Recent progress of GFR program

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Outlines

An alternative Fast reactor to SFR

- **Main assets, reactor specifications**

Overview of the main design options, zoom on:

- **Fuel, core**
- **Reactor pressure vessel, primary circuit**
- **Safeguard, Decay Heat Removal systems**
- **Overall plant layout**

Preliminary safety analysis

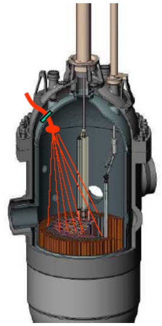
- **Safety approach**
- **DBA situations**
- **DEC situations**
- **PSA in support of the design**
- **Severe accidents**

Conclusion

The GFR: an alternative FR for longer-term

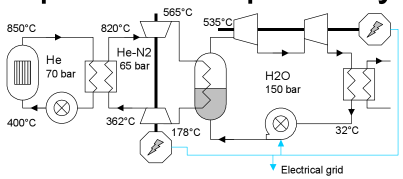
To combine Fast spectrum & helium coolant benefits

Some significant assets and a real potential



Safety (He)

- Great neutron transparency, attractive gas voiding reactivity effect < 1$
- No threshold effect: single phase cooling, chemical inertness (air, water)
- Potential for In-Service Inspection, T° instrumentation: optical transparency



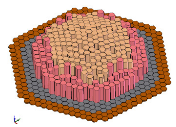
Competitivness (He)

- High temperature, potential for:
  - high energy conversion efficiency (45% - 48%)
  - a broad range of non electricity industrial applications (process heat, hydrogen, synthetic fuels…)

- Simplified management potential for repairing & dismantling: non toxic coolant, not activated, optical transparency

Fuel management (fast spectrum)

- Efficient use of natural ressources: Pu generation
- Potential for ultimate waste minimization: multi-recycling of all actinides



A promising concept, with other merits than the SFR

Innovative and challenging concept, demanding a fuel technology able to withstand high temperatures

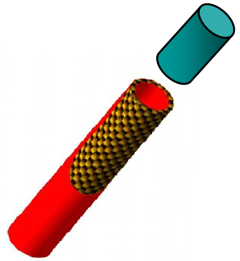
Fuel and core design

A fuel element made of refractory + high thermal conductivity materials :

- **Fuel: (U, Pu, AM)C**
- **Clad: reinforced ceramic composite SiC-SiCf**

A Plate-type fuel element investigated at first (2007, ref. for safety studies**)**

A Pin-type fuel element (2009 reference)



Nominal T_{fuel}°: up to 1200-1300°C, **T_{clad}°: up to 900-1100°C**

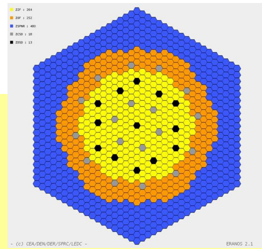
Fuel behaviour, min. of the stored energy, margins / accident

Boundary accidental cladding T° (DBC): 1600°C (a few hours)

Fission Product confinement (cladding thickness)

Ultimate accidental cladding T° (DEC): 2000°C (< ≅1h)

