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Interim Safety Analysis on TRU Burner Sodium-cooled Fast Reactor

Jonggan Hong*, Seok Hun Kang
Korea Atomic Energy Research Institute, 989-111, Daedeok-daero, Yuseong-gu, Daejeon, 34057
**Corresponding author: hong@kaeri.re.kr*

1. Introduction

KAERI has been developing a 3800 MWth TRU (transuranic waste) burner sodium-cooled fast reactor from 2018 with the aim of reducing the volume and toxicity of domestic spent fuel. At the end of 2018, a conceptual design of the burner was finished to propose a way to accomplish the complete burning of TRU in spent fuel from domestic LWRs [1].

MARS-LMR code was developed for safety analysis of liquid metal fast reactors in KAERI by updating core reactivity feedback models and sodium property based on RELAP code. MARS-LMR has been validated by both separate effect tests such as STELLA-1 and MONJU, and integral effect tests such as EBR-II and Phenix. KAERI conducted the safety analysis on PGSFR with MARS-LMR, which was included in PSID (2015) and SDSAR (2017) of PGSFR [2].

In this work, an interim safety analysis of TRU burner SFR was carried out at the conceptual design phase. The safety assessment on six accident scenarios including DBAs and DECs was conducted with MARS-LMR code. Particularly based on various reactivity feedback models for the metallic TRU fuel, inherent safety of the burner reactor was evaluated by obtaining the transient responses of the reactor under the unprotected (w/o SCRAM) accident conditions (DEC).

2. Outline of safety analysis

2.1 Overview of TRU burner SFR

The pool-type TRU burner produces 3800MWt at full power operation and is largely divided into primary heat transport system (PHTS), intermediate heat transport system (IHTS), decay heat removal system (DHRS) and power conversion system (PCS) (Fig. 1). PHTS has three mechanical pumps to supply the primary coolant into the core. Six decay heat exchangers are located in cold pool to transfer the decay heat to six DHRS trains. Six IHXs are installed in hot pool to transfer the core heat to steam generator system through six IHTS loops. Core inlet and outlet temperatures are 360 and 510°C.

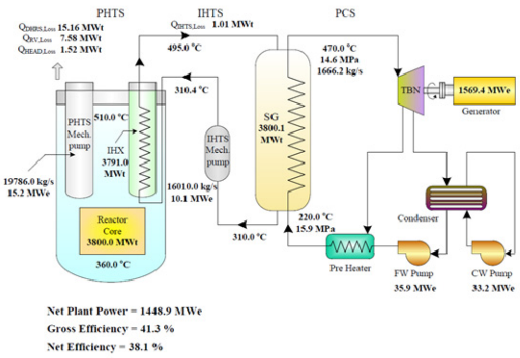

Fig. 1. Heat balance of TRU burner SFR.

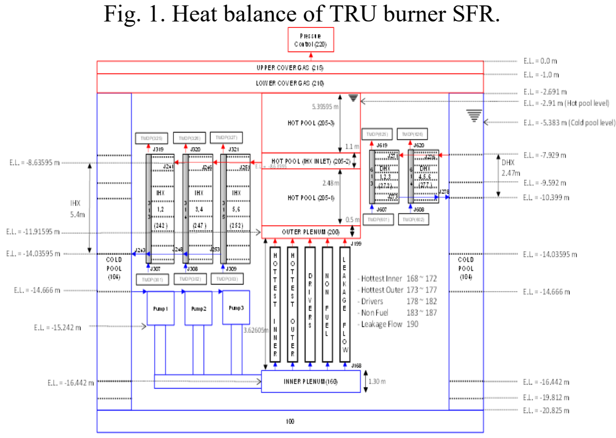

Fig. 2. PHTS nodalization of TRU burner SFR.

The core was simulated by five parallel flow channels, including the hottest driver fuel assembly of inner core, the hottest driver fuel assembly of outer core, the rest of driver fuel assemblies, non-fuel assemblies, and leakage flow (Fig. 2).

