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Overview of the ESFR Safety Design Strategy

H. Tsige-Tamirat (JRC-IET) , A. Vasile (CEA)

5th Joint IAEA-GIF Technical Meeting/Workshop on Safety of Sodium-Cooled Fast Reactors

IAEA Headquarters,

Vienna, Austria

23-24 June 2015

www.jrc.ec.europa.eu

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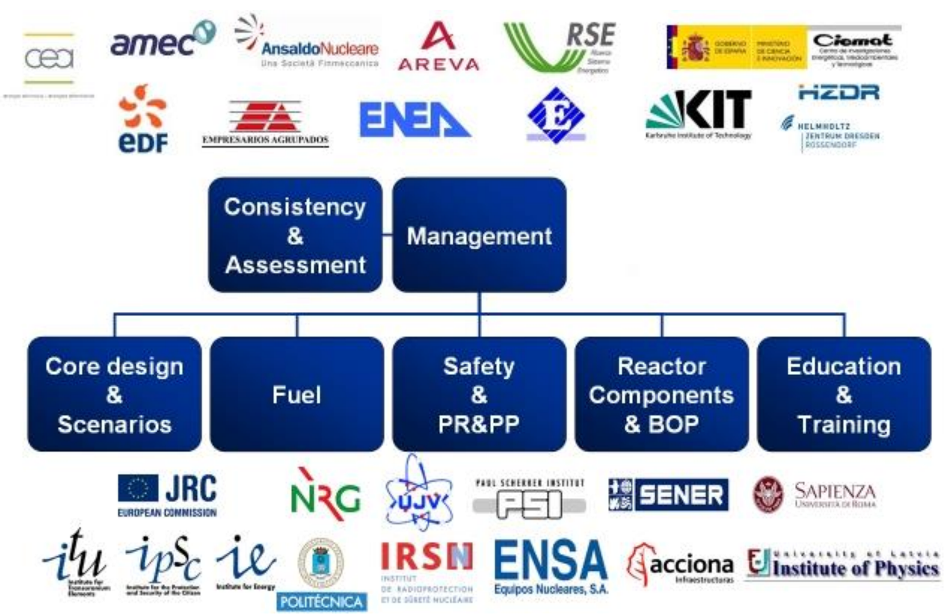
CP-ESFR project: objectives & structure

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

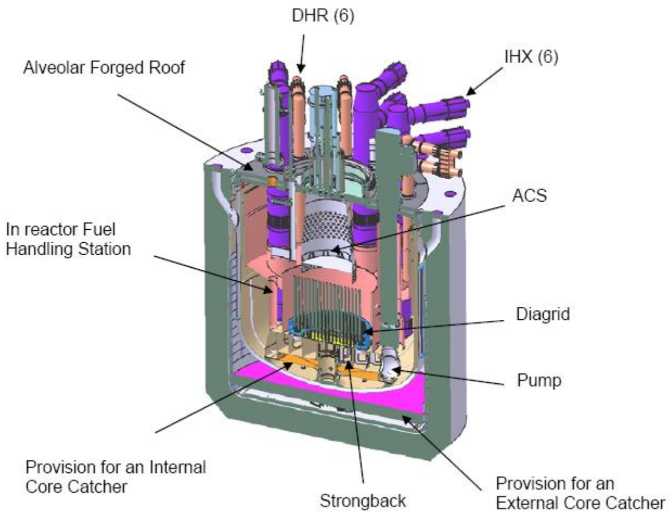
- Improved Safety to achieve a robust architecture including the robustness of the safety demonstrations
- Financial risk comparable to that of other means of energy production
- A flexible and robust management of nuclear materials
- To contribute to the re-build of European expertise in SFR technology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

Plant Layout	Pool Type
Reactor heat output	3600 MW_{th}
Net electrical output	1500 MW_e
Plant lifetime	60 Years
Global Efficiency	42%
Availability Objective	90%
IHX	6
DHX	6
Primary pumps	3
Secondary loops	6
DRC loops	6

