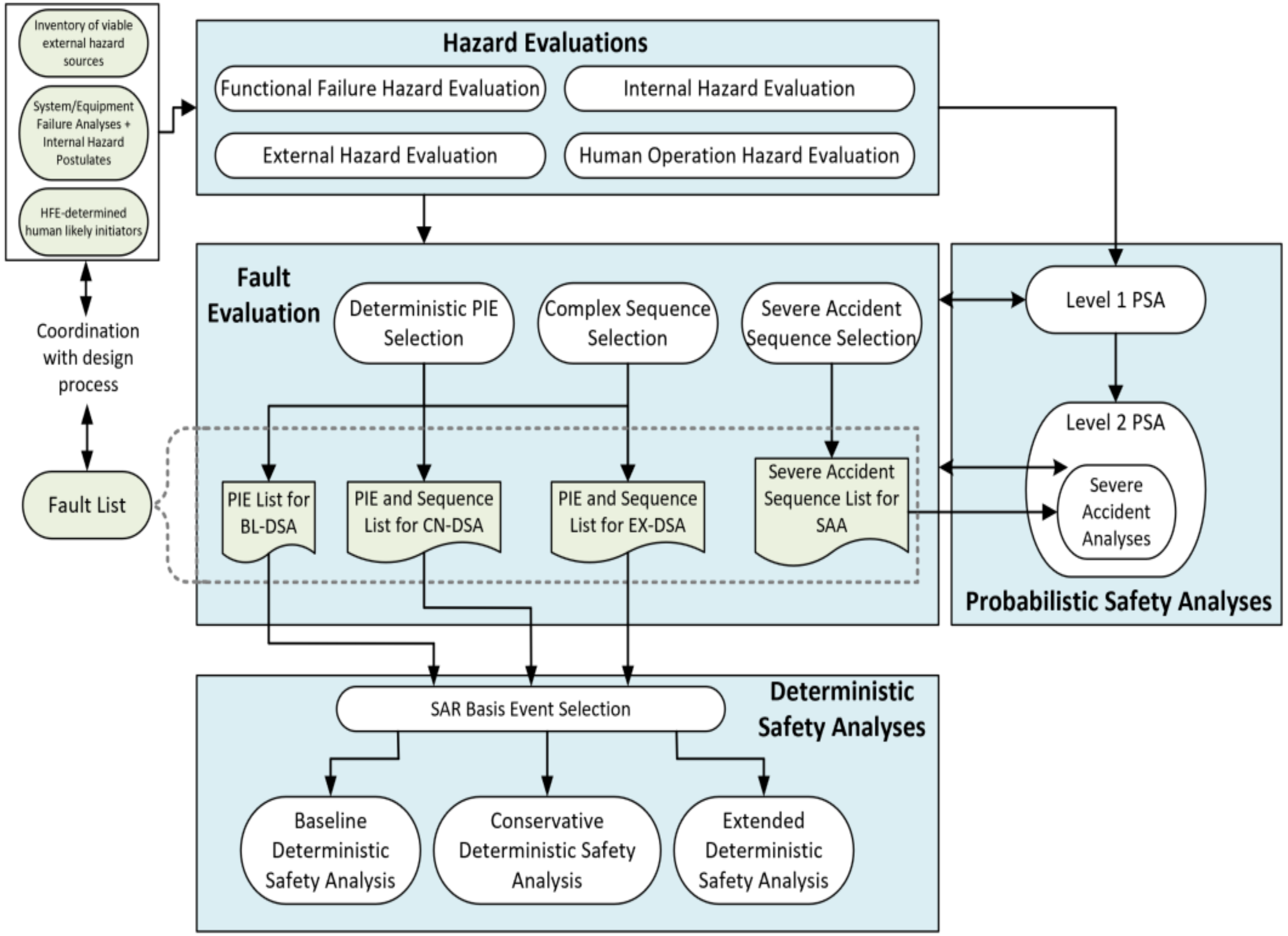
- Addition/sizing of filtered containment vent
- Potential for RPV depressurization mechanism (in addition to ICS)
- Supporting need for boration mechanism
- Precluding need for new RPV nozzle to accommodate boration
- Sizing/operation of CRDH to provide makeup
- Seismic capacity requirements for select equipment
- Shutdown nuclear safety strategies
- Potential for seismic anticipatory trip
- Development of FLEX functions
- Spatial separation in select areas for fire considerations

