severe accidents analysis in CEFR and technology gaps

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Safety Characteristics of SFR

Advantage	Disadvantage
High boiling temperature	Not in maximum configuration
High Thermal conductivity	Positive sodium voiding reactivity
Operation at low pressure	Chemical reactivity
large thermal capacity with plenty of sodium	Sodium frozen risk
	High power density and narrow flow channel in S.A.

- With the features of operating at low pressure, high thermal conductivity and high boiling temperature which means there is a large margin from sodium boiling, and the large thermal capacity with plenty of sodium in primary circuit, the SFR behaves to have inherent safety compared to light water reactors, especially behaves well in heat removal during accidents.
- The hypothetical core disruptive accident will be given much more attention, because SFR core is not in its maximum, that means molten core material relocation may lead to re-criticality, power excursion and large energy release.
- chemical reactivity of sodium means that sodium leakage into air or water will lead to sodium fire and sodium water reaction of high temperature and large energy release, which may threaten the integrity of the containment and the secondary circuit.
- Sodium may frozen in case of loss of power supply.

Severe Accidents Analysis in CEFR

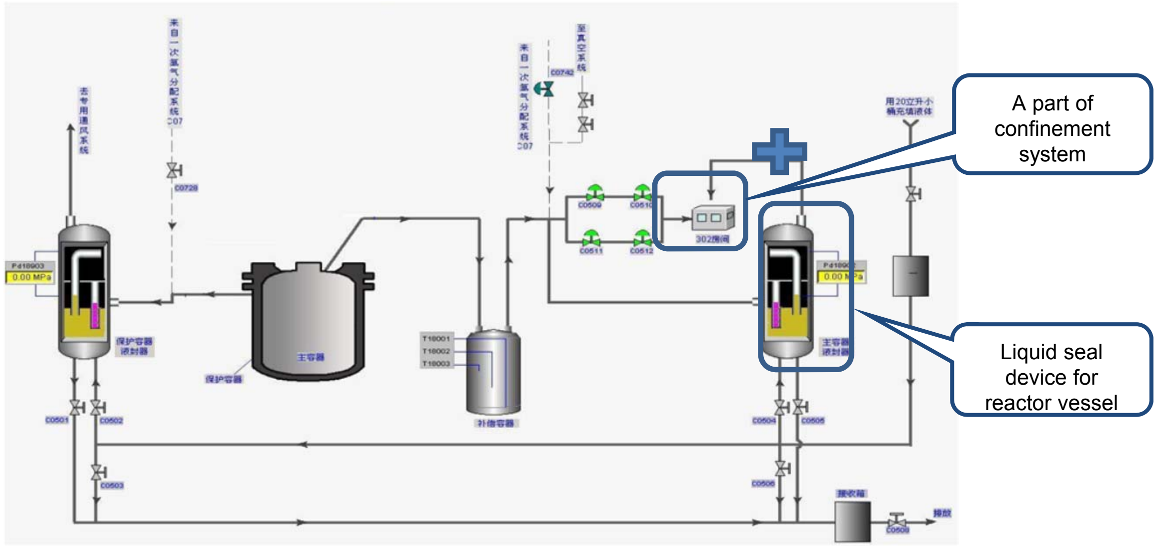
BDBA list

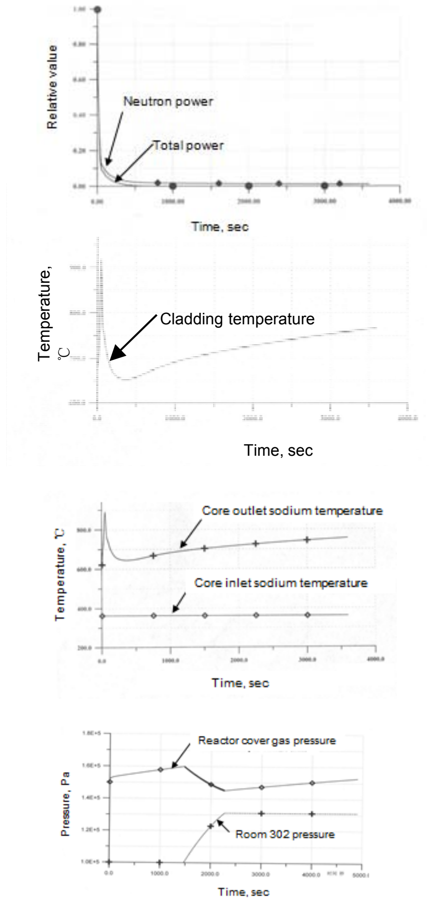
- Unprotected station black-out while air throttles of decay heat removal system couldn't open;
- Station blackout with air throttles of decay heat removal system couldn't open;
- Large sodium leakage induced by rupture of the primary sodium purification pipe with the isolation valve couldn't close;
- Large sodium leakage induced by rupture of both main vessel and guard vessel;
- Unprotected withdraw of a regulation control rod during power operation;
- Back-valves of both primary pumps close inadvertently simultaneously;
- TIB.

