Transactions of the Korean Nuclear Society Spring Meeting
Chuncheon, Korea, May 25-26 2006

Primary System Design for Lead Cooled Battery Fast Reactor BORIS

Yong H. Yu, Hyoung M. Son, Jin S. Hwang, Kune Y. Suh*
*Seoul National University, San 56-1 Sillim-dong, Gwanak-gu, Seoul, 151-744, *kysuh@snu.ac.kr*

1. Introduction

Energy needs have recently become inexorably diverse. The current situation calls for a challenge to conventional nuclear power plants designed to meet the economy of scale. It is hardly profitable to transmit electricity to remote residences such as Ulleung Island in Korea, and numerous islands in Indonesia. This implies that they should generate power on their own. In contrast to the chemically reactive sodium, lead (Pb) has gained a lot of interests in the western hemisphere since the Russian scientists have succeeded in using Pb in their fleet of nuclear submarines.

An ultra-small, ultra-long-life, versatile-purpose, fast-spectrum reactor named BORIS (Battery Optimized Reactor Integral System) is being developed at the Seoul Nation University [1]. BORIS aims to satisfy distributed energy demands, provide with inherent safety using the Pb coolant, and improve economical efficiency employing a supercritical carbon dioxide (SCO_2) Brayton cycle.

2. System Description

2.1 Fuel Material

Nitride fuels are recently being considered as an excellent choice for liquid metal cooled fast reactors. The BORIS core currently adopts nitride fuel consisting of plutonium, minor actinides, uranium and nitrogen (Pu-MA-U-N). A dominant feature of the nitride fuels is that they put together properties of both metallic and oxide fuels. They have a high heavy metal density and a high thermal conductivity generally related to metallic fuels. This makes possible for reactors to achieve high power density, high thermal performance, good core breeding, low reactivity swings, and long residency time compared to oxide fuels [2]. They also show a favorable Doppler coefficient like oxide fuels [3]. This enhances safety performance due to greater margins to failure, and gives excellent tolerance against transients such as loss of flow and transient overpower without scram as compared to metal fuels.

Nitride fuels also exhibit excellent compatibility with the liquid metal coolants and the clad materials. This compatibility increases the thermal performance of the fuel pin, and reduces the risk of accident when clad failure occurs. Further, the nitride fuels have relatively low fission gas release and fuel swelling, which enables short plenum and pins, low clad stresses, longer pin lifetime, and eventually better economics [2].

However, drawbacks do exist when using the nitride fuels for a fast reactor. A dissociation of fuel may occur at high temperatures producing free U and N_2 gas below the melting point. This problem has fortunately been solved by a strict control of the stoichiometry during the fabrication of the fuel. Recent studies have also shown that the thermal decomposition of the nitride fuel does not happen for temperatures at least 2,100 K in various environments, thus giving a large operating temperature margin [4].

2.2 Reactor Core

The reactor core is made up of 757 fuel rods without assemblies. The active core height is 0.8 m, and the core diameter is 0.9828 m.

Thermal design requires that temperatures of the reactor core structures be maintained under certain criteria so as to prevent damage of fuel materials which can advance to severe situations such as clad rupture with ensuing fission product release, flow blockage, and even meltdown of the core material. Accurate prediction of the core coolant and fuel temperatures is thus crucial in the process of core thermal hydraulic design.

BORIS uses a nitride fuel with Pb gap bonding, and HT9 clad. Use is made of thermophysical properties of $(U_{0.8}Pu_{0.2})N$ for the fuel pellet analysis.

A hand calculation was performed to solve the one-dimensional energy transport equation for the coolant with radial heat input from the clad surfaces in a single subchannel. It is assumed that the channel receives coolant only through its bottom inlet with constant flow area in the axial direction. A single phase heat transfer correlation was adopted to simulate the heat transfer between the clad and liquid metal coolant. Heat transfer coefficients are usually higher for liquid metals than other fluids because of their higher thermal conductivity. The high thermal conductivity allows the heat to be transported rapidly out into the fluid with relatively little resistance. The consequences of these differences are in the heat transfer correlation in terms of the Nusselt number *Nu*. The *Nu* behavior for liquid metals generally follows the relationship:

$$Nu = A + B(Pe)^C \tag{1}$$

In this study the heat transfer correlation for the rod bundles was used as follows [5]

$$Nu = 4.0 + 0.33\left(\frac{P}{D}\right)^{3.8}\left(\frac{Pe}{100}\right)^{0.86} + 0.16\left(\frac{P}{D}\right)^{5.0} \tag{2}$$

The calculational results with the above conditions are summarized in Table 1.