The beginning of equilibrium cycle (BOEC) was conservatively employed as a reference core condition because BOEC led to a higher maximum temperature of the fuel assembly than the end of equilibrium cycle (EOEC). Studies on three initiating events including loss of flow (LOF), transient of power (TOP), and loss of heat sink (LOHS) were conducted under the protected (w/ SCRAM) and unprotected (w/o SCRAM) conditions. Various reactivity feedback models were taken into account with the point-kinetics module, including fuel axial expansion, core radial expansion, CRDL/RV expansion, fuel Doppler, coolant density reactivity.

The automatic emergency shutdown is triggered by the reactor protection system (RPS) signals, including high power to PHTS flow ratio trip (HPFR; 110%), high central subassembly outlet temperature trip (HCSOT; nominal+15°C), high core inlet temperature trip (HCIT; nominal+15°C), high individual subassembly outlet temperature trip (HISOT; nominal+15°C), and overpower trip (OP; 110%). Dampers and blowers in DHRS trains open and turn on, respectively by decay heat removal actuation signal (DHRAS) which is triggered by high core inlet and outlet temperatures

3. Safety analysis results

3.1 Design basis accident (DBA) results

Several conditions for conservative assessment of DBAs are assumed considering application of the single failure criterion and loss of off-site power (LOOP). Firstly, a single control rod assembly is not inserted when the reactor is shutdown. Secondly, two out of six decay heat removal trains are not operable due to the single failure criterion and maintenance, respectively. Thirdly, the reactor shutdown results in loss of both on- and off-site power, and thus the IHTS and feedwater pumps are also tripped off as well as the PHTS pumps. The core flow coastdown by PHTS mechanical pump is assumed with a 8s halving time, but no flow coastdown occurs in IHTS loops because the IHTS pump is an electro-magnetic pump.

3.1.1 LOF

The loss of primary flow caused by spurious trip of PHTS pumps initiates the LOF accident. As the core flow rate decreases abruptly, the reactor emergency shutdown is triggered by HPFR trip signal at 2.1s. Once the control rods are inserted into the core, the core power decreases dramatically due to large negative reactivity (Fig 3). After the reactor shutdown, on- and off-site powers are lost, and then IHTS heat removal rate also decreases abruptly because of IHTS and feedwater pump trip off. At 8.5s, the temperature rise at the core outlet leads to automatic DHRS activation (DHRAS). DHRS heat removal rate gradually increases and starts to exceed the core power at around 40000s (Fig. 3), which keeps the coolant and fuel temperatures much lower than the sodium boiling point and fuel melting point (~1000°C), respectively (Fig. 4).

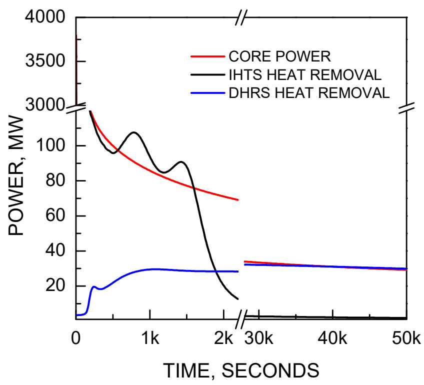

Fig. 3. Power responses of LOF accident.

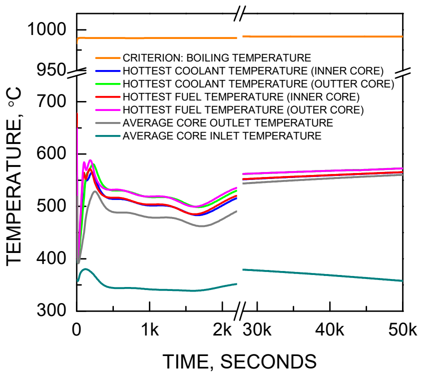

Fig. 4. Temperature responses of LOF accident.

3.1.2 TOP

A partial withdrawal of a single control rod initiates the TOP accident. Owing to the withdrawal of the control rod, positive reactivity insertion at a rate of 0.0065$/s to the maximum 0.4402$ at 67.6s occurs. Core power soars up to about 110% of normal power, but the emergency reactor shutdown is triggered by OP signal at 12.7s and the DHRAS is generated at 18.5s. DHRS heat removal rate gradually increases and begins to exceed the core power at around 40000s, which cools down the reactor safely (Figs 5,6).

