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Neutronic Comparison Study Between Pb(208)-Bi and Pb(208) as a Coolant In The Fast Reactor With Modified CANDLE Burn up Scheme.

Nina Widiawati[1], Zaki Suud[1], Dwi Irwanto[1], Hiroshi Sekimoto[2]

[1]*Nuclear Physics and Biophysics Research Group, Faculty of Mathematics and Natural Science, Bandung Institute of Technology, Indonesia.*
[2]*Nuclear Engineering, Tokyo Institute of Technology, Japan*

ninawidiawati@gmail.com

Abstract. Neutronic study of Pb(208)-Bismuth as a coolant in the Lead Fast Reactor (LFR) with Modified CANDLE burn up scheme has been conducted. Lead cooled fast reactor (LFR) is one of the fourth-generation reactor designs. The reactor is designed with 500 MW thermal power output. Modified CANDLE burn-up scheme allows the reactor to have long life operation by supplying only natural uranium as fuel cycle input. This scheme introducing discrete region, the fuel is initially put in region 1, after one cycle of 10 years of burn up it is shifted to region 2 and region 1 is filled with fresh natural uranium fuel. The reactor is designed for 100 years with 10 regions arranged axially. The neutronic calculations were performed by SRAC code using nuclear data library based on JENDL 4.0. Level burn up of Pb(208)-Bi cooled fast reactor is 530.688 GWD/MTU at BOC and 433.051 GWD/MTU at EOC whereas 190.790 GWD/MTU at BOC and 433.051 GWD/MTU at EOC for Pb(208) . The effective multiplication factor of Pb(208)-Bi Cooled Fast Reactor is 1.0554 at BOC and 1.05958 at EOC whereas 1.06703 at BOC and 1.06816 at EOC for Pb208.

1. Introduction

The accident of Chernobyl, Three Miles Island (TMI) and Fukushima Daichi has led to an emphasis on passive safety in the design of advanced reactors. Generation IV International Forum (GIF) has chosen six reactor systems for further development. The six reactor system chosen were: Gas Cooled Fast Reactor (GFR), Lead Cooled Fast Reactor (LFR), Molten Salt Reactor (MSR), Sodium Cooled Fast Reactor (SFR), Supercritical Water Cooled Reactor (SCWR), and Very High-Temperature Reactor (VHTR). Generation IV reactor systems has several specific goals, they were: inherent safety, sustainability, non-proliferation, and economical.

1.1. Lead Cooled Fast Reactor (LFR)

LFR is one of the six selected reactor systems. Some advantages of the LFR system [12]:

1. The potential for high outlet liquid metal temperature (up to $850^{o}C$) would enable the LFR to meet the hydrogen and electricity production missions.
2. The fast neutron spectrum would facilitate achieving the actinide fissioning mission

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3. By full recycling of actinides in a fast spectrum, the LFR would minimize the discharge of long-lived waste to HLW repositories and could maximize the utilization of the energy content of uranium (including depleted uranium) by transmutation of U-238 into fissionable transuranics.

1.2. Coolant

The choice of coolant for Fast Breeder Reactor (FBR) is very important because the coolant strongly influences the neutronic behavior of the core. The most recognizable effect of coolant selection is its influence on major components such as pumps and steam generators [12].

The coolant for FBR it must:

1. Minimize neutron moderation
2. Remove heat adequately from a high-power-density system
3. Minimize parasitic neutron absorption
4. Has low melting point and high boiling point
5. Has Low neutron absorption cross-section

1.3. Pb208 and Bismuth

Pb208 is one of the stable isotopes of Pb-nat. It content in Pb-nat above 52%, is high enough.