Defense in depth … built into the design from the start



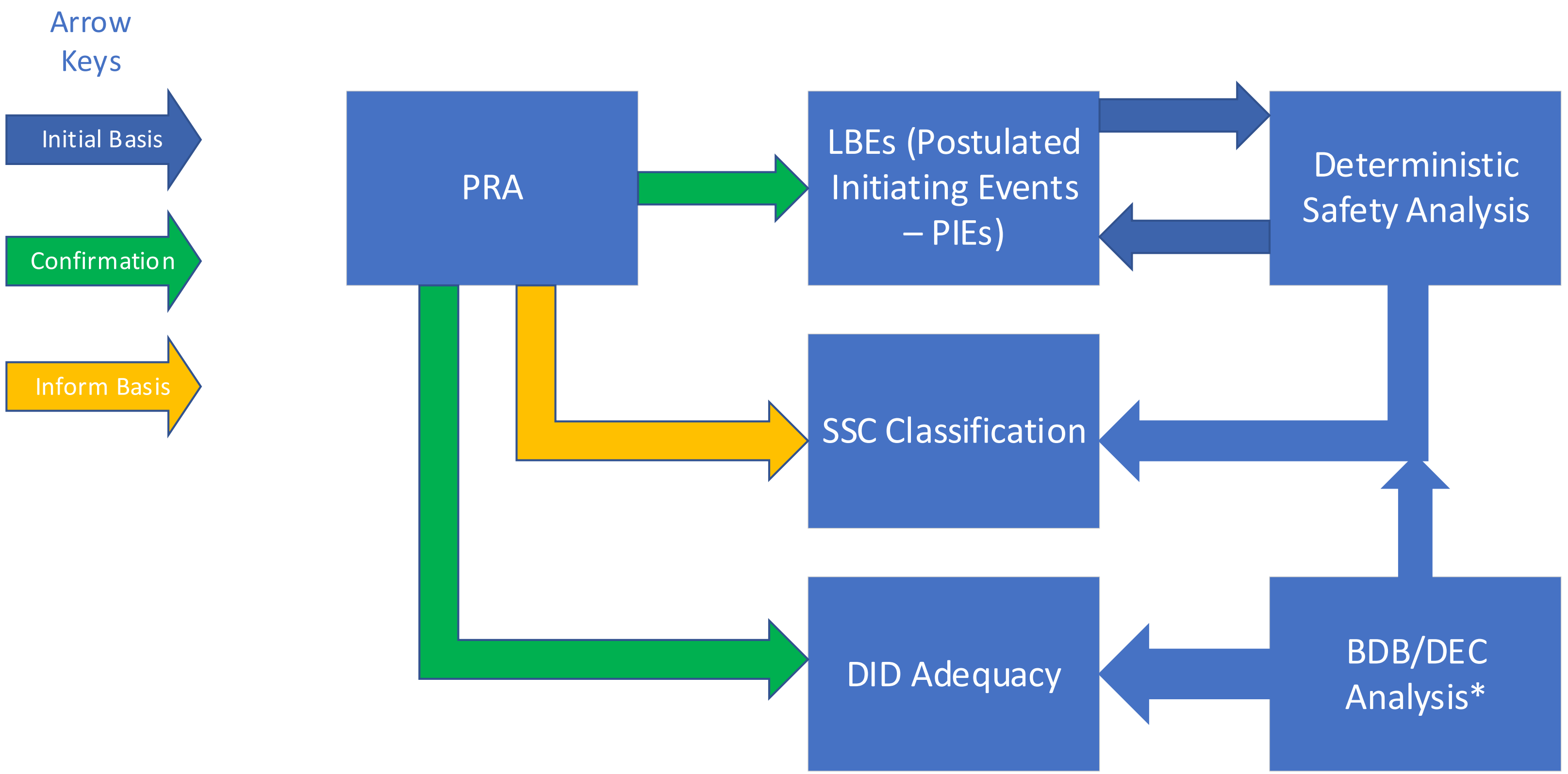
IAEA GUIDELINES SUPPORT STANDARD PLANT GLOBALLY

BWRX-300 safety strategy



- Objective of plant design is to have “a very low likelihood and degree of reactor core damage”
- This safety and reliability objective can be met by designing an