Table 1. Calculational results for single subchannel

Parameter	Value
fuel pellet diameter [mm]	23.63
clad thickness [mm]	1.0
peak fuel temperature [K]	1,140.52
peak clad temperature [K]	904.52
core coolant outlet temperature [K]	841.87

2.3 Primary System

Pressure drop in the reactor module is a key factor during system design of BORIS because the thermal energy from fission is removed by natural circulation of the Pb coolant. Thus, the natural circulation flow rate and thermal center difference between the core and the heat exchanger is determined considering the friction and form loss of the elements.

The temperature difference between the core inlet and outlet is at least 120 K according to linked calculation with the secondary side conditions. Hence, the thermal center difference in BORIS is determined to be 2.45 m. Under this condition, the major design parameters for the BORIS primary system of are presented in Table 2.

Table 2. Major design parameters for primary system

Parameter	Value
mass flow rate [kg/s]	1,276.32
velocity in core [m/s]	0.415
temperature difference [K]	120.0
total pressure drop [Pa]	3,884
thermal center difference [m]	2.45

2.4 Decay Heat Removal System

BORIS is equipped with an air cooling system as the reactor vessel auxiliary cooling system (RVACS). The standard temperature and pressure air circulates through the channel surrounding the whole reactor vessel by buoyancy without any external power.

The shutdown control rods being inserted, the core thermal power immediately plunges to about 10 % of the nominal value. Then the decay heat is gradually decreased. The decay heat transient data were taken from the Fast Flux Test Facility experimental result [6].

The initial temperature of the reactor vessel was assumed to be the core outlet coolant temperature at 833 K. Initially the air in RVACS is stagnated. Figure 1 presents the highest temperature of the reactor vessel inner wall. The maximum temperature was found to be 1,068 K at 5,600 s into the transient.

3. Conclusion

This study has provided with basic information needed to choose the suitable fuel material; set up appropriate reactor vessel geometry by performing the analysis of natural circulation and decay heat removal capabilities of RVACS utilizing computational fluid dynamics codes CFX and FLUENT; examined the liquid metal coolant behavior along the subchannels; found out whether given flux profiles and geometrical arrangement of fuel rods yield reasonable distribution of flow during nominal operation using the subchannel analysis code MATRA.

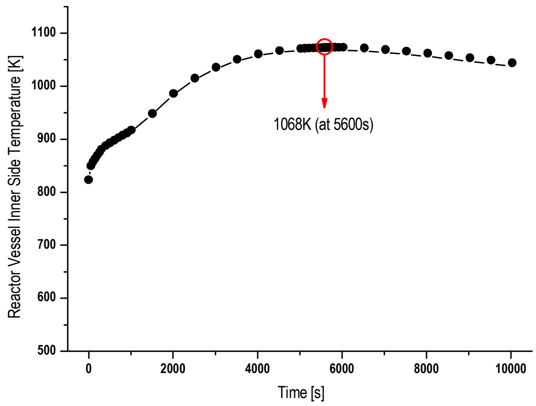

Figure 1. Maximum temperature of reactor vessel inner wall

NOMENCLATURE

D	Diameter	[mm]
Nu	Nusselt Number	
P	Pitch	[mm]
Pe	Peclet Number	

ACKNOWLEDGMENT

This work was performed under the auspices of Center for Advanced Prototype Research Initiatives (CAPRI).

REFERENCES

[1] I. S. Lee, M. S. Sohn, and K. Y. Suh, Optimized Battery-Type Reactor Integral System Design for Sustainable Energy Development, Trans. of the American Nuclear Society Winter Meeting and Nuclear Technology Expo, Tracking ID: 144108, 2005.

[2] W. F. Lyon, R. B. Baker, and R. D. Leggett, Advancing Liquid Metal Reactor Technology with Nitride Fuels, Proc. of the International Conference on Fast Reactors and Related Fuel Cycles, Vol. 2, pp. 14-18, 1991.

[3] S. M. Reynaud, and K. L. Peddicord, Re-Assessment of Nitride Fuel Potential in the Current Context of the Nuclear Industry, Proc. of the 10th International Conference on Nuclear Engineering(ICONE10), Tracking ID: 22771, 2002.

[4] M. Kato, T. Hiyama, and J. Kurakami, Thermal Decomposition Behavior of UN and $(U_{0.8}Pu_{0.2})N$, Proc. of the Workshop on Advanced Reactors with Innovative Fuels, pp. 371, 1998.

[5] M. S. Kazimi, and M. D. Carelli, Heat Transfer Correlation for Analysis of CRBRP Assemblies, Westinghouse Report, CRBRP-ARD-0034, 1976.

[6] A. E. Waltar, and A. B. Reynolds, Fast Breeder Reactor, Pergamon Press, New York, NY, USA, p. 548, 1981.