Some advantages of Pb-208 as the coolant of FBR are:

1. Has small neutron absorption in Fast Reactor (FR). Due to excess of neutrons, it can save more the fuel loading.
2. Increasing the fuel breeding in Fast Reactors
3. Hardening of FR neutron spectra. Meanwhile, hard spectrum of neutrons in FR core is preferable for incineration of minor actinides (MA).
4. Pb-Bi eutectic as a coolant gives better performance for extreme accidents than Pb because of the lower operation temperature (Zaki Suud, 1996). Pb-Bi eutectic has the low melting point but has the high boiling point.
5. The use of Pb208-Bi eutectic as a coolant expected to contribute significantly to the safety of the reactor

2. Design Concept

CANDLE (Constant Axial shape of Neutron flux, nuclide densities, and power shape During Life of Energy production) reactor system is originally developed by Prof. Hiroshi Sekimoto from Tokyo Institute of Technology, Japan. The several advantages of CANDLE reactor system, are:

1. Not required enriched fuels after the second cycle:
2. The burn-up of the spent fuel is about 40% (400 MWd/tHM): This value is competitive to the value of the presently expected FR system with reprocessing plant.
3. Can be designed also as a long-life reactor, since the burning region velocity is very low.
4. Requires more neutrons than conventional fast reactors since it does not employ reprocessing. Therefore, it is important to use a neutronically superior coolant.

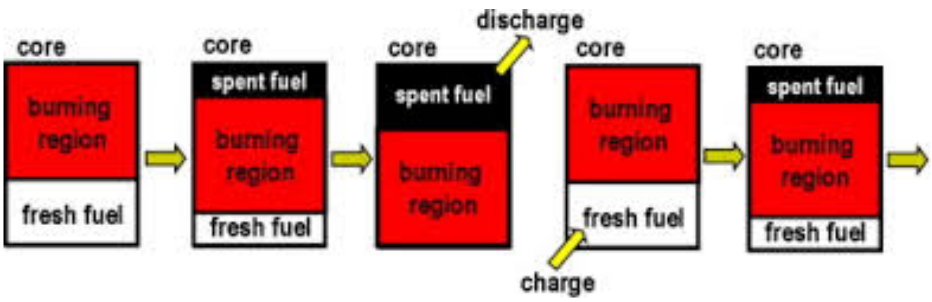

Figure 1. CANDLE burn up scheme

Modified CANDLE Reactor System

Modified CANDLE burn-up scheme allows the reactor to have long life operation by supplying only natural uranium as fuel cycle input. This scheme introducing discrete region, the fuel is initially put in region 1, after one cycle of 10 years of burn up it is shifted to region 2 and region 1 is filled with fresh natural uranium fuel. This concept is basically applied to all regions. The reactor is designed for 100 years with 10 regions arranged axially.

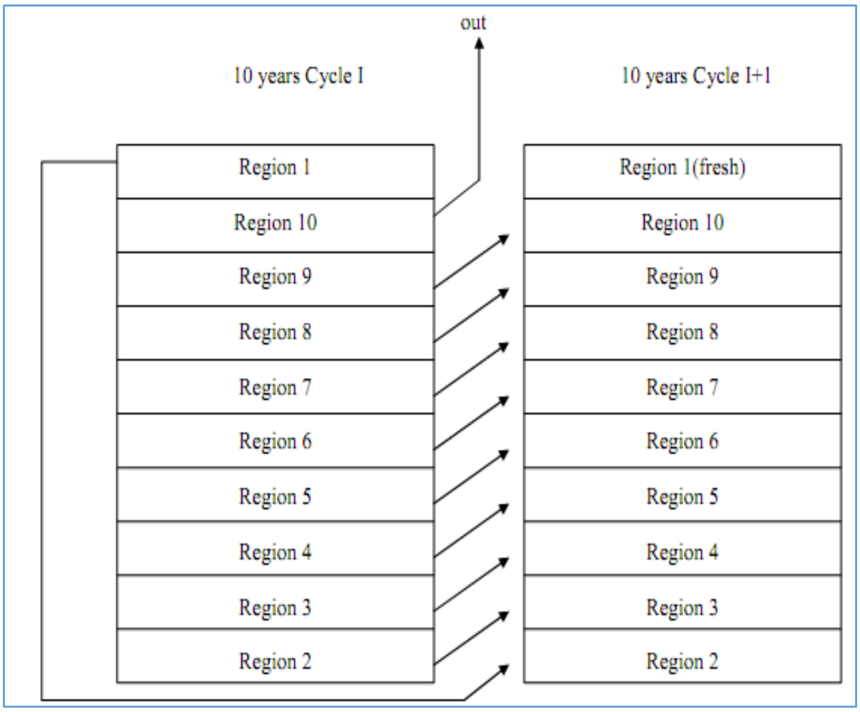

Figure 2. CANDLE burn up scheme

Table 1. Reactor Design Parameter

Parameter	Description
Thermal power	500 MWt
Number of equal volume region in core	10
Sub cycle length (years)	10
Fuel type	Uranium Nitride (UN)
Fuel volume fraction	60%
Cladding volume fraction	10%
Coolant volume fraction	30%
Fuel diameter	1.2 cm
Coolant type	Pb-208
Axial width of each region	15 cm
Active core radial width	110 cm
Reflector radial width	50 cm
fuel cell geometry	cylindrical
Core geometry	cylindrical

