Transactions of the Korean Nuclear Society Virtual spring Meeting
May 13-14, 2021

Fuel Material Selection Strategy for Marine Propulsion LFR

Hyeong-Jin Kim, JiWon Mun, Ho Jin Ryu*,
Department of Nuclear and Quantum Engineering, KAIST, Daehak-ro 291, Yuseong-gu, Daejeon, 34141, Korea
**Corresponding author: hojinryu@kaist.ac.kr*

1. Introduction

Arctic ice loss caused by rapid climate change is predicted to open the Arctic route along the Russian coast in the next decade [1]. By developing the Arctic route, the transportation distance to Europe will be reduced by about 40%, and at the time of return, transportation of low-cost Russian oil and gas is possible, which is expected to greatly contribute to international trade and energy supply stability. The average ice thickness of the Arctic route is about 5m, and it is difficult for diesel icebreakers to break the ice exceeding 2m in thickness. At the same time, diesel fuel produces fine dust and causes air pollution. Therefore, the development of a nuclear-propulsion icebreaker is essential for the exploration and development of the Arctic route.

In the case of pressurized water reactor (PWR) type marine reactors that utilize nuclear fuel compling with IAEA standard for commercial ships: 20% or less of low enriched uranium (LEU), short refueling period of about 7 years is inevitable. This short fuel life requires the private port facility for nuclear ships which significantly increases the total life cycle cost of marine reactors. Accordingly, the development of non-refueling ultra-long cycle lead cooled microreactor for economic icebreaker is ongoing in Korea. SNU has developed URANUS, a micro-modular reactor based on lead cooled fast reactors used in Russian nuclear submarine since 1996 [2], and the innovation of the URANUS design is expected to enable 30+ year ultra-long cycle operation with the initial loading of LEU fuel [3].

Since an ultra-long cycle lead cooled micro-reactor for marine propulsion is unprecedented; especially, fast reactor design has never been applied to icebreakers; constructing the optimized reactor design is challenging. And selecting the fuel material is the first part of the reactor design. The majority of conventional fast reactor projects adopted the oxide or metallic fuel design, and there have been accumulated operation experience and data. In this study, the prioritization ranking method was introduced as a fuel material selection strategy for marine propulsion LFR, and a comparative evaluation was performed. Criteria and priority were first set, and then evaluation for each criterion was performed, and finally, a comprehensive comparison was made for oxide and metallic fuel.

2. Methods and Results

The four main categories of criteria were set as follows: Licensing, manufacturability, performance, safety. Each category was divided into sub-criteria and priority was ranked. Evaluation of each sub-criterion was performed based on a literature review, a calculation based on analytic or empirical models, and computer codes. Besides, neutronics and waste management are certainly one of the key parameters to determine the reactor design, however the evaluation for each criterion resulted in satisfaoctory evaluations, so they were not included in the comparative evaluation; this work was done separately by the neutronics and fuel cycle teams in the project. Details of evaluation for other sub-criteria are described below.

2.1. Experience

Marine propulsion reactors should be able to withstand frequent power ramping situations. The majority of marine propulsion reactors adopted uranium-metal alloy or metal-ceramic dispersion fuels without a gap, in contrast to typical land-based reactors using a uranium dioxide pellet with a helium gap.

OK-150 reactor in the earliest Russian icebreaker NS Lenin adopted the oxide pellet fuel with a helium gap. After a leakage due to the fuel-cladding interaction, later Russian icebreakers adopted a U-Zr fuel without a gap. [4] The RITM-200 reactor adopted low enriched uranium ceramic-metal (LEU cermet) fuel, preventing fuel-cladding interaction by using dispersion type oxide fuel without a gap. [5] However, there has been no experience of cermet dispersion fuel for the fast reactors.

There were four nuclear-powered merchant ships, and only NS Sevmorput in Russia is currently in service. LEU uranium dioxide pellet with the helium gap was adopted for the first three ships. NS Sevmorput has the icebreaking capability and adopted U-Zr fuel without a gap. [6]

In Korea, oxide fuel fabrication technology is matured for PWR and metallic fuel has been developed to produce the driver fuel for SFR. [7]

In summary, oxide fuel is more preferred in global LFR projects. There has been accumulated experience of marine propulsion reactor for both oxide and metallic fuel. LEU-based cermet is now a common fuel type in nuclear icebreakers. [8]

2.2. Fuel performance and safety

For the evaluation of fuel performance, 3 reactor design parameters: uranium density, smeared density, required plenum space, and 5 failure modes: fuel-cladding mechanical interaction (FCMI), fuel-cladding chemical interaction (FCCI), fission gas release (FGR), fuel swelling and cladding creep were selected as evaluation criteria. In the case of safety evaluation, thermal margin and transient behavior were considered. The temperature was first calculated by the analytic model, and then evaluation for each criterion was done by conventional data and empirical correlations.