inherently safe reactor that relies on passive safety systems
- Degree of reliance should be in this order
  - Inherent Safety
  - Passive Safety
  - Active Safety
  - Procedural Controls
- BWRX-300 applies a systematic approach to achieving these objectives

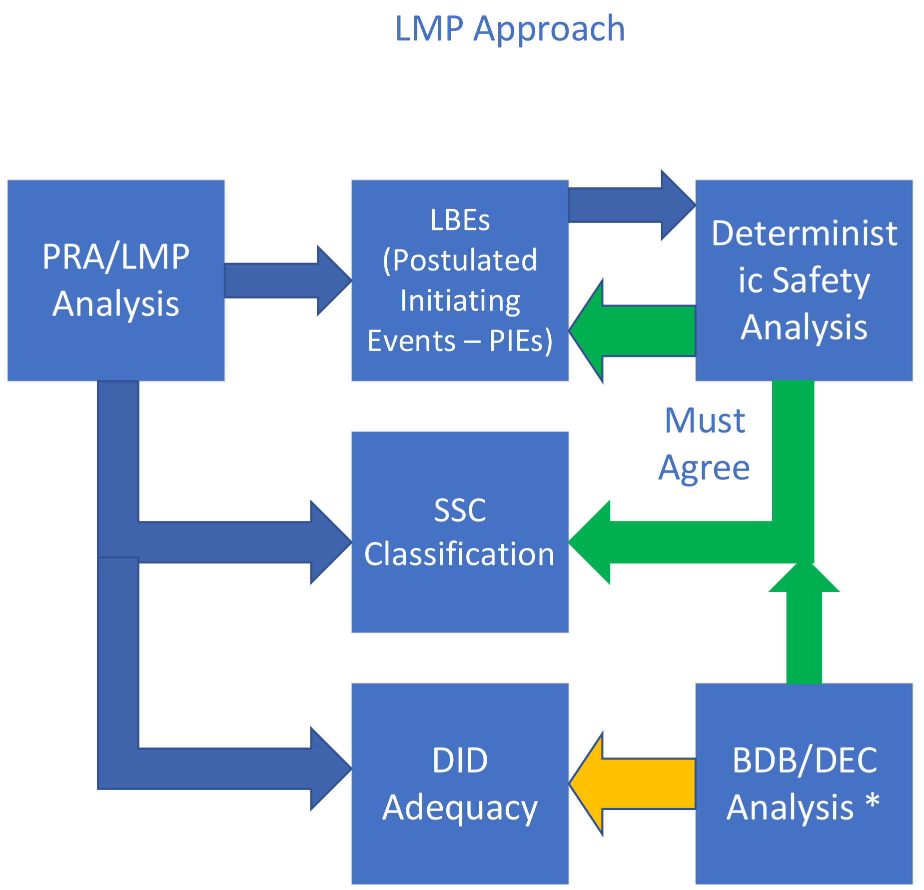
Safety Analysis – using an IAEA Approach