Non degradation of the geometry, to keep the core coolable

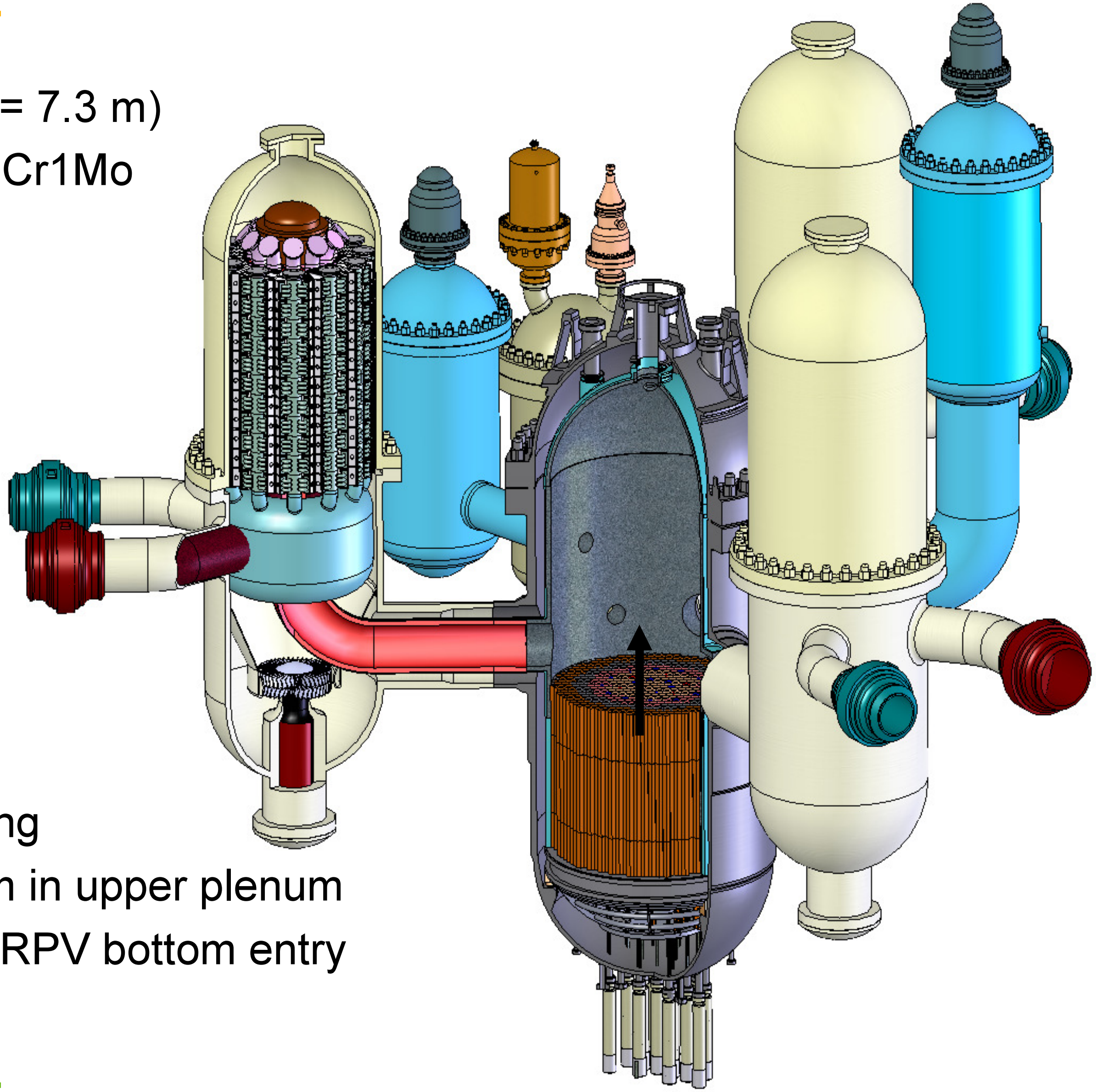


Core design

- **2400 MWth, 100 MW/m3** (trade-off neutronics performance vs safety issue)
- **$T°_{inlet/outlet}$ RPV : 400/850°C** (trade-off energy conversion η vs materials and safety issues)
- **Pressurized cool.: 7 MPa**; primary designed with **limited ΔP** to ease the gas circulation: $\Delta P_{core} \leq$ **0.15 MPa**; core designed with **favourable reactivity effects**…

Reactor pressure vessel, primary circuit

- Metallic vessel (Φ = 7.3 m)
- Vessel material : 9Cr1Mo
- Thermal shielding
- Cross-duct…



- Upward core cooling
- Fuel handling : arm in upper plenum
- CR mechanisms : RPV bottom entry

DHR means

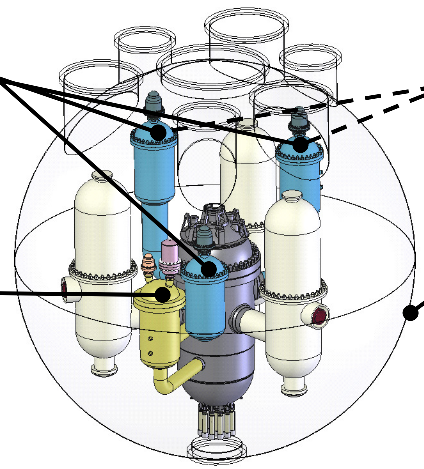
Decay Heat Removal strategy: close containment enclosing the primary circuit, diversified DHR systems to ensure core gas cooling in all situations

- **Exploiting the 3 normal loops (most frequent situations, primary integrity)**
  - **main blowers with pony motor** (being supplied by Diesel): **1°) DHR using steam generator** (by-pass of the turbine), **2°) in case of electrical grid loss, backup using a dedicated air cooler circuit (natural convection)** plugged in 2nd

- **Dedicated DHR systems (at the end of 2008)**
  - **R**eactor **H**igh **P**ressure cooling system **(in blue): 3 x 100%** with **blowers as normal systems** (0.4-7 Mpa) **& 2 x 100%** with **natural convect. as backup syst.**
  - **R**eactor **L**ow **P**ressure cooling system **(in yellow): 1 x 100% with blower designed for very low pressure (0.4-0.2 MPa)**

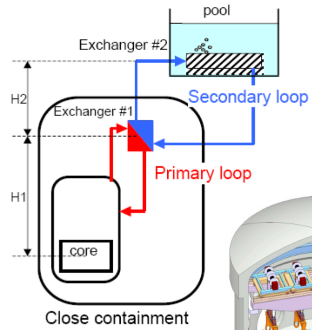
RHP, blowers (0.4-7 MPa)
axial mono stage,
Ptot < 500 KWe

RLP, blower (0.4-0.2MPa)
radial or **axial** technology
≅ 3 MWe



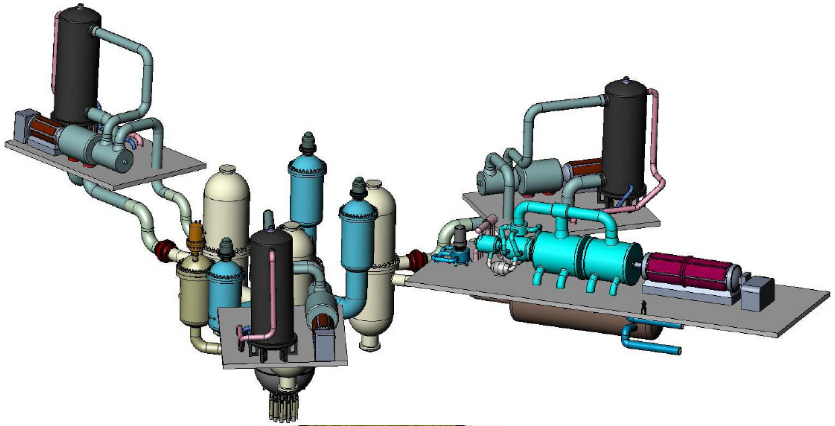
RHP, natural convection capability
$H1^{st} + 2^{nd} \cong 20$ m