R&D on severe accident analysis

- CEFR HCDA analysis
- Hypothetical ULOF and UTOP analysis using SAS4A code (in the framework of U.S.-China bilateral cooperation)

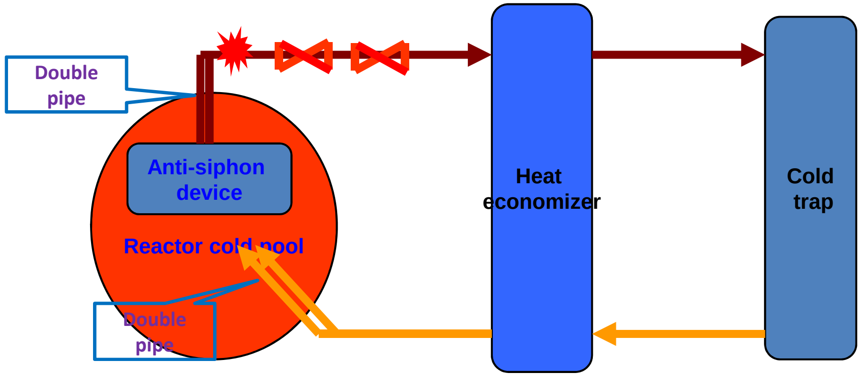
Unprotected station black-out combined with LOHS





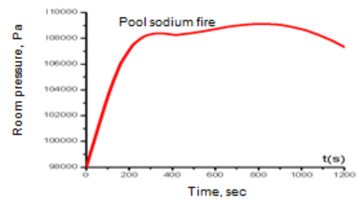
- The analysis was conducted using GRIF code from Russia and pressure simulation model;
- since it is totally loss of heat sink, the heat in the primary circuit accumulates resulting in expansion of reactor covered gas and high pressure;
- When the pressure exceeds threshold of the liquid seal device of the reactor overpressure protection system, the liquid seal opens to release covered gas to the radioactivity confinement room, then the pressure decreases and the liquid seal gets back to close;
- Liquid seal device for reactor vessel acts as the function of pressure release to protect the integrity of reactor vessel;
- The confinement room is air tightness, acting as the function of confining radioactive materials.
- The accident assumed that the operator acted 45mins later after the accident occurred.

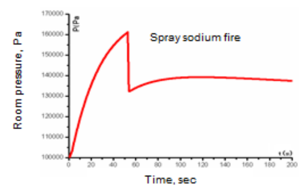
Sodium fire accident analysis

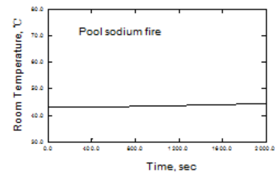


Accident analysis

1) The design basis is pool type sodium fire, but spray sodium fine is required to be analyzed for evaluating the design;
2) The pressure consequence of spray sodium fire is very high exceeding the design pressure of the room structure;
3) For spray sodium fire analysis, it's difficult to define the fraction of spray type fire.







Prevention and mitigation measures

In order to detect sodium fire and mitigate consequences of the accident, there are some design features, sodium fire detection instruments and several measures are taken:

1) Anti-siphon device is designed to terminate sodium leakage passively;
2) Apply "BOX" design concept, limiting sodium fire in a certain small room with air-tightness by physical isolation;
3) Normal ventilation system automatically shift to accidental ventilation system when sodium fire is detected;
4) In all sodium technical rooms, sodium fire restrain pans are paved all over the floor, steel liners for concrete walls are installed;
5) Smoke detector, sodium leakage detector and short circuit detector are set for detecting sodium fire;
6) Expansion graphite powder fire fighting system

