Overview of the ESFR Safety Design Strategy

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Outline

- CP-ESFR project
- Overview of the ESFR concept
- Safety objectives & principles
- Safety design strategy
- Summary
CP-ESFR project: objectives & structure

Euratom 7th FP Collaborative Project on European Sodium Fast Reactor (CP-ESFR) objectives:

- Improved Safety to achieve a robust architecture including the robustness of the safety demonstrations
- Financial risk comparable to that of other means of energy production
- A flexible and robust management of nuclear materials
- To contribute to the re-build of European expertise in SFR technology
- Assessment of different types of plant layout and core design options

Project details
Coordinator: CEA
Duration: January 2009 – June 2013
Partners: 25 European organizations
Total budget: 11.55 MEUR
EC contribution: 5.8 MEUR
Overview of ESFR Concept: plant characteristics

<table>
<thead>
<tr>
<th>Plant Layout</th>
<th>Pool Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reactor heat output</td>
<td>3600 MW\text{th}</td>
</tr>
<tr>
<td>Net electrical output</td>
<td>1500 MW\text{e}</td>
</tr>
<tr>
<td>Plant lifetime</td>
<td>60 Years</td>
</tr>
<tr>
<td>Global Efficiency</td>
<td>42%</td>
</tr>
<tr>
<td>Availability Objective</td>
<td>90%</td>
</tr>
<tr>
<td>IHX</td>
<td>6</td>
</tr>
<tr>
<td>DHX</td>
<td>6</td>
</tr>
<tr>
<td>Primary pumps</td>
<td>3</td>
</tr>
<tr>
<td>Secondary loops</td>
<td>6</td>
</tr>
<tr>
<td>DRC loops</td>
<td>6</td>
</tr>
</tbody>
</table>

⇒ **Main design objectives:**
- Simplification of structures
- Improved In-service Inspection and Repair
- Cost reduction and increased quality
- Reduction of risks related to sodium fires
- Robustness against external hazards
Overview of ESFR Concept: core characteristics

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fissile volume (m$^3$)</td>
<td>17.4</td>
</tr>
<tr>
<td>Outer core radius (cm)</td>
<td>245</td>
</tr>
<tr>
<td>Power density (W/cm$^3$)</td>
<td>206</td>
</tr>
<tr>
<td>Pu content by zone (% vol)</td>
<td>14.5 / 16.5</td>
</tr>
<tr>
<td>Fissile height (cm)</td>
<td>100</td>
</tr>
<tr>
<td>Assembly pitch (mm)</td>
<td>210.8</td>
</tr>
<tr>
<td>Pin diameter (mm)</td>
<td>10.7</td>
</tr>
<tr>
<td>Fuel residence time (efpd)</td>
<td>2 050</td>
</tr>
<tr>
<td>Average Burnup (GWd/t)</td>
<td>100</td>
</tr>
<tr>
<td>Number of pins</td>
<td>271</td>
</tr>
<tr>
<td>Mass UPuO$_2$ (t)</td>
<td>79</td>
</tr>
<tr>
<td>Mass PuO$_2$ (t)</td>
<td>12</td>
</tr>
</tbody>
</table>

Core safety improvements:
- reduction of sodium void reactivity
- lower reactivity swing
- capability of MA burning
Overview of ESFR Concept: nuclear island layout for twinned ESFRs

→ The requirements for the nuclear island layout are:

- Independent reactor safety related buildings
- Independent reactor operation, except during specific outage phases
- Functional requirements, such as fuel handling routes, components handling routes, etc.
- Three redundant electrical systems essential for reactor safety
- Geographical separation of safety systems and buildings
- Seismic resistance criteria, which leads to a single seismic raft based on seismic bearing pads
- Heavy commercial aircraft crash resistance criteria for safety related buildings
Safety objectives & principles

The safety objectives defined in the European safety framework for new NPPs and technical guidelines applied for the French EPR are considered as a basis:

- European and National regulatory requirements for radiological exposure
- The number of significant faults, which could occur frequently, has to be reduced
- The global occurrence frequency of the potentially most severe dealt with accident (e.g., whole core accident if not practically eliminated) has to be made lower than $10^{-5}$ per plant year
- There shall be no necessity of protective measures for the public in the vicinity of the damaged power plant (no sheltering, no stable iodine administration, no evacuation)
- For whole core accidents, the maximum conceivable releases would necessitate only very limited population protection measures in area and time for the public
Safety objectives & principles (cont.)