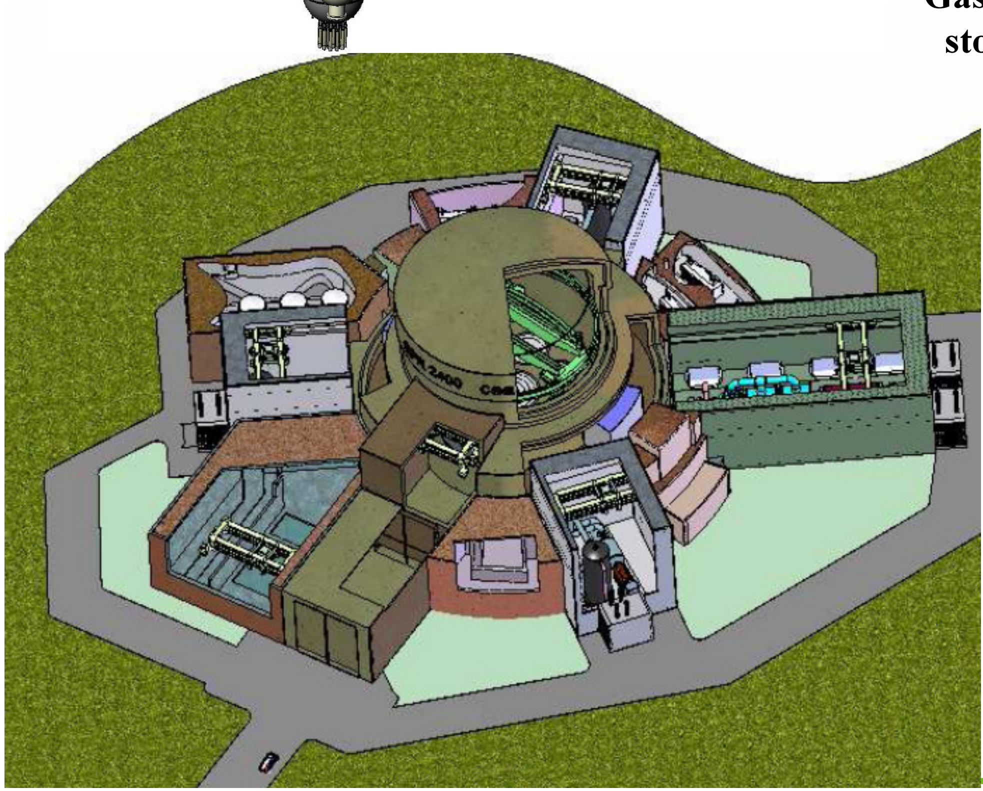
Close containment

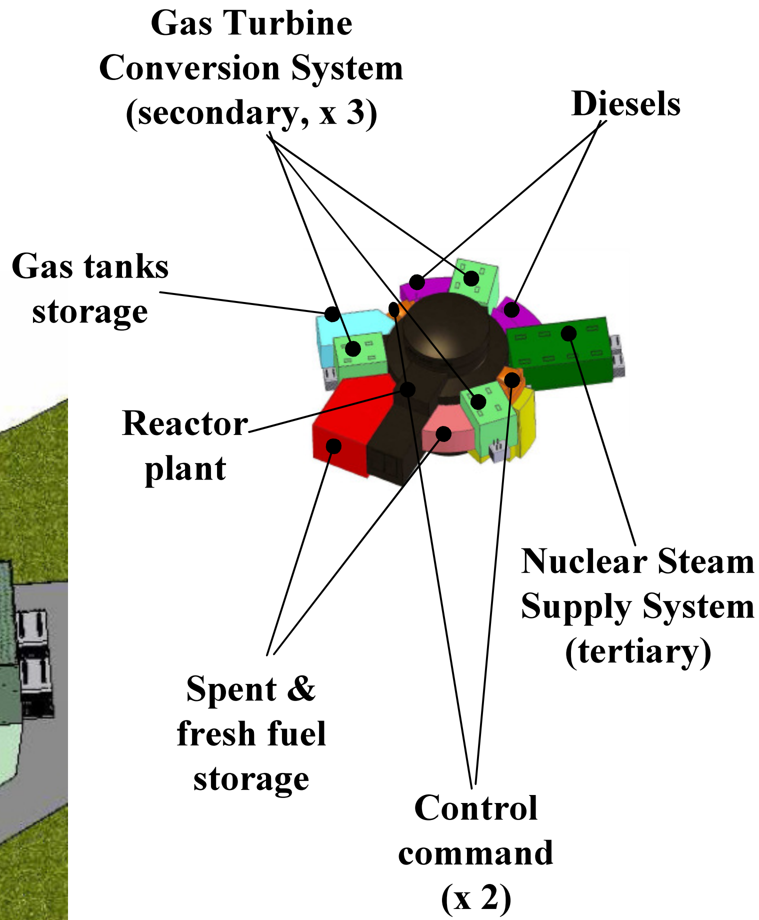


heavy gas injection tanks

GFR 2400 MWth, overall plant layout







Safety approach (1/2)

1- Governing principles

- ✓ **Defence in depth (DiD) concept**
- ✓ **Principle of physical barriers**
- ✓ **The safety functions**
- ✓ **ALARA approach for radiation protection**