Theoretic and numerical study on molten fuel behavior after TIB accident and TIB analysis

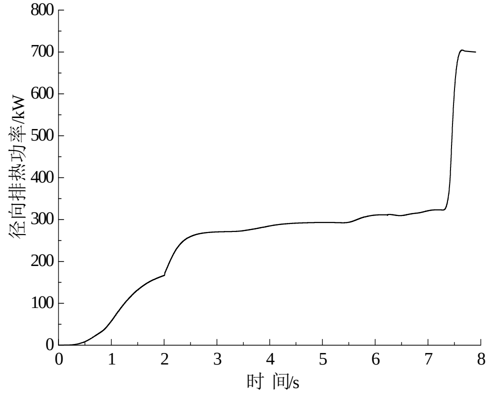
a) This study was mainly focused on the theoretical and numerical model of molten fuel behavior after TIB.

b) A code was developed, in which a two-fluid sodium boiling model to describe sodium boiling and two-phase flow is developed. The motion of molten cladding and fuel, and the collapse of fuel were dealt with empirical approach. The behavior of fuel-steel mixed volume heated boiling pool in the blocked subassembly was predicted by a semi-empirical model.

c) Using these models, numerical simulation was performed for the SCARABEE experiments and numerical result was predicted for CEFR TIB accident.

d) Whereas, the complexity of the phenomena, lack of experiment data, and short of such experience, this study was just preliminary and ceased before the melting through of the subassembly can wall;

e) "Specially designed Regulation control rod over speed alarming signal for TIB" was set for monitoring TIB.



Radial heat transfer vs. time

CEFR HCDA analysis

a) Calculate mechanical energy release of CEFR during severe accidents using SUREX and COMBUS code based on Bethe-Tait model, which is from FRANCE .

b) Since CEFR is a small scale fast reactor and sodium void reactivity is negative, there is no reasonable initiator to induce core melting, so just assumed a large and fast reactivity insertion.

Initial input:

- Initial power: nominal power 65MW;
- Initial fuel average temperature: 2900K, 3100K;
- Reactivity ramp: 20$/s, 50$/s

Calculation results:

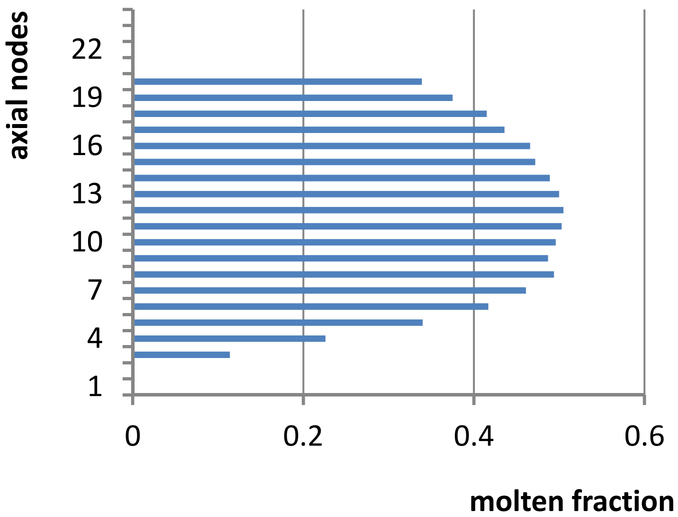
Initial Input			SUREX calculation	COMBUS calculation
Power，MW	Fuel Avg. Temperature，K	Reactivity ramp，$/s	Molten temperature before expansion，K	Mechanic Energy，MJ
65	2900	20	3134	13.5
65	3100	50	3482	28.3

ULOF and UTOP analysis using SAS4A code

a) In the framework of U.S.-China bilateral cooperation, SAS4A/SASSYS-1 code was transmitted to CIAE by U.S. DOE in 2009.

b) Now, we are doing severe accidents study based on CEFR design using SAS4A code, mainly on ULOF and UTOP accident analysis.