3.1.3 LOHS

Feedwater pumps are tripped off and the heat removal path through IHTS becomes unavailable, which initiates the LOHS accident. The emergency reactor shutdown is triggered by HCIT signal at 62.7s and the DHRAS is generated at the same time. DHRS heat removal rate gradually increases and begins to exceed the core power at around 28000s (Figs. 7,8).

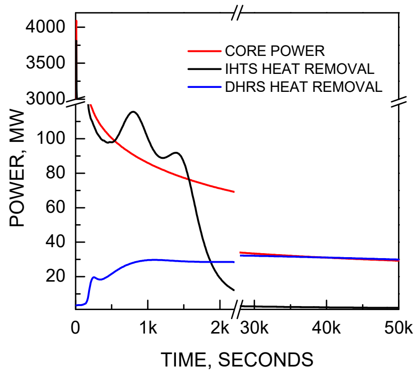

Fig. 5. Power responses of TOP accident.

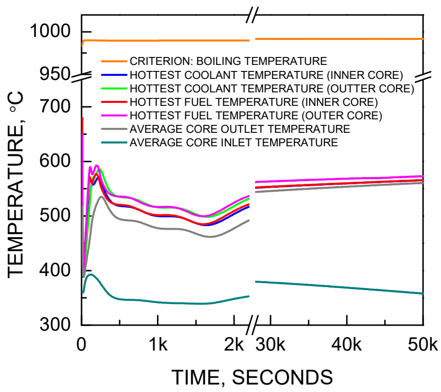

Fig. 6. Temperature responses of TOP accident.

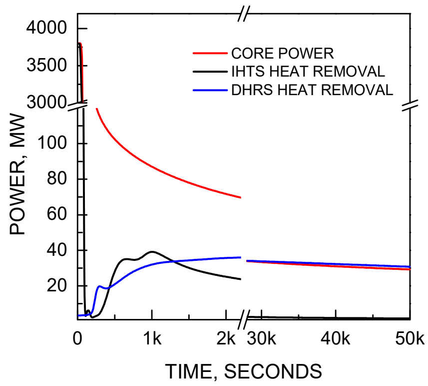

Fig. 7. Power responses of LOHS accident.

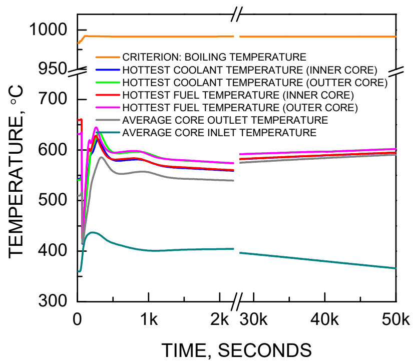

Fig. 8. Temperature responses of LOHS accident.

3.2 Unprotected accident (without SCRAM) results

The best-estimate methodology was used to figure out the transient responses of the unprotected LOF, TOP, and LOHS accidents. The uncertainties of the reactivity were not considered in this work, while included in the previous PGSFR analysis [2]. All the six trains of DHRS are operable, but reactor shutdown signal is not generated by RPS.

3.2.1 ULOF

The heat removal fails at 0s due to spurious trip of three primary pumps, leading to flow coastdown and core outlet temperature increase (Figs. 9-11). The core and coolant temperatures begin to decrease at 70s due to negative reactivity feedbacks from core radial, fuel axial and CRDL expansions, leading to core power reduction. At about 400s, the core and coolant temperatures increase again due to further flow reduction, but begin to decrease due to flow increase caused by the initiation of natural circulation in the core at about 650s.

Along with the DHRS heat removal, additional heat removal paths through the IHTSs and SGs are available during transient. Similar to results of the previous PGSFR analysis [2], it was found that the cooling capacity of IHTS during transient is sufficient to cool down the reactor to the safety condition and is much higher than that of DHRS (Fig. 11).

