Transactions of the Korean Nuclear Society Autumn Meeting
Gyeongju, Korea, October 25-26, 2012

Technical Issues in the Development of High Burnup and Long Cycle Fuel Pellets

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1. Introduction

Over the last half century, a nuclear fuel cycle, a fuel discharged burnup and a uranium enrichment of the LWR (Light Water Reactor) fuel have continuously increased. It was the efforts to reduce the LWR fuel cycle cost, and to make reactor operation more efficiently. Improved fuel and reactor performance contribute further to the reduction and management efficiency of spent fuels [1, 2].

The primary incentive for operating nuclear reactor fuel to higher burnup and longer cycle is the economic benefits. The fuel cycle costs could be reduced by extending fuel discharged burnup and fuel cycle length [3]. The higher discharged burnup can increase the energy production per unit fuel mass or fuel assembly. The longer fuel cycle can increase reactor operation flexibility and reduce the fuel changing operation and the spent fuel management burden. The margin to storage capacity limits would be also increased because high burnup and long cycle fuel reduces the mass of spent fuels. However, increment of fuel burnup and cycle length might result in the acceleration of material aging consisting fuel assembly. Then, the safety and integrity of nuclear fuel will be degraded. Therefore, to simultaneously enhance the safety and economics of the LWR fuel through the fuel burnup and cycle extension, it is indispensable to develop the innovative nuclear fuel material concepts and technologies which can overcome degradation of fuel safety.

New fuel research project to extend fuel discharged burnup and cycle length has been launched in KAERI. Main subject is to develop innovative LWR fuel pellets which can provide required fuel performance and safety at extended fuel burnup and cycle length. In order to achieve the mission, we need to know that what the impediments are and how to break through current limit of fuel pellet properties.

In this study, the technical issues related to fuel pellets at high burnup were surveyed and summarized. We have collected the technical issues in the literatures, categorized the issues and searched the recent R&D activities related with innovative fuel pellet. This preliminary literature work can inspire us to find a way to solve critical problems arisen in high burnup pellets.

2. Technical issues in high burnup fuel pellets

Increase of burnup and/or fuel cycle length means an increase of fission rate and high irradiation dose. The fission products and irradiation damages are accumulated more and more in the pellets as the fuel burnup increase. Then those will cause a pellet swelling, rod pressure increase due to fission gas release, and formation of a high burnup structure [4].

2.1. Pellet swelling and Fission gas release

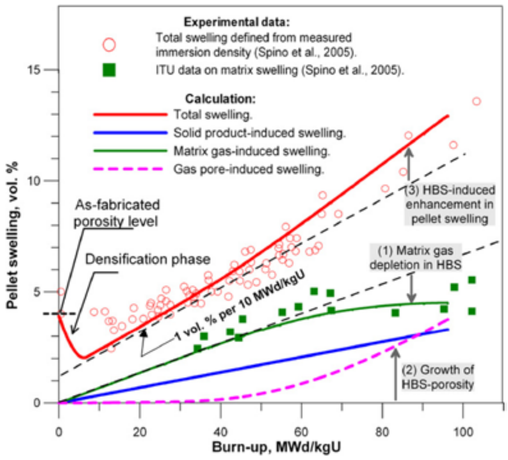

Fig. 1. Calculated pellet swelling and porosity during the steady-state irradiation to a high burnup [5].

Pellet swelling should be controlled as small as possible because it induces fuel failure. Fig. 1 shows measured and predicted pellet swelling as a function of fuel burnup in LWR UO_2 pellets. This figure implies that the formation of fission gas containing pores and their behavior attributed to non-linear increase of pellet swelling in high burnup area above 40-50 MWd/kgU. In the aspect of fuel swelling, it seems to be better to release the fission gas from the pellet. However, released fission gas increases the fuel rod internal pressure and reduces the gap conductance between clad and pellet. Those effects are also harmful to rod safety. Therefore, it is desired to develop an innovative pellet which can retain fission gas but does not form fission gas containing pores.

2.2 Formation of high burnup structure

Series of research on the microstructure evolution in irradiated UO_2 pellets showed that high burnup structure (HBS) is formed when the burnup exceeds threshold value (burnup threshold: 55-82 MWd/kgU, temperature threshold: below 1100-1200 °C) [6]. The high burnup structure is characterized by large sized pores, high porosity (10-20 %), sub-divided grains (0.1-0.3 μm), fission gas depletion from fuel matrix, etc as shown in Fig. 2. It is not clear that HBS is always opposite to burnup extension yet. However, since the fission gas in HBS pores can lead to large swelling (Fig. 1) and HBS can easily bring about the pellet surface fragmentation especially at transient condition, it might be necessary to develop the HBS formation minimizing technique.

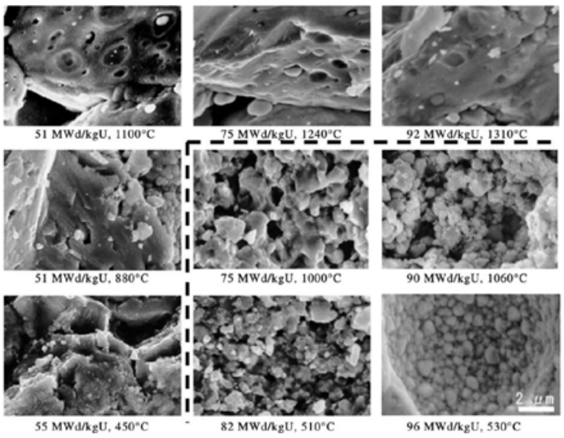

Fig. 2. SEM observations on the fracture surfaces of irradiated at different burnup and temperature [6].

2.3 Degradation of thermal conductivity

Accumulation of fission products and radiation damages increasingly reduce the thermal conductivity of UO_2 pellet [7]. Decrease of thermal conductivity increases the pellet temperature during the operation. High temperature fuel pellet reduces the safety margin because it increases thermal expansion and mass transfer rate thus increase pressure on clad and fission gas release. Therefore, it is necessary to develop a pellet with a high thermal conductivity.

3. Research activities

Various innovative concepts and related studies have been suggested and conducted to enhance the performance and safety of fuel pellet at extended burnup. Those activities include composite pellets (CERCER, CERMET) for high thermal conductivity [8], large grain pellets for fission gas retention [9], additives doped pellets for PCI remedy [10], and high density pellets for advanced reactors.

Large grain pellets can effectively retain the fission gas in the pellets. Additives doping technique enhances the deformation properties of fuel pellets at high temperature and grain size thus improves the pellet-cladding-interaction behaviors. Cold fuel composite pellets having high thermal conductivity are expected to reduce the pressure on clad caused by thermal expansion of pellet, as well as diffusional release of fission products. Thermal margins in composite fuel can be utilized for power up rate of LWRs.

3. Summary

Many researchers suggested that increase of internal rod pressure caused by fission gas and pellet swelling, formation of high burnup structure, and thermal conductivity degradation are the major technical issues should be addressed for the development of high burnup and long cycle fuel pellets. The related researches mainly focus on the mutual mechanism on fuel degradation during the fission and the comprehensive remedies to retard the fuel degradation.

ACKNOWLEDGEMENT

The authors acknowledge that this work has been performed under the Nuclear R&D Programs supported by the Ministry of Education, Science and Technology in Korea.

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