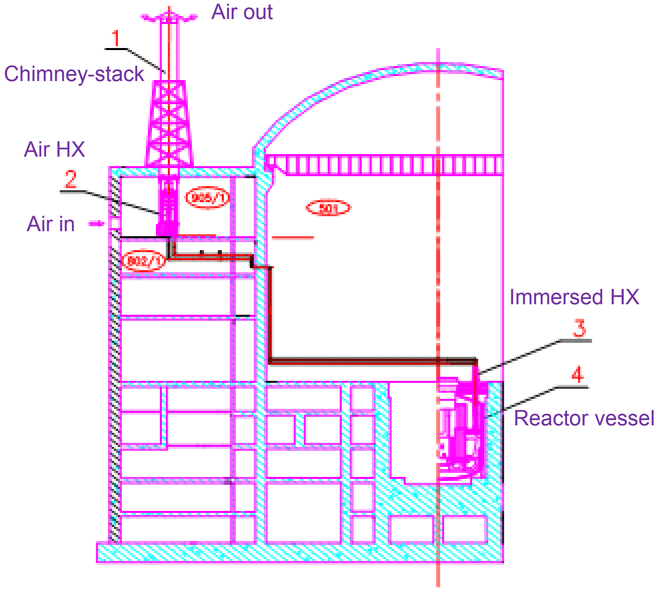
c) There will be some different phenomena related to severe accidents of CEFR because CEFR has a different fuel design, e.g. lower fission gas plenum and no upper fission gas plenum, annular fuel pellet design.



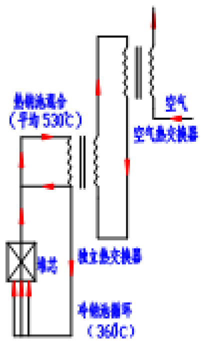
Molten fraction in drive channel in UTOP (assumed quick and large reactivity insertion)

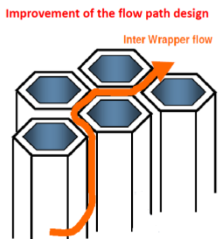
safety measures against severe accidents in CEFR

Passive decay heat removal system



Layout of PDHRS

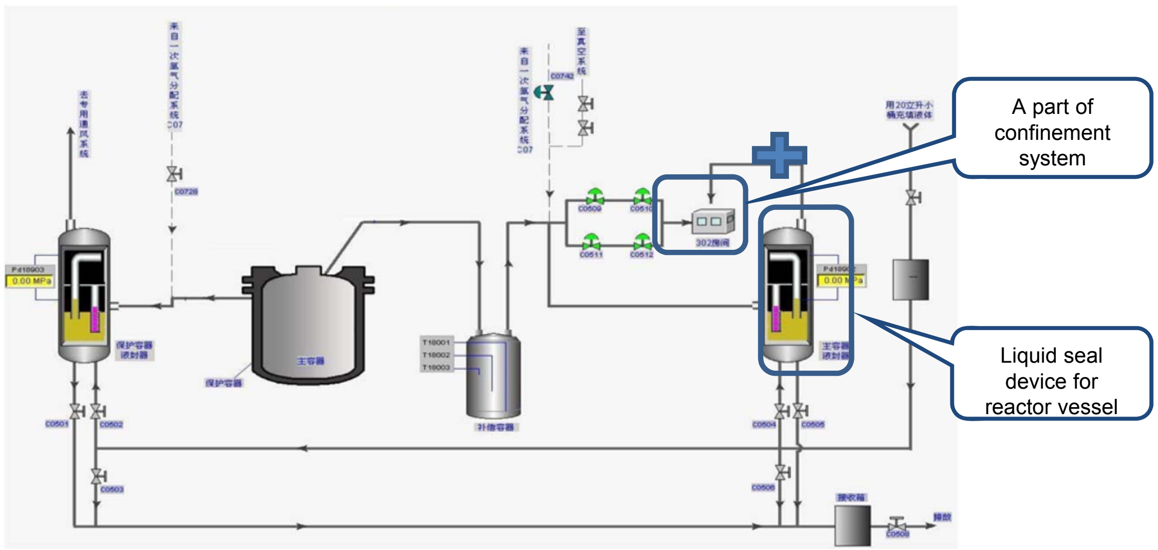




- The PDHRS is designed to have 1.05MW heat removal ability during accidents, about 1.6% of the reactor thermal power;
- In nominal operation, the PDHRS operates in standby condition with 0.0525MW heat removal.
- The ultimate heat sink is atmosphere;
- The system operates passively by natural circulation except that the air damper is powered by UPS;
- It is designed to have Inter-wrapper flow path to cool the core;
- The air damper can be opened by uninterruptible power supply, triggered by accident signal.