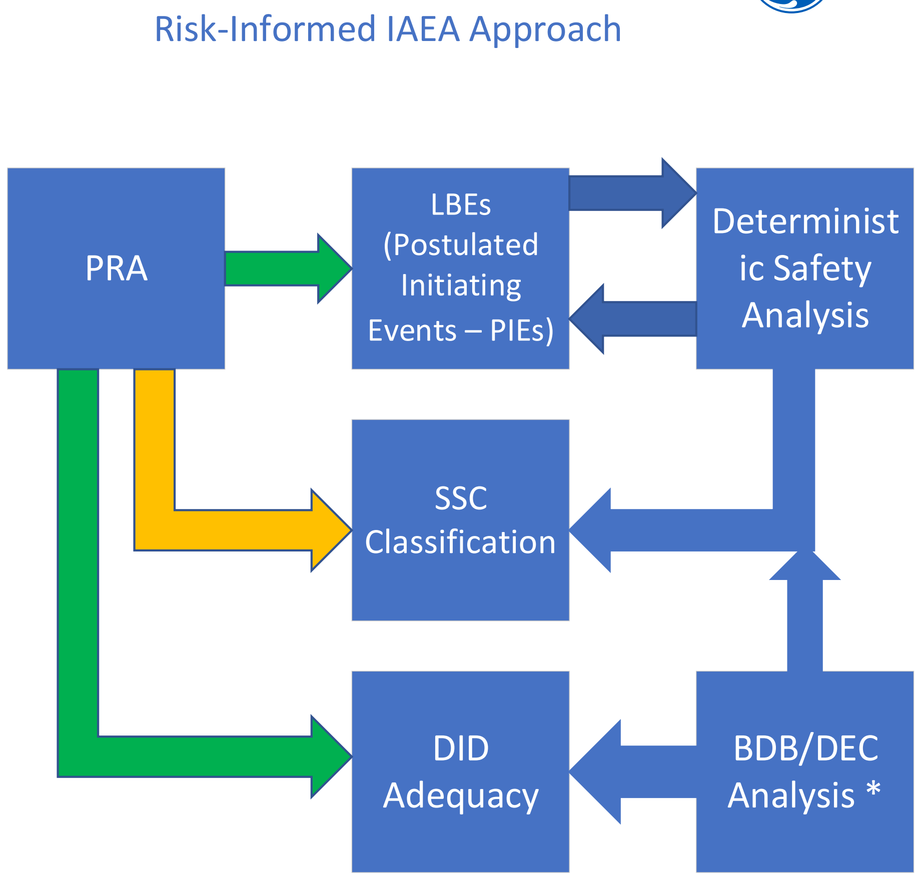


Key Points:

1) The IAEA guidance includes use of PRA/PSA to inform or confirm the results from the deterministic analysis. DID adequacy is more rigorous (5 defense levels) than the LMP process.
2) The results of the IAEA and LMP approaches would be similar, with the IAEA approach being slightly more conservative for SSC classification.

LMP and IAEA Safety Analysis Comparison





Key Point:

1) The outcome of the two processes above are similar – and can be generalized as a deterministic safety analysis that is harmonized with the PRA/PSA, with a detailed DID evaluation.
2) Under LMP, an Independent Decision-Making Panel is used to confirm the adequacy of the above.

Conclusions for the BWRX-300

- The BWRX-300 is the 10^{th} generation BWR, which incorporates features of the ESBWR and previous natural circulation BWRs, but with a simplified overall design.
- Key design features including use of the three-train ICS, which provides decay heat removal and primary pressure control, along with integral reactor coolant isolation valves results in an overall safer plant, smaller safety footprint, and lower cost design.
- Use of the IAEA approach for defense-lines along with a Safety Strategy utilizing the IAEA SSR-2/1 allows for the plant to be licensed around the world.
- Use of PSA information to inform the Design and Safety Strategy ensures both a low-risk design and a robust Safety Strategy by ensuring a comprehensive list of postulated initiating events and a well supported defense-line evaluation.