The core outlet temperature reaches the setpoint at 2.5s and the DHRAS is activated 6.0s later. At 28.6 s, the DHRS dampers fully open and the blowers begin to operate at a rated flow rate. As a result, the peak assembly outlet temperature is 789.5°C, fulfilling the safety acceptance criterion (Fi. 12).

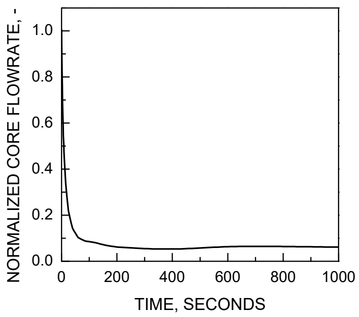

Fig. 9. Core flowrates of ULOF accident.

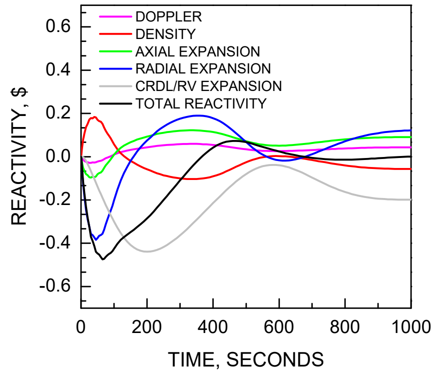

Fig. 10. Reactivity feedback responses of ULOF accident.

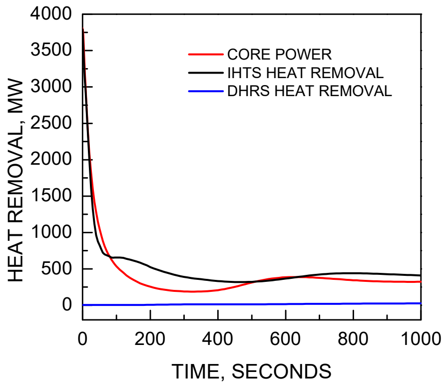

Fig. 11. Power responses of ULOF accident.

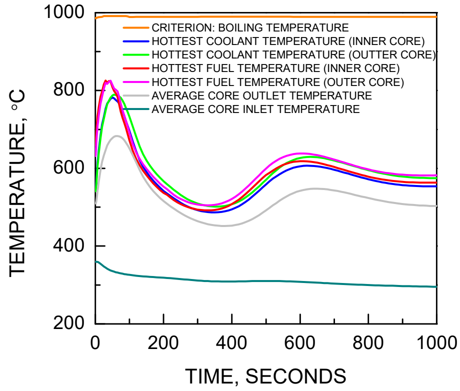

Fig. 12. Temperature responses of ULOF accident.

3.2.2 UTOP

As a transient initiator, reactivity insertion at a rate of 0.0065$/s to the maximum 0.4402$ at 67.6s is specified. The insertion leads to increase in the core power and the temperature and then the total reactivity and power decreases due mainly to negative reactivity from Doppler, fuel axial, core radial and CRDL expansions (Figs. 13-15). The core outlet temperature reaches the DHRAS setpoint at 12.2s, and the peak assembly outlet temperature is 630.6°C, fulfilling the safety acceptance criterion.

3.2.3 ULOHS

ULOHS is initiated by all feedwater pump trip off. Malfunction of heat transport path through IHTS loops causes the core inlet temperature to increase, leading to DHRS operation. After 100s of transient, the core and coolant temperatures begin to decrease due to negative reactivity insertion (Figs. 16-18). The core inlet temperature reaches the DHRAS setpoint at 58.5s, and the peak assembly outlet temperature is 571.7°C.

4. Conclusions

KAERI has carried out the interim analysis of protected and unprotected transients for the 3800MWt TRU burner with MARS-LMR code. The simulation results of all six transients indicated that no immediate safety concerns are raised, as significant margins to coolant boiling and fuel melting are kept in all results.

A revision of the TRU core design for the SFR burner is in progress at KAERI. As a future work, further investigation will continue with neutronics and sub-channel calculations of the updated TRU core design.

