Passive Safety Characteristics of the 1200MWe GEN-IV Sodium-Cooled Fast Reactor

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1. Introduction

Sodium Cooled Fast Reactors (SFRs) are the most technologically developed and the nearest-term deployment system among the Generation-IV (GEN-IV) nuclear system candidates. A conceptual design of an advanced breakeven sodium-cooled fast reactor (G4SFR) [1] has recently been developed by KAERI under the national nuclear R&D program. The G4SFR development plan focuses on particular technology development efforts to effectively meet the goals of the GEN-IV nuclear system such as efficient utilization of resources, economic competitiveness, a high standard of safety, and enhanced proliferation resistance.

In order to enhance the safety of G4SFR, advanced design features of metal-fueled core, simple and large sodium-inventory primary heat transport system, and passive safety decay heat removal system are included in the reactor design. Such favorable inherent and passive safety behaviors of G4SFR are expected to virtually exclude the probability of severe accidents with potential for core damage.

2. 1200MWe G4SFR Design Concept

The G4SFR is a liquid metal sodium-cooled fast reactor with the electricity output of 1,200MWe and uses U-TRU-10%Zr metal fuel, which is a prototypic demonstration reactor for commercial deployment. The overview of the G4SFR is depicted in Fig. 1. There are primary (PHTS) and intermediate heat transport systems (IHTS), steam generation system (SGS), and residual heat removal system (RHRS) as the reactor coolant system and connected systems. All PHTS piping and equipment is located inside the reactor vessel. Reactor building adopts the seismic base isolation system to enhance the structural safety as well as the economics. The required core thermal output is 3046.4MWt and the net plant thermal efficiency is 39.4%.

The core system adopts a radially homogeneous core scheme and is not loaded with any blanket assembly to enhance the proliferation resistance. In addition, the excess plutonium production is minimized by keeping the core conversion ratio approximately equal to unity. Each driver fuel assembly consists of 271 rods within a duct. The core has an active core height of 84.43cm and a radial equivalent diameter of 337cm. The base alloy, ternary (U-Pu-10%Zr) metallic fuel is used for a driver fuel. The fuel pin is made of sealed HT-9M tubing containing metal fuel slug in columns. Table 1 shows the major design parameters of G4SFR.

The PHTS is a pool type system and this feature provides large thermal inertia of the primary system as indicated in Fig. 1. Four Intermediate Heat Exchangers (IHX) and four pumps are included in the PHTS. SG is a once-through type with helical tube utilizing a superheated steam cycle. Two different types of RHRS are employed, one is the safety-related Passive Decay heat Removal Circuit (PDRC) system and the other is non safety-related Intermediate Reactor Auxiliary Cooling System (IRACS). The PDRC system comprises independent four loops, and each loop is equipped with single sodium-sodium decay heat exchanger (DHX), single sodium-air heat exchanger (AHX) and the heat removing sodium loop connecting DHX with AHX. The PDRC operates in a pure passive manner, while the IRACS utilizes active components such as blower and power-operated valves.

Table 1 Major Design Parameters of G4SFR

		PHTS	
OVERALL		Reactor Core I/O Temp., ⁰C	390.0 / 545.0
Net plant Power, MWe	1200	Total PHTS Flow Rate, kg/s	15455.4
Core Power, MWt	3046.4	Primary Pump Type	Centrifugal
Gross Plant Efficiency, %	41.9	Number of Primary Pumps	4
Net Plant Efficiency, %	39.4	Pump Head, MPa	0.35
Reactor Type	pool		
Number of IHTS Loops	2	**IHTS**	
Safety Shutdown Heat Removal	PSDRS	IHX I/O temp., ⁰C	325.4 / 528.0
Seismic Design	seismic isolation bearing	IHTS Total Flow Rate, kg/s	3044.7
Breeding Ratio	0.993	IHTS Pump Type	electromagnetic
Refueling Iterval, months	18	Number of IHXs	4
		Number of SGs	2
CORE			
Core Configuration	homogeneous	**Steam System**	
Core Height, mm	844.3	Steam Flow Rate, kg/s	1326.6
Axial Blanket Thickness, mm	0	Steam Temperature, ⁰C	503.0
Maximum Core Diameter, mm	3370	Steam Pressure, MPa	16.5
Fuel Form	U-Pu-10%Zr Alloy	Feedwater Temperature ⁰C	230.0
TRU Enrichment for Equilibrium Core, %	30.0		
Assembly Pitch, mm	185.24	**RHRS**	
Fuel Pins per Driver Assembly	271	Safety-Related PDRC System	4
Cladding Material	HT9	Non Safety-Related IRACS system	2

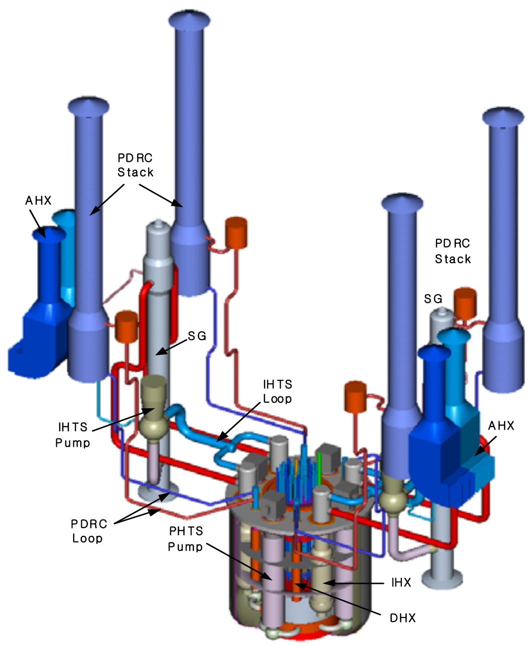

Fig.1 Schematics of the NSSS of G4SFR

3. Passive Safety Evaluation

To evaluate potential safety characteristics of the advanced safety design features of G4SFR, the plant responses and safety margins are investigated using the system transient code SSC-K [2] for three unprotected accidents of UTOP, ULOF, and ULOHS. The non-safety-related IRACS is not credited in the present analysis.

