

ULOF and UTOP Analyses of a Conceptual Small Liquid Metal-cooled Fast Reactor

Joo Hyung Seo, Ji Yong Kim, In Cheol Bang*

Department of Nuclear Engineering., Ulsan National Institute of Science and Technology (UNIST)., 50 UNIST-gil.,
 Ulsu-gun., Ulsan., Republic of Korea

Corresponding author: icbang@unist.ac.kr

1. Introduction

After the Fukushima accident, a variety of new concepts of nuclear reactor with higher safety, high economic feasibility, less radioactive waste, and high resistance to nuclear proliferation are being developed.

As one of the new concept reactors, a small liquid-metal cooled fast reactor (SLFR) that uses lead coolant is studied at the present study. The SLFR has some advantages, 1) Atmospheric pressure operation, 2) High boiling point, 3) Low activity with water and steam, 4) High retention of fission products.

The present study considered the LFR with 300MWth power. This LFR is pool-type reactor with a 9.65 m total height. It uses the UO₂ fuel and Lead-Bismuth Eutectic (LBE) coolant. Primary loop core inlet temperature is 300°C, and core outlet temperature is 450°C. It operates at atmospheric pressure. Coolant passes through the core at the bottom of the center and is heated. Heated coolant rises to the top of the reactor through the hot pool, cooled with passing the steam generator, and enters the core again after through the pump which is in the cold pool. Two pumps are used to maintain a mass flow rate of 13827 kg/s. ~20% of mass flow rate is maintained by natural circulation due to the 4m height difference between steam generators and the core although in emergency cases.

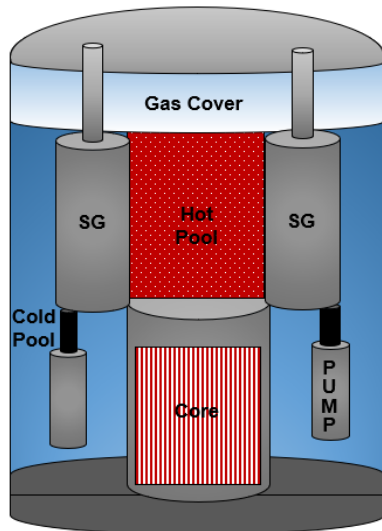


Fig. 1. Designed LFR primary loop schematic diagram

6 steam generators (SG) are used in the secondary loop. The working fluid of SG is water. 80 bar pressurized hot water enters to SG inlet, and generated steam flows to the turbine through the SG outlet. The SG inlet temperature is 250°C and the SG outlet

temperature is 360°C. The feedwater mass flow rate is 25.81kg/s per SG. One SG removes 50MWth, total 300MWth heat is removed in the secondary loop.

Two DHR trains are installed on the secondary loop. Three SGs are connected in one feedwater line and one steam line, and one DHR is vertically connected to that feedwater line and steam line. DHR train is cooled by passing through a large water pool of 30°C. One DHR system is designed to remove 12MWth heat, the total is 24MWth.

Table I: Design parameters comparisons of few LFRs and SMR [1,2,3]

	Studied LFR	ALFRED	SSTAR	PGSFR
Designer	The present study	Ansaldo Nucleare	Argonne National Laboratory	Korea Atomic Energy Research Institute
Type	Pool	Pool	Pool	Pool
Power	300MWth	300MWth	45MWth	400MWth
Coolant	LBE	Pb	Pb	Sodium
Core inlet Temperature	300°C	400°C	420°C	390°C
Core outlet Temperature	450°C	480°C	564°C	545°C
System Pressure	1 bar	1~1.5 bar	1 bar	~1 bar
Secondary working fluid	Water / Steam	Superheated steam	Supercritical CO ₂	Water / Steam

The current LFR was compared with 3 reactor designs such as ALFRED, SSTAR and PGSFR. All of them uses the pool type design and operated in a high temperature and low pressure. ALFRED and the current LFR have differences in inlet/outlet temperature although same power is given. This difference was resolved by the mass flow rate (13827kg/s at studied LFR, 25984kg/s at ALFRED).

2. Analysis Methods

The current LFR has now completed the conceptual design and safety analysis has been carried out in this paper.

2.1. Safety criterion

1) Fuel melting can occur when the reactor temperature rises during an accident. To prevent the fuel melting accident, the UO₂ fuel centerline temperature safety criterion was selected as a 2740°C, as not to exceed the melting point [4].

2) As the temperature rises and clad melts, the fuel in the clad may spill into the primary loop. The temperature below 1500°C where the 15-15Ti clad material does not melt was selected as the Design Extensions Conditions (DEC) safety criterion [5].

