Conceptual Design of Ultra-long-life Core Fast Reactor (UCFR) with Ga-based Passive Decay Heat Removal System (PDHRS)

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1. Introduction

The concept of an ultra long-cycle fast reactor was introduced in the 1950s, and recently it is being actively investigated as a means to improve uranium utilization and solve the nuclear proliferation including cost reductions, low proliferation risk, and the interim storage of spent fuel as shown in table I [1-9]. UCFR (Ultra-long-life Core Fast Reactor) is a 260MW$_{th}$ /100MW$_e$ sodium-cooled fast reactor which requires no on-site refueling and meets the need for future nuclear energy systems. UCFR is a pool type reactor with metallic fuels, four intermediate heat exchangers, two steam generators, and passive decay heat removal systems. Because gallium has the chemical reaction safety such as low oxygen reactivity compared to sodium, it can be used as a boundary material between sodium and atmosphere to enhance the nuclear safety of UCFR. In this research, design studied for neutronics and thermal-hydraulics are included. The safety performance of UCFR will be analyzed with MARS-LMR. Although MARS-LMR was originally intended for a safety analysis of liquid metal-cooled reactor, gallium properties were newly added to this code which is applicable for gallium-cooled systems. The properties of various liquid metals are indicated in table II[10-12].

Table I: Several research of UCFR

	Country	Capacity	Years	Coolant	DHRS
CANDLE	Japan	200MW$_{th}$-1540MW$_{th}$	30	LBE	-
TWR	USA	1200MW$_{th}$/ 500MW$_e$	40	Na	D.G. RAVCS
SSTAR	USA	45MW$_{th}$/ 20MW$_e$	30	Pb	-
4S	Japan	30MW$_{th}$/ 10MW$_e$	30	Na	RVACS
PASCAR	Republic of Korea (SNU)	100MW$_{th}$/ 35MW$_e$	20	LBE	RVACS
UCFR	Republic of Korea (UNIST)	260MW$_{th}$/ 100MW$_e$	30-60	Na	Ga-based PDHRS

Coolant : Coolant in the primary system
DHRS : Decay Heat Removal System
PDHRS : Passive Decay Heat Removal System

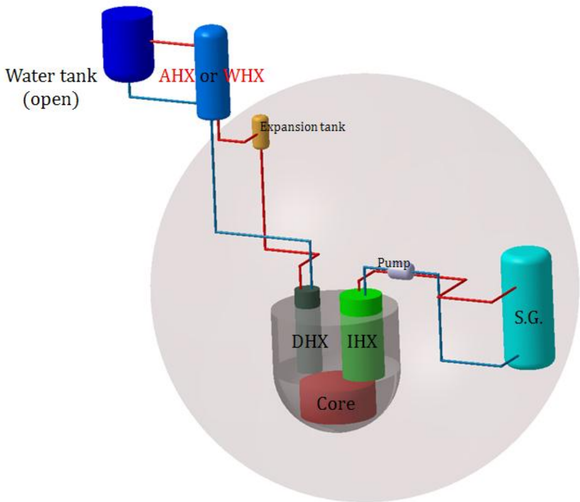

Fig. 1. Schematic of UCFR-100

2. Design of UCFR

Fig. 1 indicates the schematic of UCFR-100. The main difference of UCFR compared to other reactors is gallium-based PDHRS (Passive Decay Heat Removal System). This research considers gallium as a liquid metal coolant in decay heat exchanger that may enhance the passive safety features of UCFR. By using gallium, UCFR-100 can operate not the air but water as an ultimate heat sink.

Table II: Thermo physical properties of liquid metals

	Na	LBE	Ga
Atomic Weight	22.997	208	69.723
T_m (°C)	97.8	123.5	29.76
T_b (°C)	892	1670	2204
ρ (kg/m^3)	*880	*10300	6095
C_p (J/kg·K)	*1300	*146	381.5
k (W/m·K)	*76	*11	29
μ (10^3kg/m·s)	*0.34	*1.7	1.810
Σ_a (m^{-1})	0.03147	0.003034	0.148
β (10^{-6}K^{-1})	200	130	59.5

** evaluated at 300 ℃*
Thermo properties of Ga are evaluated at 32 ℃

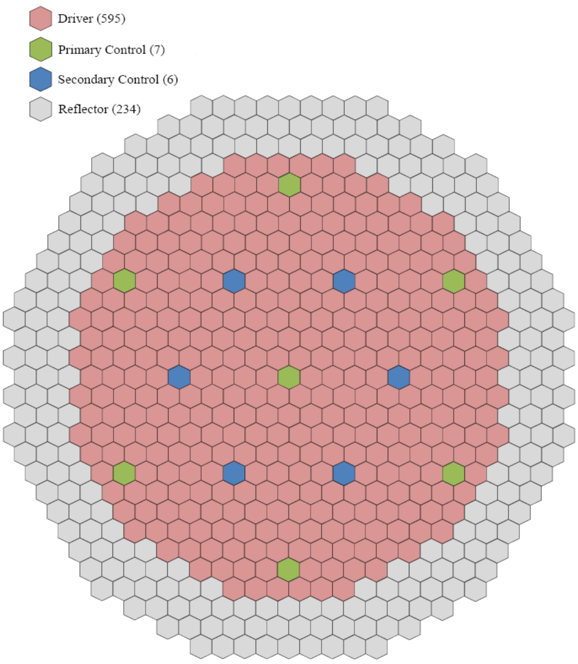

Fig. 2. Core layout of UCFR

Table III shows the design parameters of UCFR-100.