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3. Calculational Method

The neutronic calculations were performed by SRAC (Standard thermal Reactor Analysis Code system) code using nuclear data library based on JENDL 4.0. The SRAC (Standard Reactor Analysis Code) system is designed and developed at Japan Atomic Energy Research Institute (JAERI). The system covers production of effective microscopic and macroscopic group cross-sections, cell and core calculations including burn-up and fuel management.

For neutronic calculation, we use PIJ module for calculating burnup of the fuel cell and CITATION module for multi groups diffusion calculation. First, we assume the power density level in each region. Then we perform the burnup calculation using the assumed data. The burn-up calculation is performed using cell burn-up in SRAC code which then gives eight energy group macroscopic cross section data to be used in two-dimensional R-Z geometry multi groups diffusion calculation. The average power density in each region resulted from the diffusion calculation is then brought back to SRAC code for cell burn-up calculation. This iteration is repeated until the convergence is reached.

4. Results and Discussion

4.1. Burn up Level

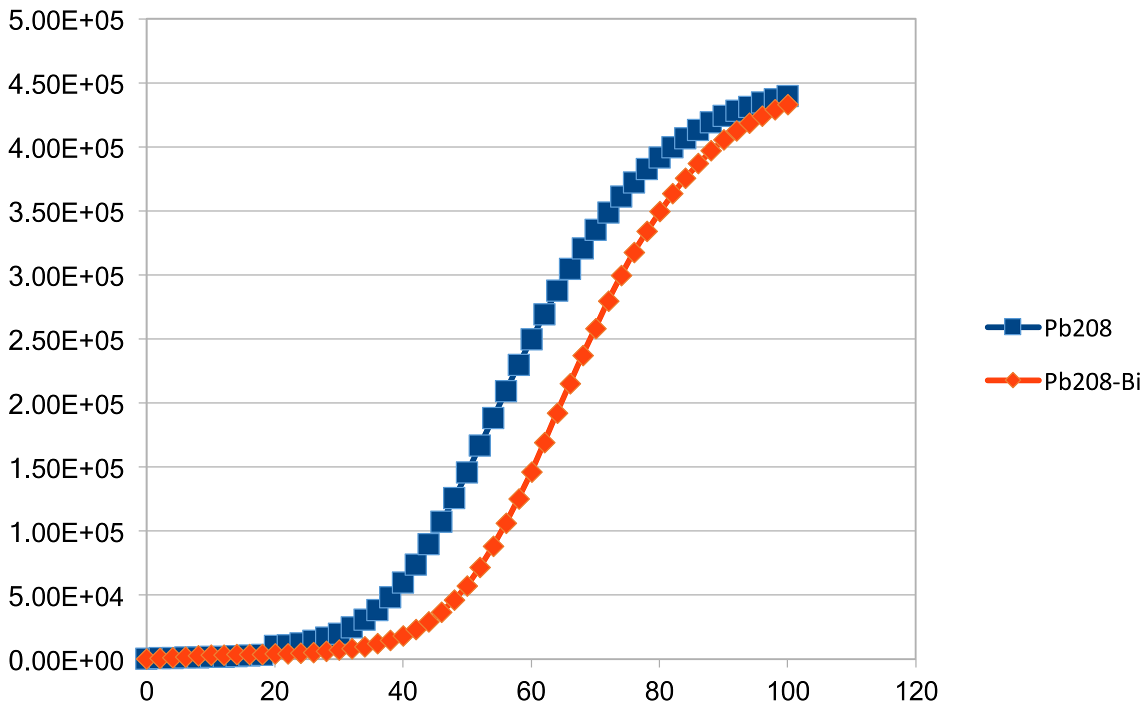

Figure 3. Burn up Level comparison between different coolant

Fig. 3 shows the burn up level of the reactor with different coolant. Reactor with Pb208 as the coolant has burn up level higher than Pb208-Bi as the coolant. It is mean that reactor with Pb208 produces fissile fuel faster and gain in core fuel loading due to excess of neutrons.

