The Current Status of Accident-Tolerance Enhanced Breakthrough Fuel Design R&D in US after Fukushima Daiichi Accident

Sung-Tae Yang*, Ji-Eun Jung, Kyung-Ho Roh
Korea Hydro & Nuclear Power Co., Ltd. Jang-Dong 25-1, Yuseong-Gu, Daejeon, Korea, 305-343
* *Corresponding author :* fuse@khnp.co.kr

1. Introduction

After Fukushima Daichi accident in 2011, where a station blackout (SBO) led to a loss of coolant and core melt-down, has further underscored the value of any breakthrough fuel technologies that could enhance nuclear fuel's ability to cope with severe accident.

While complete mitigation of fuel degradation in a severe accident is challenging, improved cladding materials that can reduce the rate of oxidation in these severe accident could allow operators additional response time before significant core damage and fission product release.

The current fuel geometry and basic properties of fuel and cladding materials have limited designers' options to make further advances in improving fuel efficiency while meeting the regulatory and operational parameters

A major limitation which has implications on fuel safety margins is the propensity of zirconium alloy fuel cladding to lose strength and rapidly react with steam to produce a significant quantity of hydrogen in the early phase of a Loss of Coolant Accident(LOCA).

2. Design Limitation of Conventional Zr-alloy fuel

To assess the potential candidate of possible breakthrough fuel technologies, it is helpful to reflect on the key design parameters for current fuel designs. These parameters are summarized below.

<u>Regulatory Aspect:</u>

- DNB Margin
- Pellet Centerline Melting
- Design LOCA and RIA Limits (cladding hydriding)
- Rod Average Burn-up Limit of 62 GWd/MTU (US)
- Rod Internal Pressure and Cladding Liftoff
- 1% Residual Ductility Limit at Discharge (for PCMI control)
- 5% U-235 Enrichment Limit

<u>Operational Aspect:</u>

- AOA(Axial Offset Anomaly) or CIPS(Crud Induced Power Shift) due to excessive sub-cooled boiling, crud deposition and boron hideout
- CILC (Crud Induced Localized Corrosion)
- Power Ascending Rate Restriction and PCI-SCC(Pellet Cladding Interaction-Stress Corrosion Cracking)
- Fuel Assembly Bow
- GTRF(Grid To Rod Fretting)

3. Major Design Features of Breakthrough Fuel

Any new fuel designs concept for future use in LWRs to increase accident tolerance must have the following characteristics:

- Delay Fission Product Release and Fuel Meltdown in Severe Accidents (High Melting Temperature)
- Reduce/Delay the Rate of Hydrogen Generation
- Sufficient Strength at Elevated Temperatures
- Maintain High Fuel Reliability
- Maintain Good Attributes Under Normal Operation, such as compatibility with reactor coolants

US R&D on advanced fuels program focus on :
(1) Compatible with Current Fuel & Core Design
(2) Ready for In-reactor Demonstration as LTR(Lead Test Rod) or LTA(Lead Test Assembly) within 10 years.
(3) Overall Fuel Economics while recognizing the likelihood of higher initial implementation costs

4. Current Candidate Technologies for Improving Fuel Safety Margins in US

(1) Silicon Carbide (SiC) Composite Cladding and Channels

SiC cladding has the advantage of lower neutron cross section and reduced rate of reaction with steam at 700-1300^{o}C. SiC weave composite is a very tough structure and will unlikely to fail by catastrophic fracture.

The first proposed SiC composite cladding consists of an inner monolithic SiC layer formed by chemical vapor deposition(CVD), a middle SiC weave made of 15-20 μm SiC fibers which is impregnated with SiC via a chemical vapor infiltration(CVI) process to fill the holes in the weave, and an outer monolithic SiC layer formed by CVD. Tests of SiC cladding material have been performed in test reactors at MIT and ORNL.

Attempts to improve SiC cladding hemeticity have been made by forming a composite SiC – Zr alloy cladding. Idaho National Laboratory (INL) is currently pursuing Zircaloy tubing wrapped with SiC weave. It remains challenging to bond SiC to the Zircaloy cladding and innovative technologies will be needed.