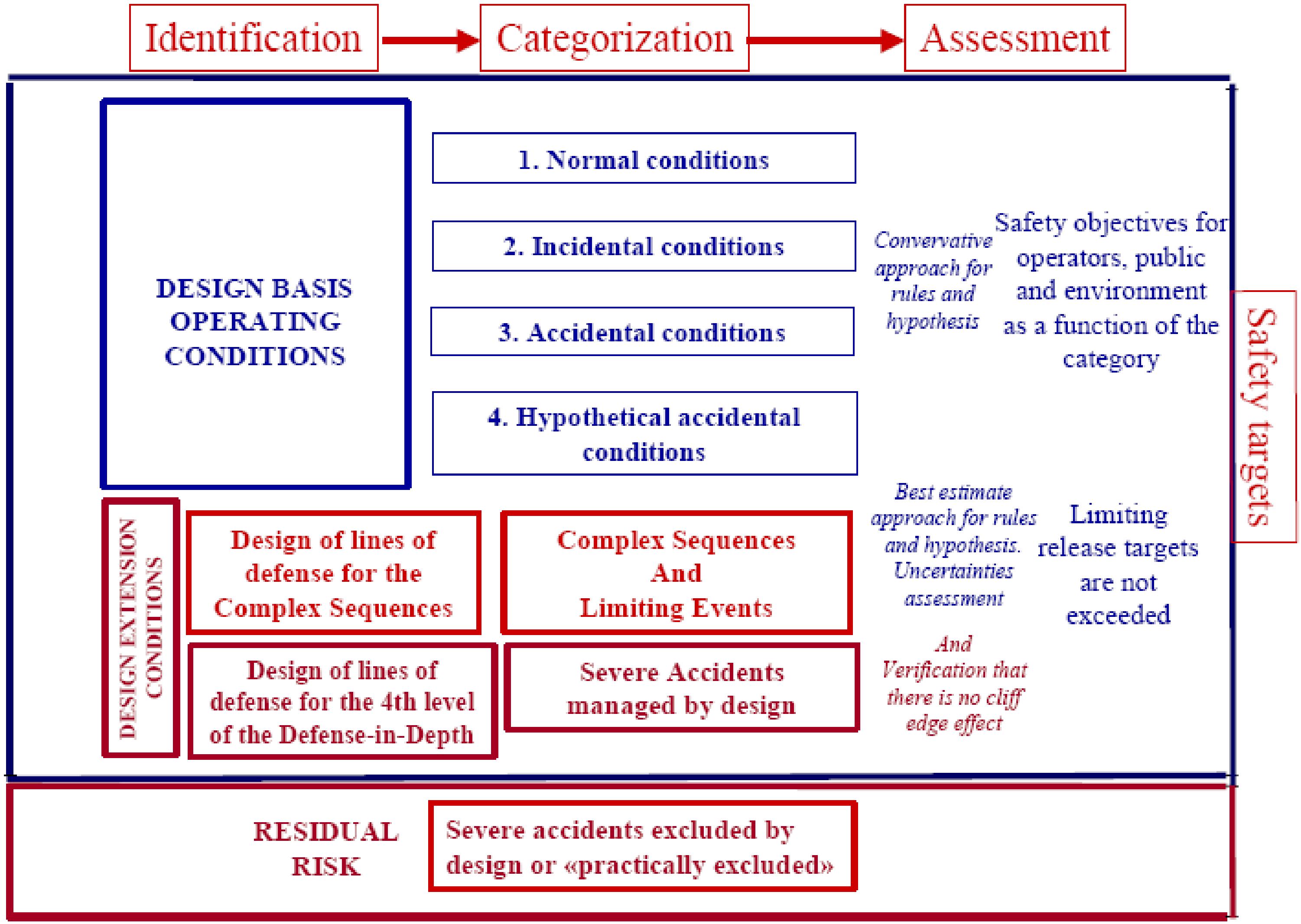
2- General frame of the safety analysis

- **Identification and preliminary categorization of initiating events (IEs)**

- **Deterministic rules for the safety analysis**
  - Categorization of bounding situations resulting from IE + single aggravating failure (only the safety systems are considered available for DBAs)
  - Categorization of complex sequences

- **Combination of deterministic and probabilistic methods**
  - LOP, study of operating conditions, PSA and feed-back on categorization
  - Objective provision trees as an help to draw an invetory of safety provisions

Safety approach (2/2)



Deterministic analysis (1/2)

- **Objectives : assessment of the performance and of the robustness of the DHR system (DBA), including cross failures (DEC)**

- **Situations considered :**

  DBAs : 100 % PN + EI + single aggravating failure

  - Intermediate states still to be addressed

  DEC : → 100 % PN + EI (DEC)

  → Complex sequences → 100 % PN + EI (DBA) + multiple failures

- **Acceptance criteria :**

  category 3 situations :

  upper plenum temperature < 1250°C ; clad temperature < 1450°C

  category 4 situations, the more limiting criterion being considered among :

  fuel temperature < 2000°C ; clad temperature < 1600°C

  upper plenum temperature < 1250°C ;

  no degradation of the fluid channel able to prevent the core cooling ;

  category 3 and 4 :

  controlled state must be reached at the end of the sequence

- **Single agravating failure considered**

  the failure of a Diesel train

  the failure of a blower when actuated

  the failure of the opening of a DHR loop

  the failure of the closing of a main loop

  → The one having the most adverse effect is considered for each IE

Deterministic analysis (2/2)