The safety approach demonstration has to be robust:

- The safety approach has to be developed and implemented in the design at early stage
- The operational and licensing background of SFR technology has to be considered
- ALARA principle is implemented
- Concerning the consideration of whole core accident (if not practically eliminated), the design provisions should avoid the risk of mechanical energy release in order to provide a convincing demonstration of the capability of structures to withstand the consequences of the accident
- The protection of the public with respect to chemical releases due to sodium has to be assessed
### Safety objectives & principles (cont.)

The safety objectives are achieved through the application of the defense-in-depth principle:

<table>
<thead>
<tr>
<th>Original design of the plant</th>
<th>Level of defence in depth</th>
<th>Objective of the level</th>
<th>Essential means</th>
<th>Associated plant condition categories</th>
<th>Radiological consequences</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Level 1</td>
<td>Prevention of abnormal operation and failure</td>
<td>Conservative design and high quality in construction and operation</td>
<td>Normal operation</td>
<td>Regulatory operating limits for discharge</td>
</tr>
<tr>
<td></td>
<td>Level 2</td>
<td>Control of abnormal operation and failure</td>
<td>Control, limiting and protection systems and other surveillance features</td>
<td>Anticipated operational occurrences</td>
<td>Regulatory operating limits for discharge</td>
</tr>
<tr>
<td></td>
<td>Level 3 (1)</td>
<td>Control of accident to limit radiological releases and prevent escalation to core damage conditions (2)</td>
<td>Safety systems</td>
<td>DID Level 3.a</td>
<td>No off-site radiological impact or only minor radiological impact (see NS-G-1.2/4.102)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Control of accident to limit radiological releases and prevent escalation to core melt conditions (3)</td>
<td>Accident procedures</td>
<td>Postulated single initiating events</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Level 4</td>
<td>Practical elimination of situation that could lead to cady or large releases of radioactive materials</td>
<td>Engineered safety features (4)</td>
<td>DID Level 1.b</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Control of accidents with core melt to limit off-site releases</td>
<td>Accident procedures</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Emergency planning</td>
<td>Level 5</td>
<td>Mitigation of radiological consequences of significant releases of radioactive materials</td>
<td>Off-site emergency response</td>
<td>Postulated core melt accidents (short and long term)</td>
<td></td>
</tr>
</tbody>
</table>
Safety objectives & principles (cont.)

The demonstration of the adequacy of the design is made through the consideration of two comprehensive lists of events:

- **Dealt with events** corresponding to transients considered in the design including both DBC & DEC →

- **Practically eliminated situations** corresponding to situations for which a set of adequate design and operational provisions are implemented in such a way that their consequences need not be considered in the design

<table>
<thead>
<tr>
<th>Plant conditions</th>
<th>Events</th>
<th>Indicative Fr/year</th>
</tr>
</thead>
<tbody>
<tr>
<td>DBC1 Normal operation</td>
<td>Power operation, normal transients, commissioning</td>
<td>&gt; $10^{-2}$</td>
</tr>
<tr>
<td>condition</td>
<td>initiating events might occur several times during the plant life</td>
<td></td>
</tr>
<tr>
<td>DBC2 Anticipated</td>
<td>initiating events are not expected to occur during the plant lifetime</td>
<td>$10^{-2} - 10^{-4}$</td>
</tr>
<tr>
<td>Operational Occurrences</td>
<td>return to operation</td>
<td></td>
</tr>
<tr>
<td>DBC3 Design Basis Accident</td>
<td>initiating events are not expected to occur during the plant lifetime</td>
<td>$&lt;10^{-4}$</td>
</tr>
<tr>
<td>Accident</td>
<td>plant restart not required</td>
<td></td>
</tr>
<tr>
<td>DBC4 Design Basis Accident</td>
<td>low frequency events considered in the design corresponding to multiple failures</td>
<td>$&lt;10^{-5}$</td>
</tr>
<tr>
<td>DEC Design Extension</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Condition</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Safety objectives & principles (cont.)

- Definitive criteria for DBC and DEC are given by the radiological limits.
- For the safety assessment, criteria associated with the loading are used:
  - The fuel and clad
  - The structural integrity of the equipment performing core support function
  - The confinement barriers

<table>
<thead>
<tr>
<th></th>
<th>Fuel limits</th>
<th>Fuel pin clad limit</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>DBC1</strong></td>
<td>No melting</td>
<td>No open clad failure</td>
</tr>
<tr>
<td><strong>DBC2</strong></td>
<td>No melting</td>
<td>No clad failure except due to random effects</td>
</tr>
<tr>
<td><strong>DBC3</strong></td>
<td>No melting</td>
<td>No systematic (i.e., large number of) clad failure</td>
</tr>
<tr>
<td><strong>DBC4</strong></td>
<td>Any predicted localized “melting” to be shown to be acceptable. Simultaneous and coincident clad failure and fuel melting must be excluded</td>
<td>No systematic clad melting. Any predicted localized clad melting may be acceptable provided that it can be shown that it does not lead to material relocation</td>
</tr>
<tr>
<td><strong>DEC (without whole core accident)</strong></td>
<td>No whole core accident</td>
<td></td>
</tr>
<tr>
<td><strong>DEC (whole core Accidents)</strong></td>
<td>No unacceptable damage of containment structures</td>
<td></td>
</tr>
</tbody>
</table>
Safety Design Strategy

- The safety design strategy aims at identifying challenging events and at optimizing the prevention and mitigation measures including the possibility for practical elimination.