4.2. The infinite neutron multiplication factor

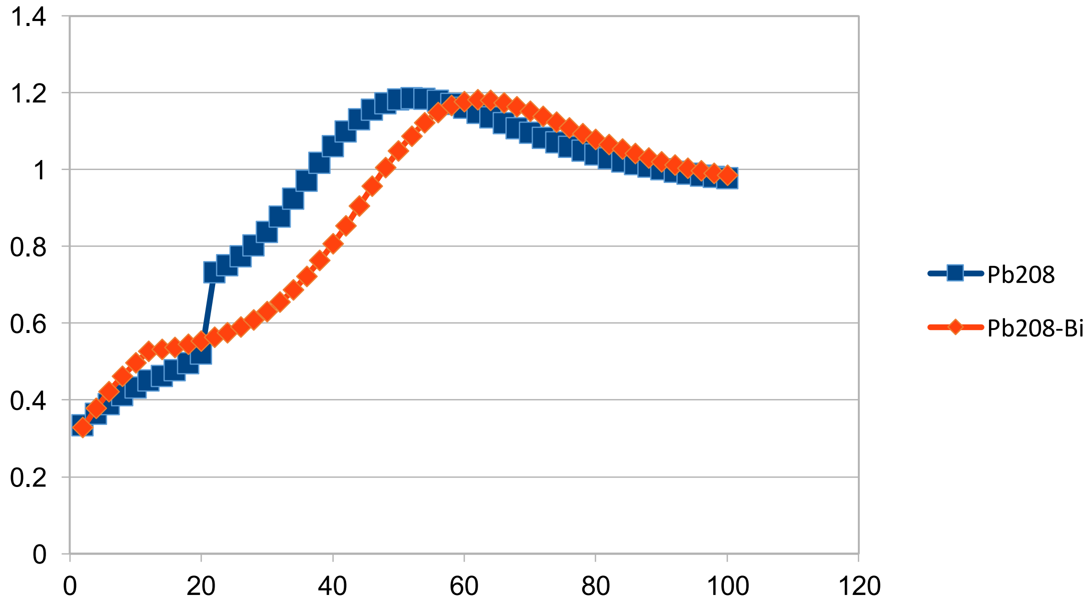

Figure 4. infinite neutron multiplication factor comparison between different coolant

Fig. 4 shows the infinite neutron multiplication factor of reactor with different coolant. Reactor with Pb208 as coolant has k-inf lower than Pb208-Bi as the coolant in the beginning. It is because the neutron is used to breeding. After 20 years, K-inf for Pb208 as coolant higher than Pb208-Bi as the coolant because of its Low neutron absorption cross-section. Then decrease because of fission product accumulation.