safety measures against severe accidents in CEFR

Overpressure protection system combined confinement system



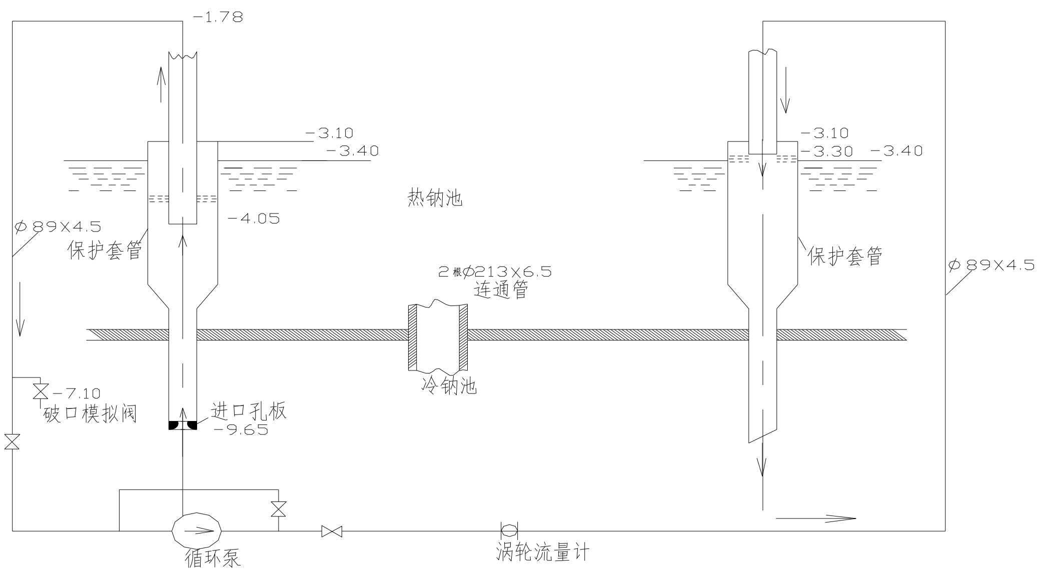
- The performance of liquid seal device for pressure release was demonstrated; But more serious scenarios, such as large energy release during HCDA is not considered.

- Liquid seal device for reactor vessel acts to release pressure for protecting the integrity of reactor vessel;
- The confinement room with leak tightness acts to confine radioactive materials.

safety measures against severe accidents in CEFR

Anti-siphon device

- Anti-siphon device is for breaking siphon function to terminate sodium leakage passively when the primary purification pipe rupture to avoid large sodium leakage and maintain the level of rector vessel;
- As preventive measures against severe accident, the performance was demonstrated.



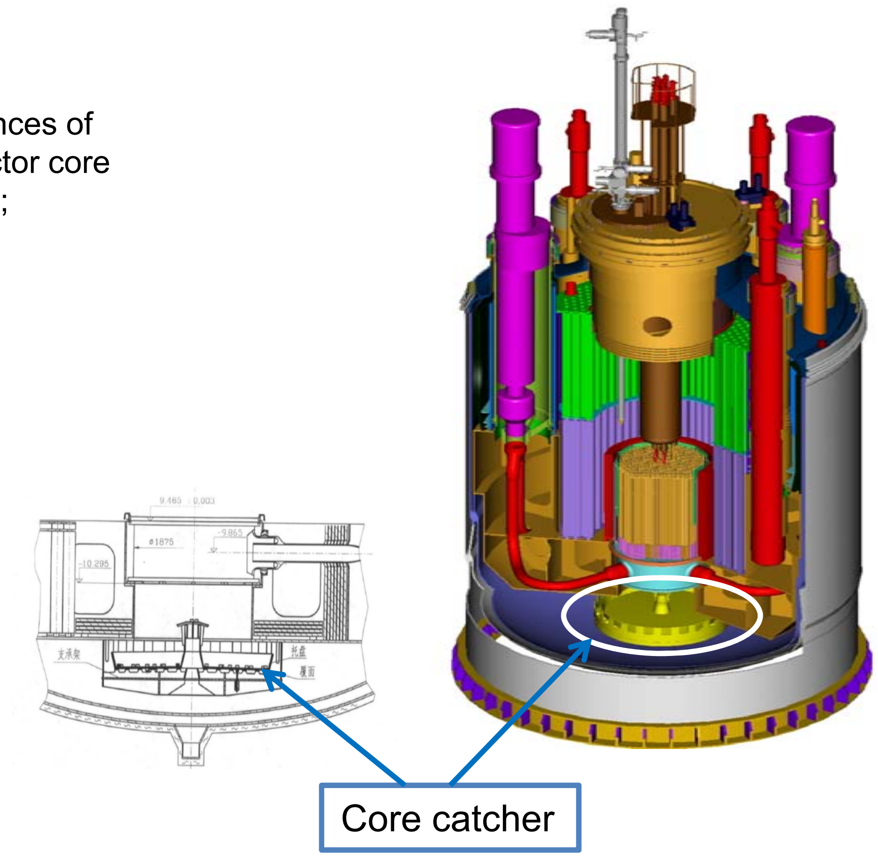
Illustrative diagram of anti-siphon device and the primary auxiliary pipe