The clad failure can occur at high temperatures below the melting point. In SVBR 75/100 and SNCLFR-100 reactor, the safety criterion is 650°C to prevent clad failure by creep rupture [6]. Referring to studies, the clad failure criterion of studied LFR using 15-15Ti clad is also selected as 650°C.

3) Freezing or boiling of primary coolant is dangerous in the LFR because it can cause flow blockage and reactor pressurization. It is known that the melting point of LBE is 125°C and the boiling point is 1670°C [7]. The current LFR also selected 125°C to 1670°C as safety criterion in Design Basis Conditions (DBC), DEC.

The reactor structure can become weak in corrosion when the coolant temperature exceeds 500°C~550°C or lead coolant velocity over 2m/s. Reactor satisfy these conditions in steady state, but it was not included in the safety criteria of an accident.

2.2. Analysis condition

The safety analysis performed by several conceptually designed LFRs was investigated.

ULOF, ULOOP, and UTOP accident scenarios have been analyzed in the ALFRED [1,8]. ULOF, ULOOP, and UTOP have been analyzed in the M²LFR-1000. ULOF and UTOP have been analyzed in the SVBR 75/100. In lead coolant case, secondary loop overcooling accidents were importantly considered because of lead's high melting temperature (327°C). But LBE coolant case, overcooling accidents were excluded because it has a low melting point(125°C). In the current LFR, ULOF accident in which the primary side pump trip, ULOHS accident in which heat is not removed due to a secondary turbine trip, ULOOP accident in which the pump and turbine are tripped due to an offsite power loss, and UTOP accident in which one control rod assembly was withdrawn and positive reactivity was inserted into the core were analyzed. The SCRAM signal failed in all unprotected case.

3. Results and Discussion

Accident analysis was performed using the MARS-LBE code. SCRAM signal is activated in two cases, 1) pump speed lower 5 rad/s after the accident, and 2) the core outlet temperature rises over 470°C.

Among the analyzed accidents, ULOF and UTOP accidents which had higher peak temperatures are reported below.

3.1. Unprotected loss of coolant (ULOF)

At 3 seconds, the primary pumps trip and the accident begin. At 13 seconds, a SCRAM signal fails. The control rod does not fall, and the reactor core does not stop. The secondary side works normally.

The peak coolant temperature is 576.68°C, the peak cladding temperature is 634.69°C, and the maximum fuel temperature is 659.51°C.

After the accident occurs, coolant and fuel temperatures rise. Because the SCRAM signal fails, the coolant temperature increases more than 470°C. When the temperature rises, due to negative reactivity feedback by Doppler effect and negative coolant temperature coefficient, the power is decreased.

Since the primary flow decrease and heat has not been removed to the coolant, the clad temperature is increased more than the increment of the fuel temperature. The flows are changed to the natural circulation after 30 seconds.

The SG is removing heat during normal operation. The power does not decrease to decay heat level and new state is established after 1000 seconds. The new state has an overall higher temperature than the normal operation and it has a lower thermal margin. Peak temperatures of coolant, clad, and fuel are below the safety criterion.