Before SiC can be considered as a candidate for LWR fuel cladding, many technical obstacles will need to be resolved, which include fabricability, weldability, and hemeticity.

Another project on SiC is underway with EPRI funding to demonstrate fabricability of BWR channels. The channel application should be easier because of the thicker wall, relaxed tolerances on uniformity, and no requirement of hermeticity. The BWR channel concept could be the fastest route to gaining operational experience in a commercial LWR.

(2) MAX Phase Material Cladding Coating

A family of ternary carbides and nitrides, known as MAX phases, combine attractive properties of both ceramics and metals, and has been suggested for potential advanced fuel coating technology.

MAX Phase Material = $M_{n+1}AX_n$ (n=1,2,3)

(Where, M is early transition metal, A is group A element, X is carbon or nitrogen)

The materials show high mechanical damage tolerance in terms of creep, thermal/mechanical fatigue and fracture resistance. The specific activities of Ti_3SiC_2, Ti_3AlC_2, and Ti_2AlC were compared to those of SiC and Alloy 617, two leading candidate materials for next generation reactor components. The specific activities of MAX phases were similar to SiC and three orders of magnitude less than Alloy 617 after 10–60 years decay for all three activation times in both the fast and thermal spectra. As with SiC, the main radioisotopes after a decay period of 10 years for all three activation times in the MAX phases are tritium and C^{14}. Neutron irradiation results of Ti_3SiC_2, Ti_3AlC_2, and Ti_2AlC experimentally confirmed the neutron transmutation analysis.

(3) Fully Ceramic Micro-encapsulated(FCM) Fuel with small TRISO particles fully embedded in SiC pellets

ORNL is working under DOE-NE Advanced Fuel Development Program more revolutionary fuel design trying to transport the TRISO fuel, which was originally designed for high temperature gas cooled reactor, for LWR applications. The FCM fuel is to encapsulate small TRISO fuel particles (nominally 0.8-2.0 mm diameter) in a SiC "fuel pellet" of the same configuration as a typical UO_2 pellet, Figure 1. The TRISO fuel particle, as shown in the left of Figure 1, is designed with 2 graphite and one SiC barriers to contain the fuel and fission products.

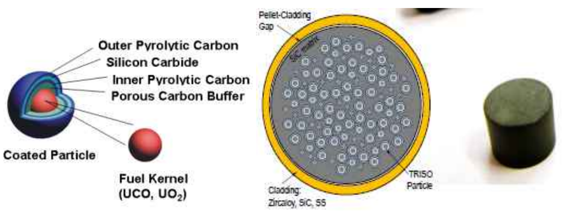

Figure 1. Configurations of FCM Fuel Design by ORNL

(4) Refractory Metals, Molybdenum alloy cladding

EPRI proposed Mo-based fuel cladding to be developed to utilize its high melting temperature and high strength. This concept involves Mo-duplex and Mo-triplex metal composite cladding. A high strength Mo alloy cladding is bonded with a thin Zr-alloy on the outer surface to form a duplex cladding. The Zr-alloy outer layer is designed to have similar corrosion property as the current Zr-alloy fuel cladding, thus making the cladding fully compatible with reactor coolants. The outer Zr alloy layer will be fully oxidized to a ZrO_2 layer in the early stage of a loss of coolant accident (<800-1000^oC), which is equivalent to an in-situ formation of a stable ceramic coating (ZrO_2) to protect the underlining Mo alloy cladding from attack by steam.

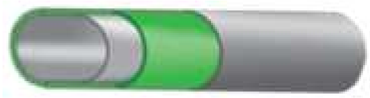

Figure 2. Mo-triplex metal composite cladding

5. Conclusions

In US, DOE and EPRI are actively involved in the development of accident tolerance breakthrough fuel design. DOE's aggressive approach make its R&D bodies to be ready for in-reactor demonstration as LTR or LTA within 10 years. Their R&D strategy harmonized with its stake-holders ; government, utility, fuel vendor, research institute, university and so on.

We should review our current R&D strategy on accident tolerance breakthrough fuel, and make our own roadmap on commercial LWR advanced fuel R&D with consensus among related stake-holders.

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