- The identified challenging events include the three families of sequences:

- The prevention and mitigation measures are deduced from:
  - Previous experience feedback
  - Innovations for safety enhancement

- Safety enhancements should explore possibilities for:
  - Reactor and core characteristics with minimization or avoidance of risk
  - Favorable natural behavior (i.e., favorable reactor behavior in case of transient combined with the failure of active systems)
  - High-performance detection of abnormal events
Safety Design Strategy: Guidelines for the implementation of the main safety functions

The main requirement for reactivity control function is to achieve high reliability based on:

- Redundancy and diversity for I&C components, absorber elements and monitored physical parameters
- Independence of the shutdown systems
- Fail-safe behavior
- Design and fabrication with adequate codes and standards
- Safety qualification of the systems
- Permanent monitoring of the capability to perform the shutdown function
Safety Design Strategy: Guidelines for the implementation of the main safety functions

Decay heat removal function

- Implement very reliable systems capable to maintain the reactor in safe conditions for long time
- Implement redundant and diverse systems considering common mode failure and the risk of failure due to internal and external hazards
- Provisions for the operability of the DHR systems in case of failure of electrical power supply
- Implement provisions for both maintaining the corium in a sub-critical state and decay heat removal
- The design strategy should aim to practically eliminate the failure of DHR systems
Confinement

- Consequences to the environment should be sufficiently limited avoiding any technical need for off-site accident management
- The failure of a single barrier should not lead to unacceptable consequences for workers
- Capability to monitor radiological releases
- Measures for mitigation of radiological releases in case of CDA in view of:
  - Mechanical energy release inside the primary circuit
  - Sodium ejection outside the primary circuit with potential for sodium fire
  - Capability to contain the radiological products
  - Provisions for maintaining the corium in a safe state
Safety Design Strategy: Practically eliminated situation

- Reactivity accidents:
  - Large coherent gas ingress into the core
  - Collapse of the core support structures
  - Large core compaction
  - Reactivity accidents during fuel handling

- Decay Heat Removal function:
  - Unacceptable primary sodium draining; risks associated to the loss of primary circulation through intermediate heat exchangers, the DHR heat exchangers uncovering, the core uncovering
  - Failure of natural circulation
  - The failure of all systems needed for decay heat removal including the potential for common cause failures
Safety Design Strategy: R&D

- Reactivity control function:
  - Additional efficient provisions complementary to the shutdown systems have to be implemented for achieving and maintaining the reactor in an acceptable shutdown state
  - Independence and diversity of the provisions relative to shutdown systems
  - Core design and possibly implementation of adequate design provisions to limit large reactivity insertion in case of CDA

- Decay heat removal function:
  - Enhancement of the reliability of the DHR system to practically eliminate its failure as initiator of whole core accident
  - Independence, diversification and redundancy of the DHR system
  - Provisions for post-CDA heat removal function
Safety Design Strategy: R&D

Confinement to robustly mitigate consequences of whole core accidents:

- Core designs and complementary safety features, allowing minimization of mechanical energy releases:
  - risk limitation for unacceptable core criticality potentially resulting from sodium voiding and core melting
  - risk of energetic interaction between molten fuel and sodium
- Development of robust core-catcher and associated decay heat removal capability
- Implementation of robust confinement measures considering:
  - possible loadings due to mechanical energy releases, sodium fire, sodium-concrete interaction, etc.
  - weak points due to potential by-pass of the confinement structures
  - accident management capability at long term
Summary

- The ESFR safety approach is deterministic complemented by PSA insight
- Safety provisions are defined and sized with respect to the potential risks considering general safety objectives and principles
- Adequate consideration is given to safety provisions for prevention and mitigation of accident consequences
- Impact of internal and external hazards is considered
- The design adequacy with respect to safety objectives is demonstrated by:
  - The analysis of the consequences of dealt with events
  - The practical elimination of a limited set of situations, which relies on the implementation of successive diverse and reliable design and operating prevention provisions
- The Systems, Structures and Components are identified and classified with respect to their safety importance