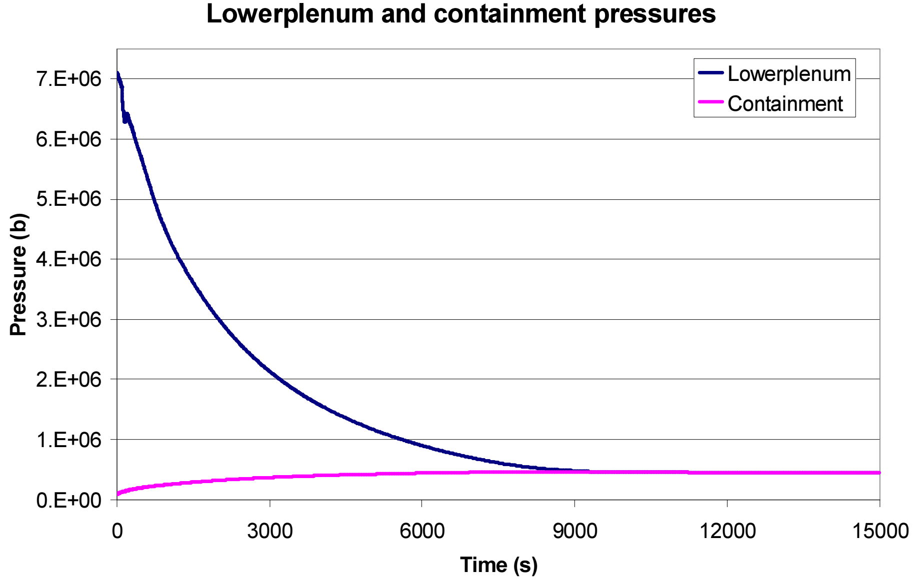
LOCAs preliminary discrimination and classification status

- Small leaks compensable with the HSS (limit size to be defined)
  - **Category 2**
- Small breaks controllable with natural convection (heavy gas injection) in case of failure of the forced convection means
  - **up to 3 inches, category 3**
- Large breaks
  - **Inducing a reverse flow in the core (could require an additional decoupling criterion on the cooling transient on clads and vessel)**
  - **larger than 3 inches, Category 4**

Some examples of transients (DBA Conditions)

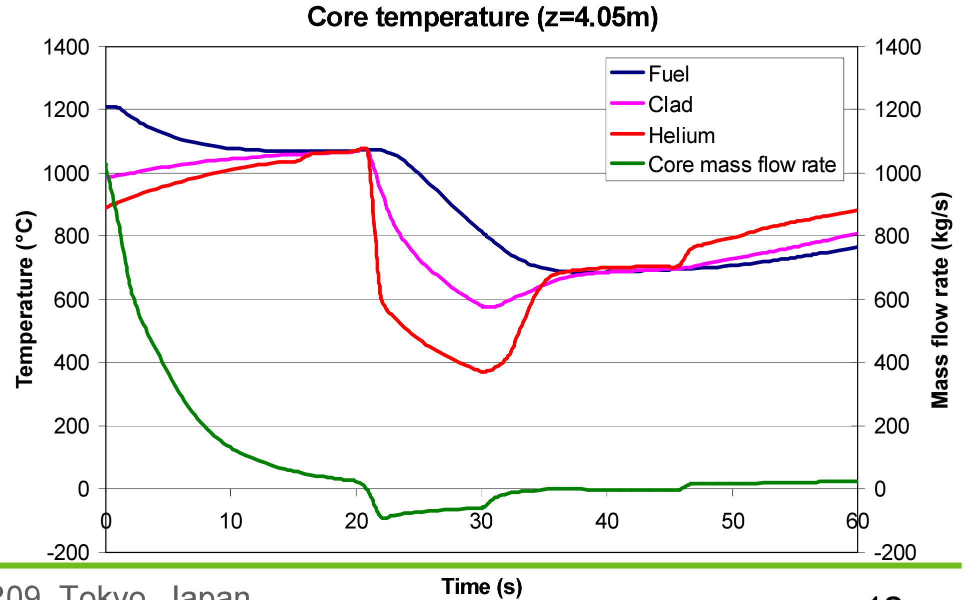
CATHARE2 calculation of a 1 inch break (cat. 3 accident)

pressure transient



CATHARE2 calculation of a 10 inches break (cat. 4 accident)

temperature and flow rate transient



Summary results of transients (DEC Conditions)

Results of Cathare calculations

Situation	Maximum clad temperature
Blackout (2 DHR in natural convection)	1006°C
Blackout with 1 DHR loop available	1040°C
Blackout with 1 DHR loop available and a primary valve failed open	1090°C
IHX 10 inches break with 1 DHR loop available	1190°C
IHX 10 inches break with 1 DHR loops available in natural convection	1470°C
Primary circuit 10 inches break with 1 DHR loop available	1560°C
Primary circuit 10 inches break combined with a failure of closure of one primary isolating valve with 2 DHR loop available	> 1600°C for 15 mn (frequency < 10-7/yr)
Primary circuit 10 inches break combined with a failure of starting of one DHR blower and the failure of isolating of this loop	Possible core damage (frequency << 10-7/yr)
ULOFA with DHR loops in natural circulation	> 1600°C for 170 s (frequency < 10-7/yr)

- **Experimental tests are foreseen to confirm that a short duration temperature excursion beyond 1600°C is acceptable as stated by the acceptance criteria**

- **Nevertheless, the occurrence frequency of such sequences has been assessed as residual thanks to the PSA results**