Demonstration facility for anti-siphon device

safety measures against severe accidents in CEFR

Rector core catcher

- For mitigation the consequences of possible core melting, a reactor core catcher is designed in CEFR;



Lessons learned from Fukushima Accident

- The Fukushima accident is induced by extremely natural disaster, which is the combination of external events of earthquake and following tsunami beyond the design basis;
- The root cause of the accident is Long term station black-out caused by extremely natural disaster, safety review on long term station black-out is needed;
- Total loss of Ultimate Heat Sink is not taken into account in the design;
- Cooling and heat removal of the spent fuels storage is not adequate in accident conditions of long term loss of AC power supplies.

Technology gaps on safety measures against severe accidents

a) Strengthen Safety measures against extreme external events

- Based on characteristics of specific plant site, some extreme external events should be considered in the design.
  - For the specific plant site, earthquake and tsunami may not be the main point, however, specific extreme hazard for the specific site should be considered;
  - In the area where the Fukushima accident occurred, external hazard of earthquake and tsunami should be paid more attention in design;
  - Severe weather disasters, such as the ice and snow calamity in South China 2008, should be considered to prevent potential sodium frozen during SBO;
  - For a inland site in China, a flooding hazard may be the contribution, or sometimes a severe drought should be considered for ultimate heat sink;
  - PSA method should be strengthened on analysis of external events.

Technology gaps

b) Containment design against large scale radioactive materials release should be emphasized

- For SFRs, Containment and its safety features should be able to withstand extreme scenarios including HCDA and large scale radioactive sodium fire.
- The reactor primary coolant boundary and primary cover gas boundary should be independent from the containment.

Technology gaps

c) Strengthen Decay heat removal system design

- Combination of decay heat removal system designs by active mechanism and passive mechanism should be considered;
- Decay heat removal system with air cooled exchanger which using atmosphere as ultimate heat sink against loss of heat sink should be incorporated in the design;
- Safety design and measures should be considered to prevent sodium freezing in case of loss of power supply which may lead to coolant circulation blockage;
- With the flow path of inter-wrapper as the major one, performance of natural circulation cooling the reactor core by the function of immersed heat exchangers in the hot pool, should be demonstrated by experiments.

Technology gaps

d) Prevention and mitigation measures against core recriticality and following HCDA should be considered

- Recriticality has a high potential to occur in medium and large fast reactor core;
- A annular fuel pellet design may be helpful for early discharge of molten fuel to avoid recriticality scenarios, further R&D should be conducted;
- In-vessel core catcher, is very helpful for retention of molten core and keeping integrity of the primary coolant boundary.

Technology gaps

e) Passive safety features

- The action of passive safety features is very crucial for mitigation of severe accidents in extreme severe situations;
- But the success of passive safety features is much dependent on physical process which many influencing factors act on;
- A robust demonstration should be conducted on passive safety features, accounting for all possible severe scenarios;
- Reliability analysis and availability analysis of passive safety features should be strengthened.

Technology gaps

f) Ensure power supply

- Emergency power supply should be ensured in case of long-term loss of off-site power;
- Diversity and redundancy of emergency power supply should be considered;

Summary

- Sodium fast reactors have many favorable inherent safety characteristics compared to LWR;
- CEFR is a small fast reactor and designed to have many passive features, so that behaves well in case of BDBAs;
- Based on accidents analysis of CEFR and learned from Fukushima accidents, more technology gaps on safety measures against severe accidents should be strengthened.

Thanks for your attention!