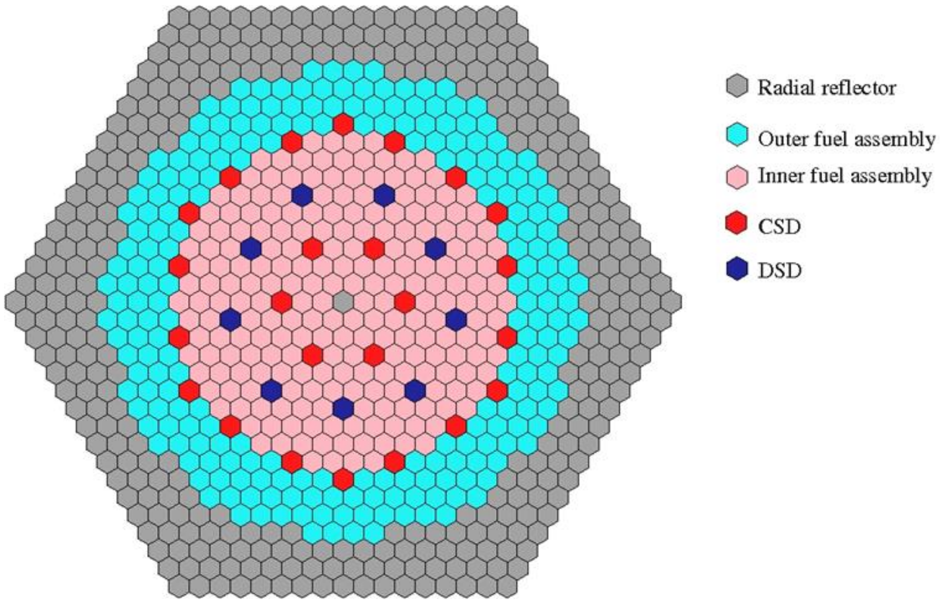


➔ **Main design objectives:**

- 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

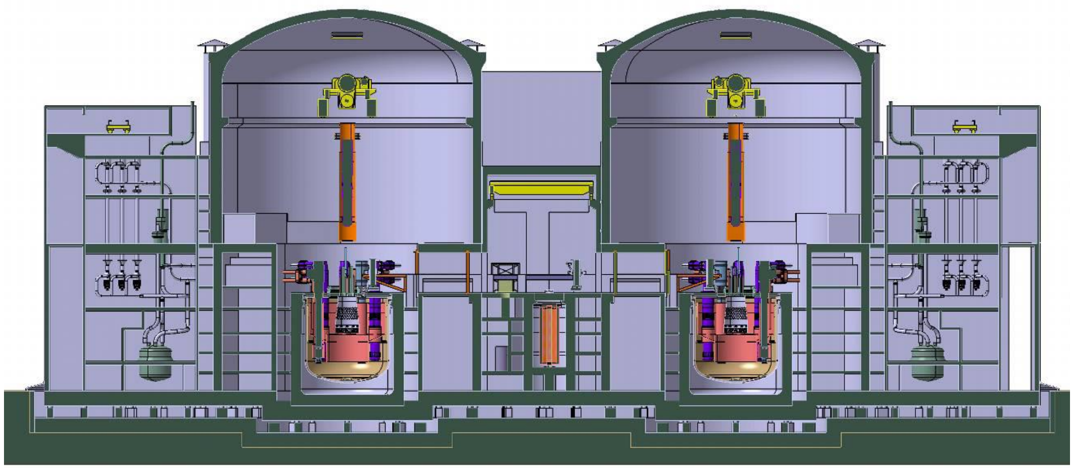
Fissile volume (m^3)	17.4
Outer core radius (cm)	245
Power density (W/cm^3)	206
Pu content by zone (% vol)	14.5 / 16.5
Fissile height (cm)	100
Assembly pitch (mm)	210.8
Pin diameter (mm)	10.7
Fuel residence time (efpd)	2 050
Average Burnup (GWd/t)	100
Number of pins	271
Mass $UPuO_2$ (t)	79
Mass $Pu0_2$ (t)	12



➔ **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:

	Level of defence in depth	Objective of the level	Essential means	Associated plant condition categories	Radiological consequences
Original design of the plant	Level 1	Prevention of abnormal operation and failure	Conservative design and high quality in construction and operation	Normal operation	Regulatory operating limits for discharge
	Level 2	Control of abnormal operation and failure	Control, limiting and protection systems and other surveillance features	Anticipated operational occurrences	Regulatory operating limits for discharge
	Level 3 (1)	Control of accident to limit radiological releases and prevent escalation to core damage conditions (2)	Safety systems Accident procedures	DiD Level 3.a Postulated single initiating events	No off-site radiological impact or only minor radiological impact (see NS-G-1.2/4.102)
		Control of accident to limit radiological releases and prevent escalation to core melt conditions (3)	Engineered safety features (4) Accident procedures	DiD Level 3.b **Selected multiples failures events** including possible failure or inefficiency of safety systems involved in DiD level 3.a	
	Level 4	**Practical elimination of situation that could lead to early or large releases of radioactive materials** **Control of accidents with core melt to limit off-site releases**	**Engineered safety features to mitigate core melt** **Management of accidents with core melt (severe accidents)**	**Postulated core melt accidents (short and long term)**	Limited protective measures in area and time
Emergency planning	Level 5	Mitigation of radiological consequences of significant releases of radioactives materials	Off-site emergency response Intervention levels	-	Off site radiological impact necessitating protective measures

Source: Safety Objectives for New Power Reactors, WENRA Reactor Harmonization Working Group

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

Plant conditions	Events	Indicative Fr/year
DBC1 Normal operation condition	**Power operation, normal transients, commissioning**	
DBC2 Anticipated Operational Occurrences	**initiating events might occur several times during the plant life**	**> 10^{-2}**
DBC3 Design Basis Accident	**initiating events are not expected to occur during the plant lifetime return to operation**	**10^{-2} - 10^{-4}**
DBC4 Design Basis Accident	**initiating events are not expected to occur during the plant lifetime plant restart not required**	**< 10^{-4}**
DEC Design Extension Condition	**low frequency events considered in the design corresponding to multiple failures**	**< 10^{-5}**

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

	Fuel limits	Fuel pin clad limit
DBC1	No melting	No open clad failure
DBC2	No melting	No clad failure except due to random effects
DBC3	No melting	No systematic (i.e., large number of) clad failure
DBC4	Any predicted localized "melting" to be shown to be acceptable. Simultaneous and coincident clad failure and fuel melting must be excluded	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
DEC (without whore core accident)	No whole core accident	
DEC (whole core Accidents)	No unacceptable damage of containment structures	

Safety Design Strategy

- The safety design strategy aimes 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:
  ➔Loss Of primary Flow , Transient Over Power and Loss Of Heat Sink
- 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

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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

Safety Design Strategy: Guidelines for the implementation of the main safety functions

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

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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

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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

SEVENTH FRAMEWORK PROGRAMME

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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

SEVENTH FRAMEWORK PROGRAMME

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