Probabilistic analysis

➢Level 1 PSA as a support to the reactor design

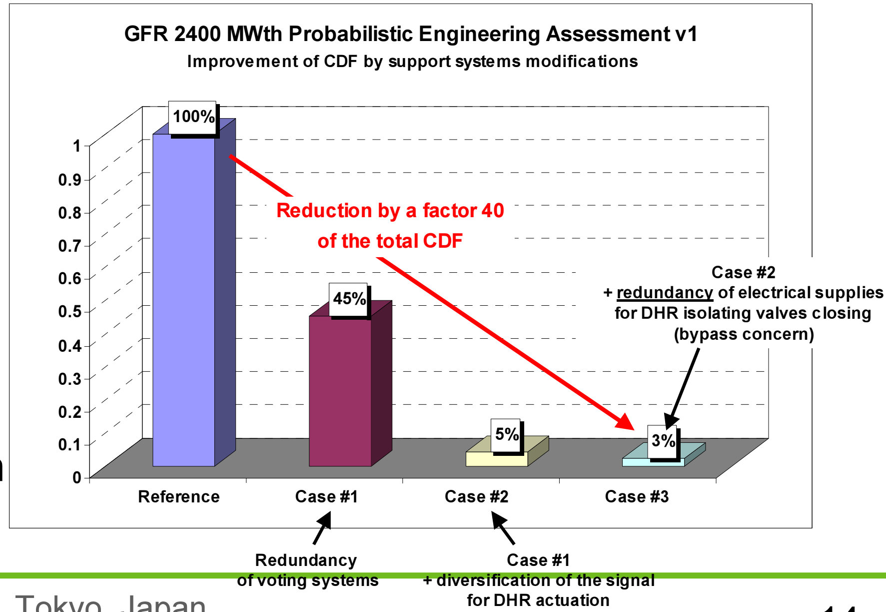
- ➢ **Identification of plant vulnerabilities**
- ➢ **System interdependencies and common cause failures (CCFs)**
- ➢ **Examination of risk benefits of various design options**
- ➢ **Will help to design optimization of safety systems in terms of redundancy and diversification (the definition of the DHR means already takes into account the early results of the PSA analysis)**

➢Initiating events considered

- ➢ **Consistent with the deterministic analysis (LOOP, LOFA, LOCA)**
- ➢ **Plus inadvertent reactor trip**

➢Results

Identification of the major contributors in the Core Damage Frequency : failure of the reactivity control and failure of the isolation of IHX 2nd circuit



Impact of design changes on core damage frequency

Severe accidents : the work in progress

The objective : to distinguish the severe plant situations that will managed by design from that practically eliminated

The approach : the various severe plant situations are gathered according different families, depending on:

- The integrity of the safety barriers
- The dynamics and the magnitude of the phenomena
- The threshold effects
- The possibility to control the key phenomena playing a role in the course of the accident

The material behaviour : considering that the GFR safety largely relies on the behaviour of the core materials at high temperature, **an experimental campaign is under way (SiC oxidation) and other tests are under elaboration**, starting from transient calculations in order to define the relevant temperature range and the associated atmosphere (nitrogen, air, steam, etc)

GFR viability : conclusions

The GFR appears as a promising concept according to the GEN IV objectives, complementary for long-term to Sodium Fast Reactor

GFR target : sustainable energy for electricity production with a high efficiency (48%) + high temperature for a broad range of other industrial applications

GFR design : a first consistent design has been defined (refractory fuel, reactor technologies common with the VHTR, large unit power, active/passive safeguard systems)

GFR feasibility : global confidence in the viability of the concept, satisfactory performances, great effort put on the safety analysis (deterministic and probabilistic) no showstopper was identified

GFR R&D : considering the progress already made on the concept as a whole, the priority is the fuel technology (design, fabrication, behaviour at nominal conditions and high temperature, etc)

Next step: viability report by 2012

BACK-UP

Deterministic analysis (1/2)

➢Category 3 reference situations

Bounding situations	Maximum clad temperature	Maximum upper plenum temperature
LOOP with 2 DHR loop available (DHR valve failure)	1005°C	922°C
1 inch LOCA with a main loop open (ML valve failure)	1024°C	897°C
1 inch IHX break	1010°C	909°C
1 inch secondary break	985°C	900°C

➢Category 4 reference situations

Bounding situations	Maximum clad temperature	Maximum upperplenum temperature
10 inches LOCA with 2 DHR loop available (DHR valve)	1470°C	1160°C
10 inches IHX break	1070°C	918°C

➢Additional design basis situations : assessment

→of the performance of 1 DHR loop

→of the ability of the reactor to face multiple failures (robustness)

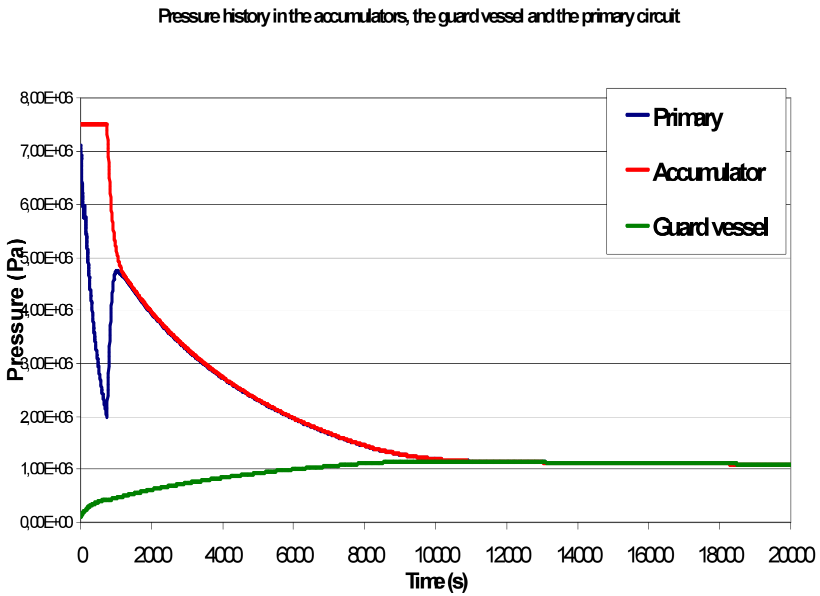
→ of the success criterion of particular sequences of the PSA