4.3. The change of atomic density during operation

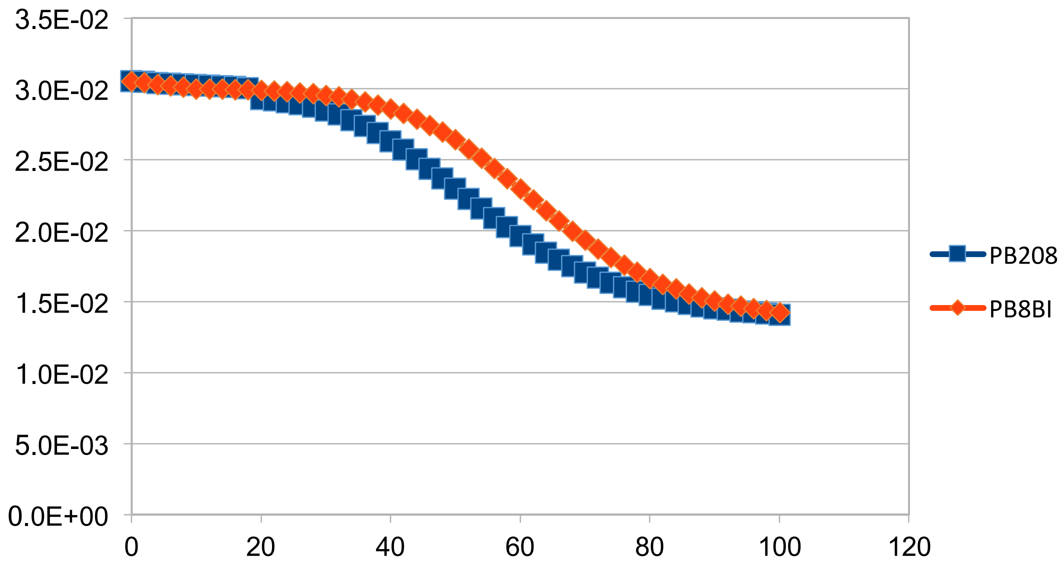

Figure 5. the change of atomic density during operation comparison between different coolant

Fig. 5 shows the change of atomic density during operation. Reactor with Pb208 as coolant has an atomic density of U-238 lower than Pb208-Bi as the coolant during operation. It is because the excess neutron is used to breeding U-238.

4.4. The change atomic density of Pu-239 during operation

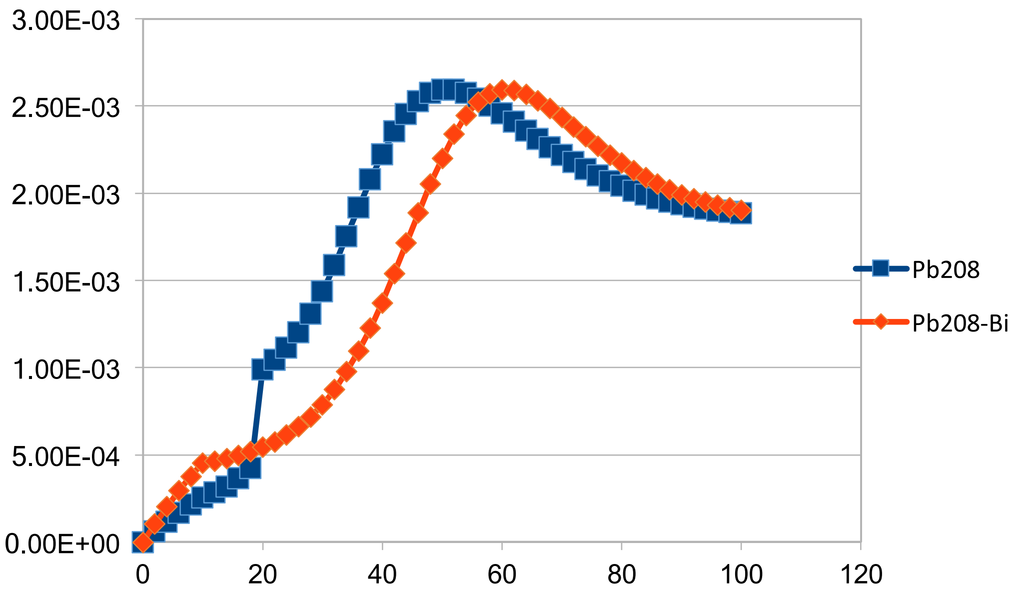

Figure 6. the change of atomic density during operation comparison between different coolant

Fig. 6 shows the change atomic density of Pu-239 during operation. Average Reactor with Pb208 as coolant has the atomic density of Pu-239 higher than Pb208-Bi as the coolant in the beginning. It is because Pb208 makes the production of Pu-239 faster.