2.1 Core Design of UCFR-100

The design power of UCFR-100 is $260MW_{th}$ /$100MW_e$ and the thermal efficiency is assumed as 38.5%. The metallic form of fuel material (U-5Zr) has been chosen due to its high thermal conductivity [8]. The active core region will move from bottom to top over the designed period. The active core height is 1.0m and the equivalent core diameter is 3.8m. The inlet and outlet temperature of coolant are 700 and 850K respectively.

2.2 Materials

Because the concept of UCFR is designed to be operating with no fueling during the overall operation period, the design requirement of the cladding would

Table III: Design parameters of UCFR

Design parameter	Design value
Core power	$260MW_{th}$ ($100MW_e$)
Coolant	Na
Fuel	U-5Zr
Core lifetime	30-60 yrs
Core inlet/outlet temperature	700K/850K
Equivalent core diameter	3.8m
Active core height	1.0m
Cladding	HT9

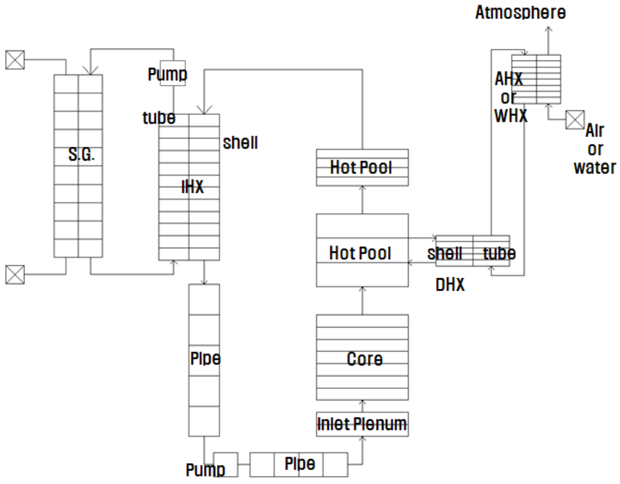

Fig. 3. Nodalization of UCFR

be more challengeable than that in conventional fast reactors [13]. In this research, HT-9 was used as the cladding material as shown in table III.

2.3 Heat Transport Systems

UCFR consists of two primary/secondary pumps, four intermediate heat exchangers (IHX), two steam generators (S.G.) and two gallium-based PDHRS as shown in Fig 3. This figure shows the Nodalization of UCFR. To simulate the safety analysis of UCFR at design basis accidents (DBAs) using MARS-LMR, the design of each heat transport system have to be performed to set the heat balance. Geometrical configurations in heat exchangers are required to satisfy a pressure loss low enough to permit full heat transport capability [9]. To calculate the optimized geometry of each heat exchanger in UCFR, the pressure drop and overall heat transfer coefficient can be determined by [14-16]

$$\Delta P = f\left(\frac{L}{D}\right)\frac{\rho V^2}{2} \quad (1)$$

$$U = \frac{1}{\left(\frac{1}{h_{tube}}\right)+\left(\frac{1}{h_{shell}}\right)} \quad (2)$$

where, f is friction factor, L is D is diameter, ρ is density and V is velocity. In eq. (2), h_{tube} is and h_{shell} is heat transfer coefficient for tube side and shell side of the heat exchanger respectively.
To get the heat transfer coefficient at each side, the correlations related to heat transfer for liquid sodium were used as follows [17,18].

$$Nu_{tube} = 4.0 + 0.025Pe^{0.8} \quad (3)$$

$$Nu_{shell}^{cross} = 5.36 + 0.1974 Pe^{0.682} \quad (4)$$

where, Nu is Nusselt number and Pe is Peclet number.

3. Summary and Further Study

Considering needs to improve uranium utilization and solve the nuclear proliferation, ultra-long cycle fast reactor has been developed. UCFR is a $260MW_{th}/100MW_e$ sodium-cooled fast reactor which requires no on-site refueling during design period with metallic fuels (U-5Zr), HT-9 cladding, four intermediate heat exchangers, two steam generators, and Ga-based PDHRS. Through this paper, new PDHRS using gallium that can be remove decay heat passively for an infinite time is suggested. In Ga-based PDHRS, the both water and air as an ultimate heat sink will be can be considered because gallium has the chemical reaction safety. In this research, design study for neutronics and thermal-hydraulics were also included. For safety analysis of UCFR using MARS-LMR, detailed design of UCFR with Ga-based PDHRS will be required.

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