In summary, uranium density is much higher in the case of metallic fuel, but the smeared density is higher in oxide fuel. Due to the low FGR of oxide fuel, the required plenum space is less. Oxide fuel shows drawbacks in FCMI due to hard pellet characteristics, but metallic fuel has higher FGR, swelling, FCCI, or fuel-coolant interaction. Cladding creep is negligible in both cases. Metallic fuel shows inherent safety features, and oxide fuel has a similar density with the coolant, so melt-down re-critically is less probable.

2.3. Weighting by priority rank

The priority for each sub-criterion was ranked in four steps, and the weighting value was designated accordingly. Advantages and drawbacks according to the fuel material for each criterion were evaluated, then the total score was summed for final comparison. Five high priority criteria: global LFR trend, FCMI, FCCI, melt-down recriticality. Two mid-high priority criteria: icebreaker/ship experience, uranium density. Nine middle priority criteria: local manufacturability, fuel performance code, fuel smeared density, plenum space, thermal conductivity, FGR, fuel swelling, cladding creep, transient behavior. Three low priority criteria: global fast reactor experience, global manufacturability, thermal margin, fuel-coolant interaction.

In terms of experience, there is no ongoing global LFR project using metallic fuel. In Korea, PWR oxide fuel fabrication technology is in state of art, and metallic fuel fabrication technology is developed for SFR. However, there is no experience with high-assy LEU oxide fuel.

In terms of fuel performance and safety, uranium density and thermal conductivity are much higher in metallic fuel but have a lower smeared density. Also, the required plenum space is larger in case of metallic fuel. There is much less FGR, fuel swelling in oxide fuel compared to metallic fuel. Both fuels suffer FCCI problem, but metallic liner between fuel-cladding for preventing FCCI, can be introduced in oxide fuel case. Metallic fuel has an inherent-safety feature but suffers fuel-coolant interaction problem more. Oxide fuel has almost the same density as LBE coolant, so the melt-down recriticality problem is mitigated.

3. Conclusions

In this study, key parameters for the fuel material selection were set, and the advantages and drawbacks of each parameter were evaluated.

In general, oxide fuel has a higher industrial manufacturing experience, better chemical stability and melting point, lower swelling, FGR, FCCI. On the other hand, metallic fuel has a harder neutron spectrum and fuel-coolant compatibility, higher uranium density and thermal conductivity, inherent safety at transient.

For the comprehensive evaluation, priority ranking and scoring were performed. This approach concludes that the oxide fuel has more advantages for the marine propulsion LFR.

This analysis is expected to contribute to the design of LFR for marine propulsion purposes.

ACKNOWLEDGMENT

This work was supported by the National Research Foundation of Korea (NRF-2019M2D1A1067210) funded by the Ministry of Science and ICT.

REFERENCES

[1] Humpert, Malte, and Andreas Raspotnik. "The future of Arctic shipping along the transpolar sea route." Arctic Yearbook 2012.1 (2012): 281-307.
[2] Choi, Sungyeol, et al. "URANUS: Korean lead-bismuth cooled small modular fast reactor activities." Small Modular Reactors Symposium. Vol. 54730. 2011.
[3] Nguyen, Tung Dong Cao, et al. "DEVELOPMENT OF SMALL MODULAR LFR DESIGNS FOR ICEBREAKER SHIP." Institut Teknologi Bandung Bahçeşehir University, 2019.
[4] Reistad, O., & Ølgaard, P. L., “Russian nuclear power plants for marine applications”, NKS-138 (2006)
[5] “STATUS OF SMALL AND MEDIUM SIZED REACTOR DESIGNS”, IAEA Report (2012)
[6] Freire, Luciano Ondir, and Delvonei Alves de Andrade. "Historic survey on nuclear merchant ships." Nuclear Engineering and Design 293 (2015): 176-186.
[7] Song, Kee-Chan “The status of nuclear fuel cycle R&D at KAERI”, 2009 KAIST colloquium
[8] Craig F.Smith, GEN 4 International Forum (GIF), “Lead-Cooled Fast Reactor”, Naval Postgraduate School (2017)