Bounding situations	Maximum clad temperature	Maximum upperplenum temperature
LOOP with 1 DHR loop and a main loop open (<= cat. 4)	1150°C	915°C
1 inch LOCA with one DHR loop available (cat. 4)	1110°C	935°C

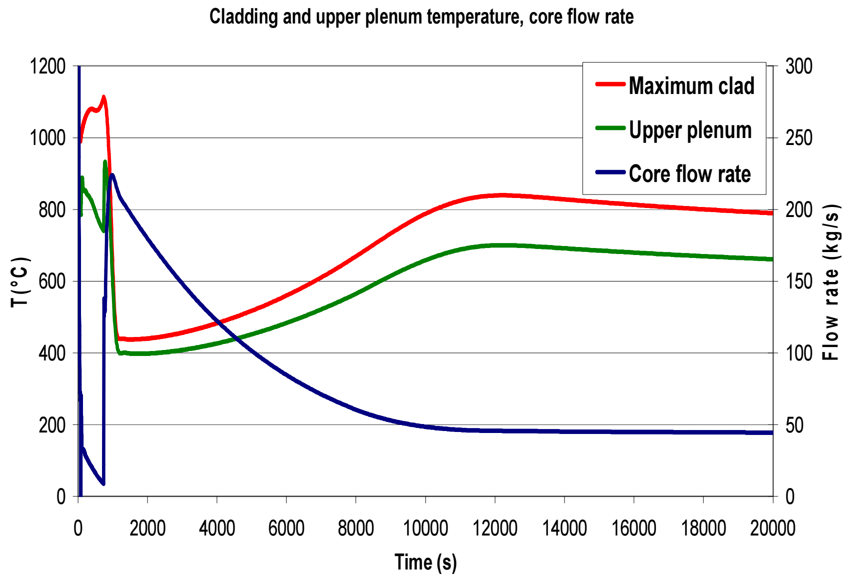
Deterministic analysis (2/2)

➢ SB-LOCA with failure of blowers at demand (cat.4 <= 4)

- **Tests are foreseen to assess nitriding process (→ the objective is to keep a coolable geometry)**
- **Argon is also an acceptable heavy gas candidate**



Pressure transient



Thermal transient

➢ LB-LOCA with failure at 24 h (DEC) → envelopped by the previous situation

Probabilistic analysis (1/3)

➢Level 1 PSA a a support to the reactor design

- Identification of plant vulnerabilities
- System interdependencies and common cause failures (CCFs)
- Examination of risk benefits of various design options
- Will help to design optimization of safety systems in terms of redundancy and diversification