The UTOP event is initiated at the full power by inserting 2.67 cents per second for 15 seconds (total 40 cents), representing the withdrawal of all control rods. It is assumed that the primary and secondary sodium flows remain constant at the rated conditions. The power and flow transients during the initial 1000 seconds are shown in Fig. 2. The reactor power reaches a peak of about 1.45 times the rated power at 33 seconds and then slowly decreases to seek equilibrium with the available heat sink provided by the coolant system heat capacity and the heat rejection by the SGs. The powers begin to level off at about 1.06 times the rated power by 1000 seconds. The self-regulation of power without scram is mainly due to the passive reactivity feedbacks as shown in Fig. 3. Therefore, the UTOP event results in no fuel failures and no sodium boiling.

The ULOF accident is driven by the coast down of the core flow following all primary pumps trip. Since the power to flow ratio is a key parameter that determines the consequences of the accident, the pump coast down plays an important role for the plant safety. The fuel is heated up by a mismatch between the core heat generation and the heat removal during the event. The core power and natural circulation flow rate at 600 seconds, predicted by SSC-K, are 10.3% and 6.7% of the rated values, respectively.

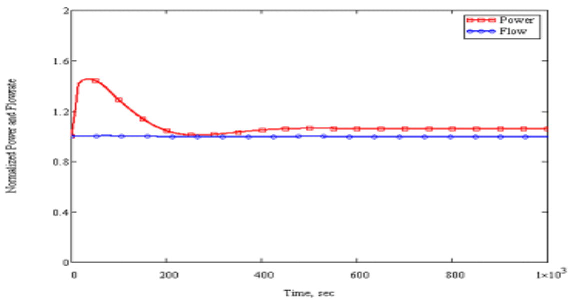

Fig.2 Normalized Power and Flowrate during UTOP

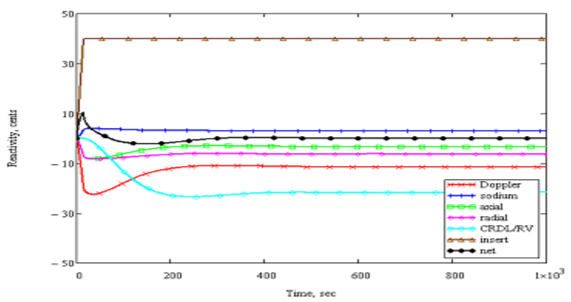

Fig.3 Reactivity Feedback during UTOP

The predicted cladding temperature (801°C) holds above the threshold of eutectic formation (790°C) during 88 seconds. However it satisfies the acceptance criteria of the 0.3 hours holding time. Therefore no cladding damage is expected during the ULOF accident.

The ULOHS accident is assumed to start with loss of heat rejection capability at all of the SGs, with PHTS and IHTS pumps continuing to run. The only heat removal is conducted by the passive heat removal system of the PDRC. The rapid slightly increase of the fuel temperature in the early phase of the transient is attributed to the degraded heat removal through the IHXs. The fuel temperatures ultimately reach a quasi-equilibrium condition as the core heat generation rate is balanced with the heat removal rate by the PDRC, as shown in Fig. 4. A summary of peak temperatures of the safety criteria predicted by SSC-K is presented in Table 2.

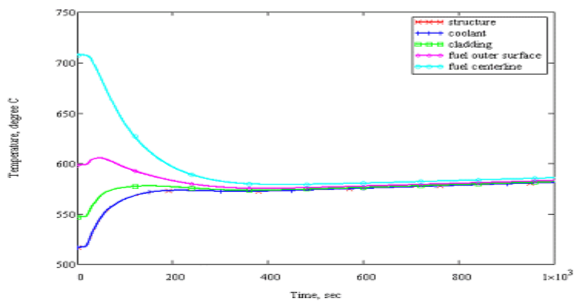

Fig.4 Hot Channel Temperatures during ULOHS

Table 2 Summary of Peak Temperatures during ATWS

	Peak Fuel Temp., ℃	Peak Clad Temp., ℃	Av. Core Outlet Temp., ℃	Peak Na Temp., ℃
Limit	1,070	700-790 (<0.3hr)	650-700 (<5hr) 700-760 (<1hr)	Pump on: 1,055 Pump off: 940
0.4$ UTOP (Pump on)	832	658	599	623
ULOF (Pump off)	824	801 (88 s)*	600	795
ULOHS (Pump off)	708	582	579	581

* holding time

4. Conclusion

It has been shown that the G4SFR design has inherent and passive safety characteristics and is accommodating the selected ATWS events. The inherent and passive safety features of the reactor design make the core shutdown with sufficient margin and passive removal of decay heat with matching the core power to heat sink by passive self power-regulation. Such design features provide self-protection in severe ATWS conditions without producing high temperatures and conditions that might lead to more severe accidents, such as coolant boiling, fuel melting, cladding failure and loss of structural integrity.

REFERENCES

[1] Y. M. Kwon et al., "Unprotected Accident Analyses of the 1200MWe GEN-IV SFR Using the SSC-K Code," KAERI/TR-4019/2010.

[2] Y. M. Kwon et al., "SSC-K Code Users Manual, Rev.1," KAERI/TR-2014/2002.