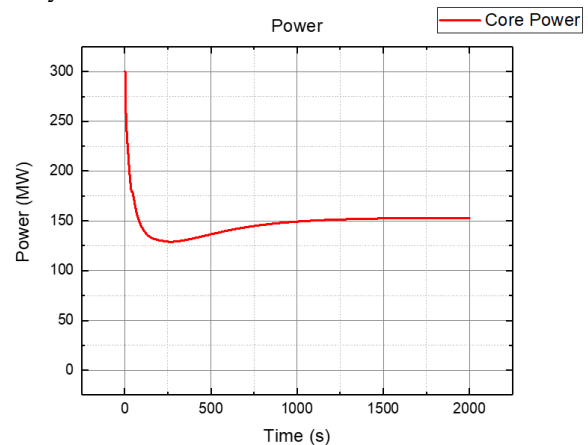


Fig. 2. A. Reactor power under ULOF case

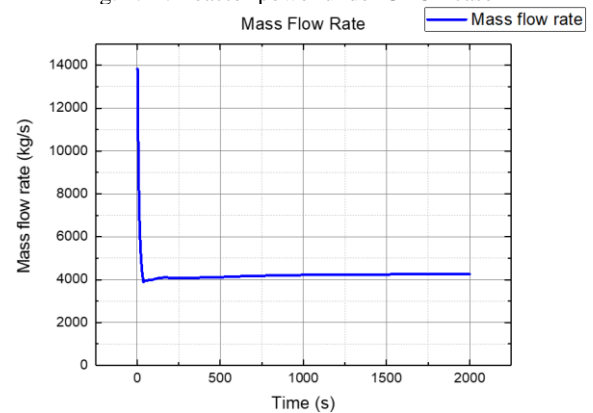


Fig. 2. B. LBE coolant mass flow rate under ULOF case

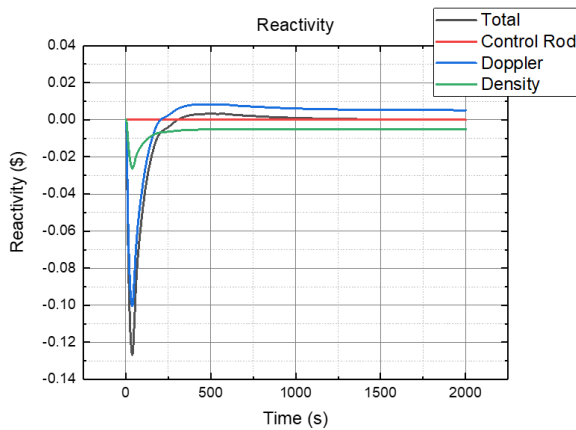


Fig. 2. C. Core reactivity of ULOF case

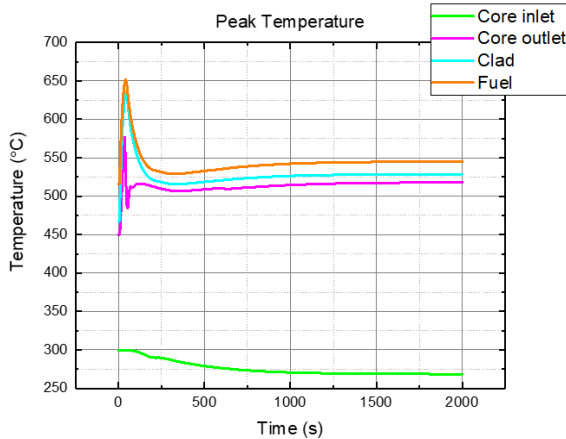


Fig. 2. D. Coolant inlet/out temperature, clad temperature, fuel temperature under ULOF case

Table II: Peak temperatures comparison with ALFRED at ULOF

	The current LFR	ALFRED
Peak coolant temperature	577°C	710°C
Peak clad temperature	635°C	764°C

The peak temperatures of the current LFR and ALFRED were compared. In the ULOF case, ALFRED had a higher peak coolant / cladding temperature and it had lower thermal margin. ALFRED has a higher core inlet temperature because of the lead coolant, and so its normal operation mass flow rate is two times higher than the current LFR. This difference makes the higher peak temperature has been appeared in ALFRED.

3.2. Unprotected transients overpower (UTOP)

The accident begins with one control rod assembly pulled out in 3 seconds. A positive reactivity of \$0.498 is inserted over 2 seconds. The SCRAM signal fails, primary pumps and secondary turbines operate normally. The control rods are not inserted.

The peak coolant temperature is 933.25°C, the peak cladding temperature is 980.65°C, and the maximum fuel temperature is 1131.65°C.

With the positive reactivity insertion, the power increases rapidly to 1194MWth after 110 seconds. By Doppler effect and negative coolant temperature coefficient, negative reactivity feedback is inserted. The 0.498\$ positive reactivity is continuously inserted, but due to the negative reactivity, the peak positive reactivity is 0.45\$ in 6 seconds. When the total reactivity becomes negative, the power is decreased, and the new state is established after 1000 seconds. The new state has a higher power level than the steady state. The flow rate hardly changed as the pump operated normally.