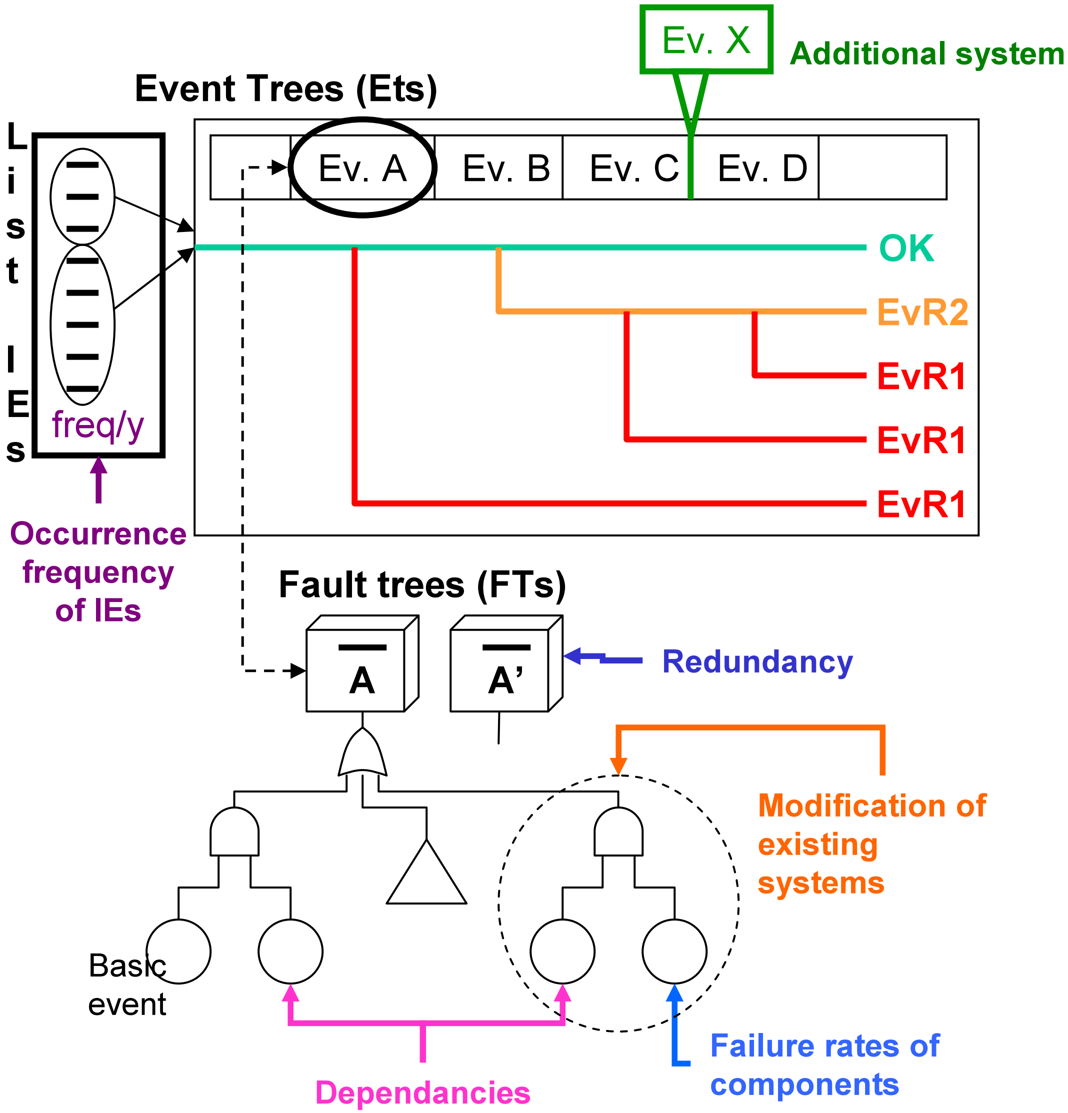
➢Initiating events considered

- Consistent with the deterministic analysis (LOOP, LOFA, LOCA)
- Plus inadvertent reactor trip
- All IEs will be taken into account in the next version of the PSA

➢Consideration about uncertainties

- Reliability of natural convection with a specific methodology (FP5 : RMPS)
- Technological uncertainty associated to very innovative components
- Physical uncertainty due to the performance of an innovative system
- Investigation on the most relevant failure rates for components and associated approach

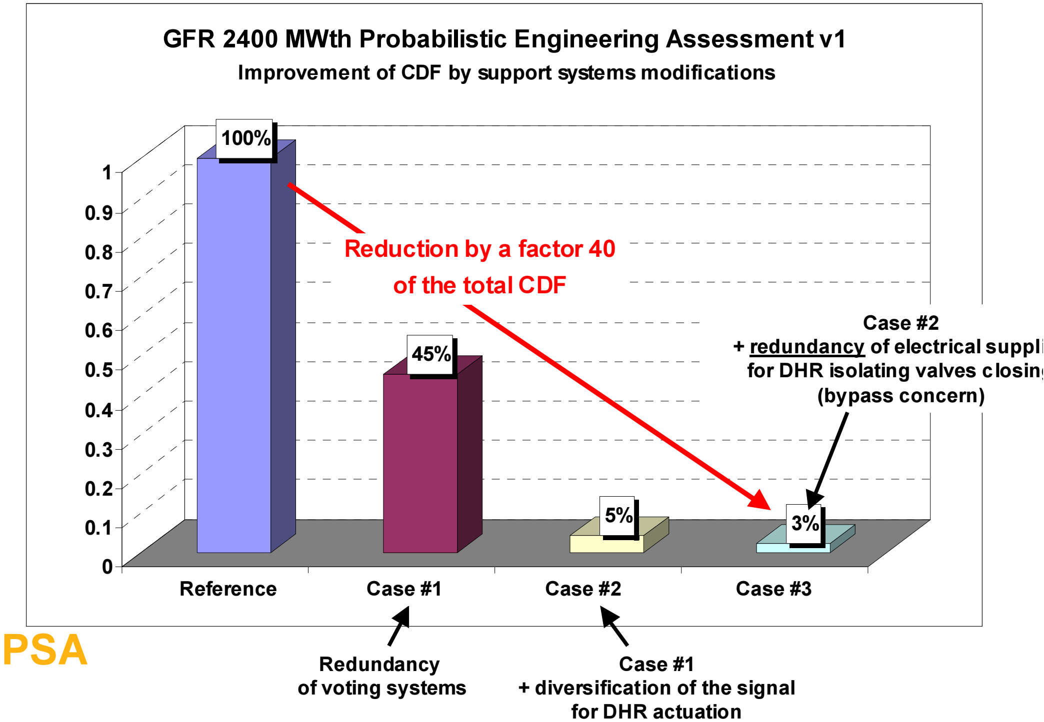
Probabilistic analysis (2/3) : sketch of the PSA modelling



Probabilistic analysis (3/3) : feed-back on design

➢ Design improvments through the PSA (signal elaboration is considered)

- ➢ **The PSA brought a complementary approach not only focused on system performance but also on their ability to be actuated**



➢ Other lessons learned from the PSA

- ➢ **Prioritization of R&D effort (design, study of severe accidents)**
- ➢ **The robustness of the DHR system must be improved for frequent pressurized situations (however current approach is very conservative : only DHR loops)**
- ➢ **Dependencies within the DHR system will be reduced**

Conclusions

➢Conclusions from DBAs analysis

- Good performance of the DHR system in FC and NC
- Low power blowers that can be supplied by NC for pressurized situations and for SB-LOCAs as well as for the long term control of LB-LOCAs
- Considering the dimensionning and the robustness of te DHR system (redondancy and diversification), by-pass situations due to wrong primary flow pathway permit to fulfill te decoupling criteria with a comfortable margin in most of the situations including te fast depressurization transients associated to a more limited margin.

➢Conclusions from DECs analysis

- The approach is up to now very conservative because all the systems should be assumed available as in our studies, the HSS and the main loops are not actuated but should be considered for risk reduction of frequent initiating events as suggested by PSA results
- Complex sequences at nominal and intermediate pressure can be controlled, even in NC
- The study of very hypothetical situations resulting from fast depressurizations combined to multiple failures leading to core by-pass had underlined the necessity to have support systems enabling the risk of wrong circuit configuration to be reduced (the same conclusions have been drawn from the PSA)
- PSA enabled to I/C system to be reinforced, thus leading to a large safety improvment

➢ Futur work

- The scope of the analysis will be extended (deterministic and PSA)
- Consideration of the use of the main loops and of the HSS
- Improvment of redundancy and diversification of flow pathway configuration components