ACKNOWEGMENT

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[2] KAERI (SFRA), Specific Design Safety Analysis Report (SDSAR) of PGSFR 2017.

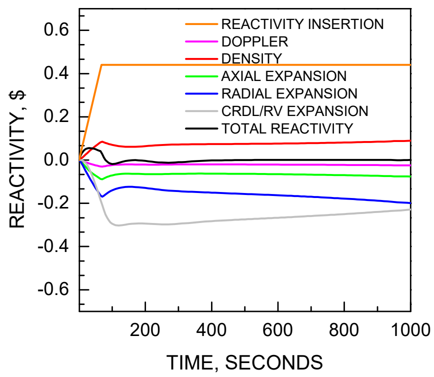

Fig. 13. Reactivity feedback responses of UTOP accident.

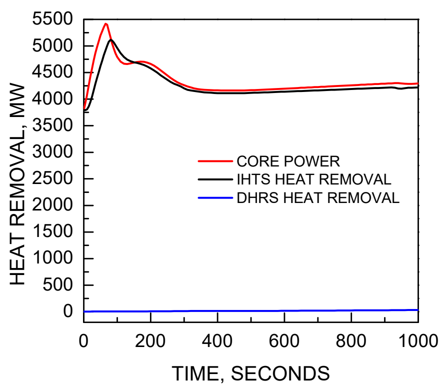

Fig. 14. Power responses of UTOP accident.

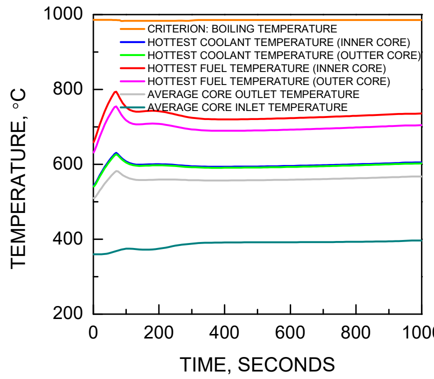

Fig. 15. Temperature responses of UTOP accident.

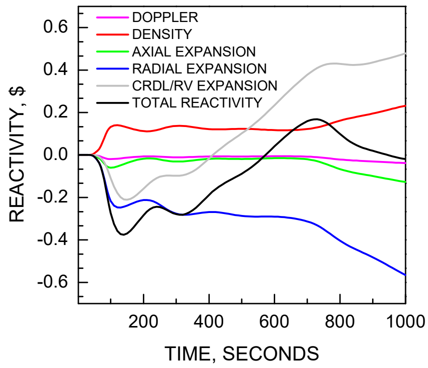

Fig. 16. Reactivity feedback responses of ULOHS accident.

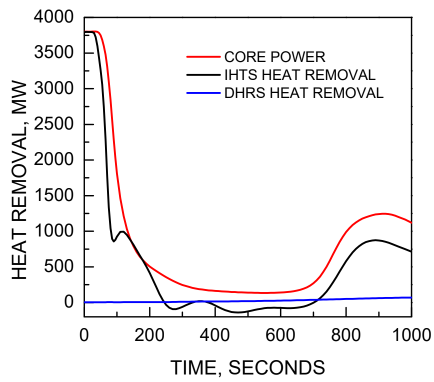

Fig. 17. Power responses of ULOHS accident.

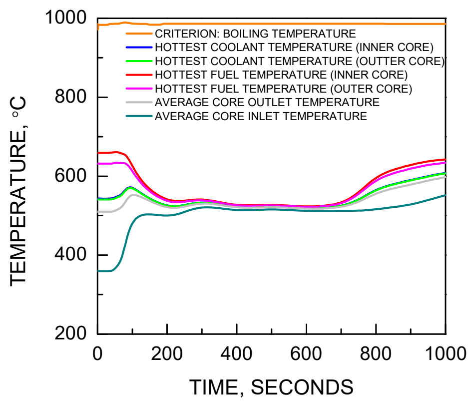

Fig. 18. Temperature responses of ULOHS accident.