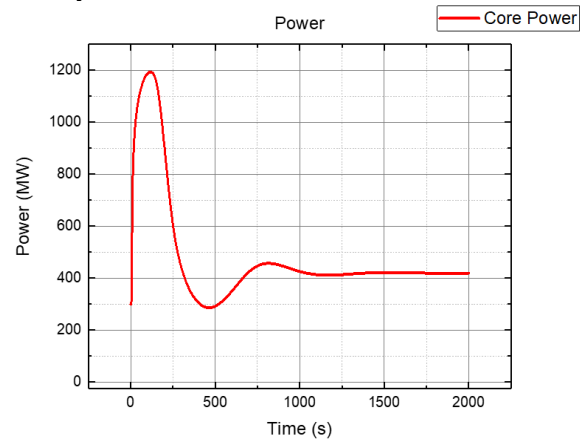


Fig. 3. A. Reactor power under UTOP case

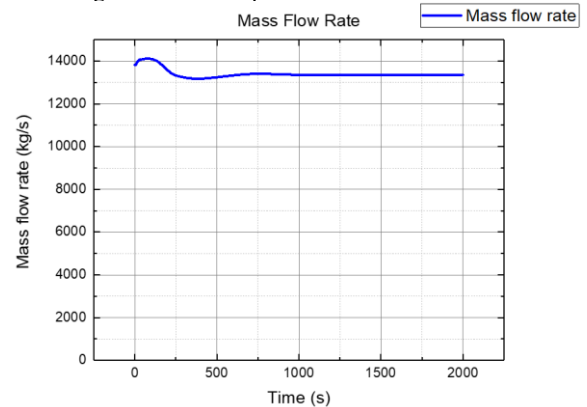


Fig. 3. B. LBE coolant mass flow rate under UTOP case

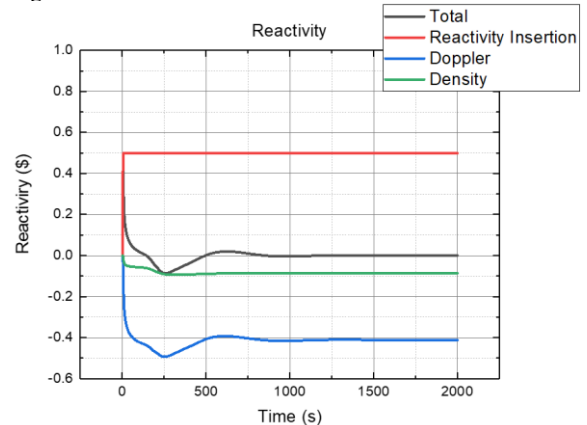


Fig. 3. C. Core reactivity of UTOP case

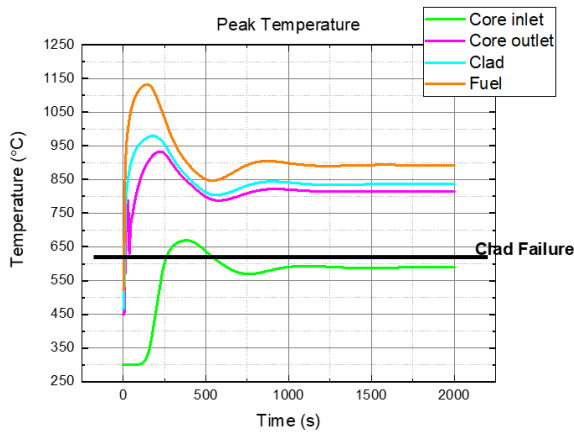


Fig. 3. D. Coolant inlet/out temperature, clad temperature, fuel temperature under UTOP case

The overall reactor thermal margin is reduced. The fuel temperature is increased more than the increment of the coolant/clad temperature. The clad and coolant temperatures increase next and have similar behavior with the fuel temperature change.

Among the analyzed accidents, UTOP had the highest peak temperature. In this case, peak coolant temperature and maximum fuel temperature were below the safety criterion. The peak cladding temperature did not exceed the melting point, but it exceeded the clad failure temperature.

The peak cladding temperature, peak coolant temperature and maximum power of the current LFR and ALFRED were compared.

Table III: Peak temperatures and power comparison with ALFRED at UTOP

	The present LFR	ALFRED
Reactivity insertion	400pcm	250pcm
Maximum power	1194MWth	610MWth
Peak coolant temperature	933°C	Below 600°C
Peak clad temperature	981°C	Below 600°C

Higher maximum power, peak coolant temperature, peak cladding temperatures had appeared in the current LFR. The LFR had a smaller thermal margin in this case: reactivity insertion by removing one control rod assembly. Because the amount of positive reactivity insertion when the one control rod is withdrawn is different.

4. Conclusion

Safety analysis for a Small LFR design has been performed. Four accidents were selected and analyzed: ULOF, ULOHS, ULOOP, and UTOP. In this study, two accidents with relatively higher peak temperatures increased under the conditions were introduced. Reactivity, power level, mass flow rate, and peak temperature behaviors in two accidents were analyzed. In both accidents, a new state was established, and peak cladding temperature was below the melting point. The

new state had a lower thermal margin than the steady state. Operating the reactor at a new state for a long time is not recommended due to the low thermal margin. In addition, analysis results are compared with ALFRED results. In terms of control rod worth, design changes and comparisons with other LFR designs are necessary.

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