4.5. The change integrated conversion ratio during operation

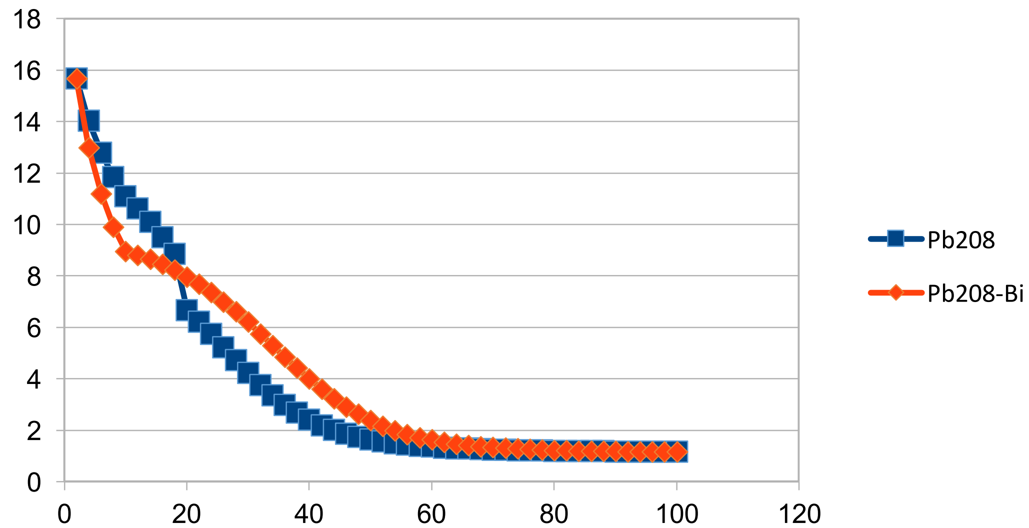

Figure 7. the change of atomic density during operation comparison between different coolant

Fig. 7 shows the change integrated conversion ratio (Inte-CR) during operation. Pb-208 has higher Inte-CR than Pb208-Bi at BOL because of its capability to produces than consume. After almost 20 years Pb208 burn the fuel lower than Pb208-Bi

4.6. *The effective neutron multiplication factor*

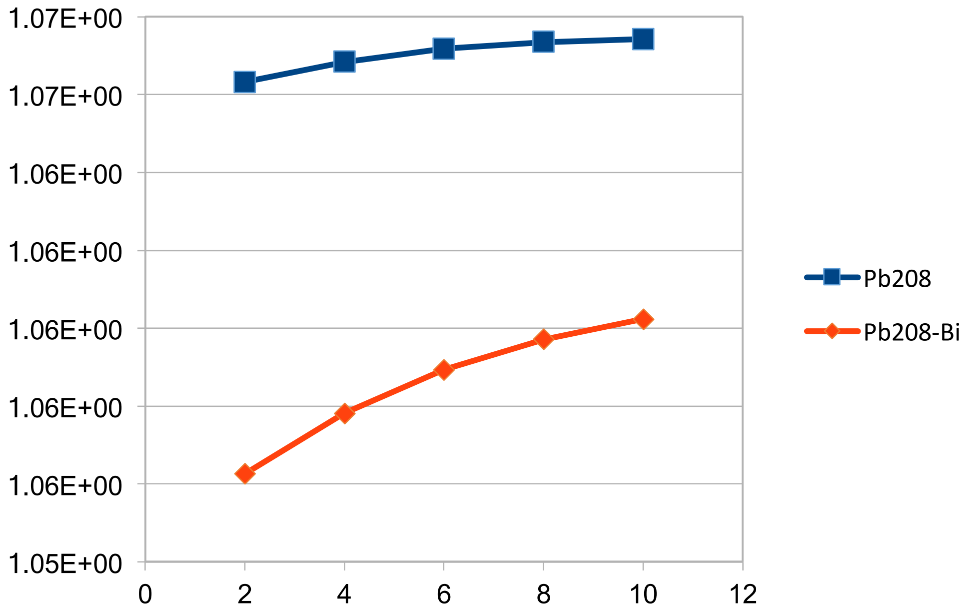

Figure 8. the change of atomic density during operation comparison between different coolant

Fig. 8 shows the effective neutron multiplication factor of the reactor with different coolant. Reactor with Pb208 as coolant has k-eff higher than Pb208-Bi as coolant at BOL. It is because Pb208-Bi as the coolant has Low neutron absorption cross-section.

5. Conclusion

- The neutronic aspect between Pb-208 and Pb208-Bismuth eutectic is not too much difference
- The k-eff of Pb208 as a coolant higher than Pb208-Bismuth eutectic
- Pb208-Bismuth eutectic probably gives better performance for extreme accidents than Pb208 because of the lower operation temperature. It is because Pb208-Bi eutectic has low melting point but high boiling point (almost same as Pb-208)

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