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Phenomenon Identification and Ranking Table development study of ODS ATF fuel

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1. Introduction

From 2017 to the present, KAERI has been conducting the development of safety evaluation technology for accident tolerant fuel project. Unlike conventional nuclear fuel, which consisted of a single material of Zirconium alloy and UO_2, accident tolerant fuel (ATF) was composed of a cladding and a pellet made by combining various materials. In KINS Safety review guidelines for light water reactors (Rev. 6) [1] 4.2, it should be evaluated whether the previous design basis and Specified Acceptable Fuel Design Limit (SAFDL) are applicable to the new fuel design using the new material at a given temperature, burnup and power. If it is not applicable, it is stated that a new standard should be established based on appropriate data.

In this paper, a CrAl-ODS-Zry4 cladding and 5% Mo microcell pellet (hereinafter denoted as ODS-Mo ATF fuel) as shown in Fig. 1 is evaluated based on the previous design basis and, if necessary, a new SAFDL is established. The evaluated design basis are stress and strain, fatigue, oxidation and hydriding and CRUD, irradiation growth, rod internal pressure (RIP), cladding collapse, overheating of cladding, overheating of fuel pellet. Fatigue [2], oxidation and hydriding and CRUD [3], irradiation Growth [4] were already presented at 2021 KNS spring meeting.

Based on the published research results about ODS-Mo ATF fuel, the importance level is presented according to the margin for each design basis using the PIRT format, and the knowledge level is determined according to the possessed data. This is different from the original purpose of the PIRT to determine the importance and knowledge level of the specified phenomenon for a specific reactor and scenario. The purpose of this paper is to summarize the results of previously mentioned projects that have been carried out so far, and to provide basic data that can be referenced when preparing PIRT for future commercialization and licensing research.

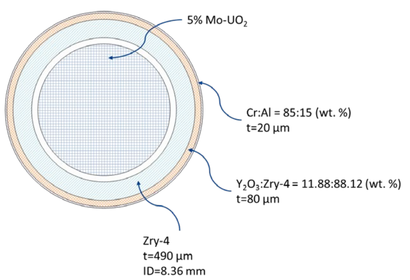

Fig. 1 CrAl-ODS-Zry4 cladding and Mo-UO_2 pellet

2. Design basis for cladding stress and strain

2.1 Stress assessment of ODS-Mo ATF fuel cladding

In the ODS-Mo ATF fuel cladding having a multi-layer structure, the discontinuity of stress distribution is observed as shown in Fig. 2 because the mechanical properties of each layer are different. Therefore, after obtaining the material properties (Elastic modulus, yield strength, etc.) through in- or out-of-pile tests and applying them to the computer code along with the analysis model derived from the multi-layer stress evaluation methodology, the stress in each layer should be calculated and compared with the stress limits.

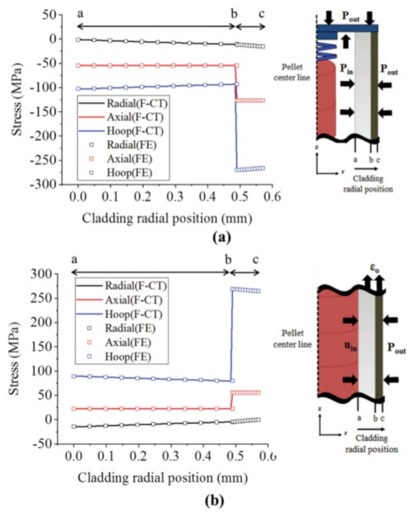

Fig. 2 ATF fuel cladding radial stress distribution [5]

2.2 Strain assessment of ODS-Mo ATF fuel cladding

Through analytical evaluation, it should be evaluated whether the strain imposed on each layer reaches the strain limit of each layer or the entire cladding. The strain limit value of the ODS-Mo ATF fuel cladding is set as the strain value at which the mechanical ductility of the cladding is maintained through the irradiated cladding mechanical test. In addition, within the strain range in which the ductility of the cladding is maintained, there is a possibility of fracture due to cracks in the coating. This should be investigated and, if necessary, new tolerances need to be established.

2.3 SAFDLs related to cladding stress and strain

In order to apply the stress and strain SAFDLs for the conventional fuel cladding to the multi-layered ODS-Mo ATF fuel cladding, it is necessary to develop an appropriate methodology. A new damage and failure mechanism may exist due to delamination or cracks in the coating layer unlike the conventional fuel cladding, so suitable methodologies need to be developed.

3. Design basis for fuel rod internal pressure

3.1 Rod internal pressure assessment of ATF fuel

Since the Mo-UO2 pellet has a lower central temperature than the UO2 pellet, the thermal diffusion region is relatively reduced and the amount of fission gas release (FGR) is decreased. Therefore, RIP is expected to be decreased. As shown in Fig. 3, it is judged that the amount of FGR may be reduced by the Mo metal wall, which prevents fission gas diffusion. But it is possible to apply the exiting FGR model for a conservative approach. However, the verification process through tests is necessary to confirm the FGR change by the Mo metal wall.

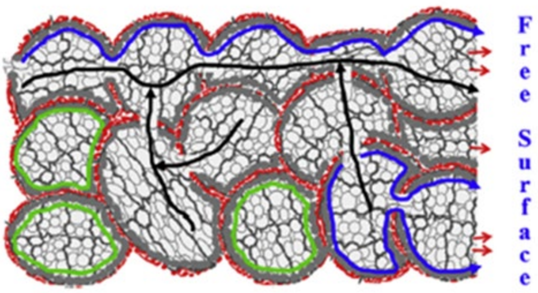

Fig. 3 Fission gas release path of Mo-UO2 pellet [6]

3.2 SAFDLs related to rod internal pressure

It is judged that the RIP of the Mo-UO2 pellet may be lower than that of the conventional UO2 pellet. Therefore, the currently licensed RIP limit can be sufficiently used.

4. Design basis for cladding collapse

4.1 Cladding collapse assessment of ATF fuel cladding

Assuming that the ODS-Mo ATF fuel cladding is manufactured with the same ovality as the conventional cladding produced by KEPCO-NF, in the case of free standing of the cladding, the critical collapse pressure is obtained from Equation (1) [7]. It can be seen that critical collapse pressure (q_{cr}) is proportional to the cube of the thickness of the cladding (t), and proportional to the modulus of elasticity (E) of the cladding.

$$q_{cr}^2 - \left\{ \frac{\sigma_{ys}}{m} + (1+6mn)P_{cr} \right\} \bullet q_{cr} + \frac{\sigma_{ys}}{m} \bullet P_{cr} = 0 \qquad (1)$$

where, $m = r/t$: the thinness of the cladding thickness
$N = \delta / r$: ratio of ovality(δ) to radius

In the case of ODS-Mo ATF fuel cladding, the critical collapse pressure is larger than that of the conventional cladding because the thickness of the cladding is about 20 μm larger. In other words, it is expected that the possibility of instantaneous collapse of the cladding due to the pressure difference between the inside and outside of the beginning of life (BOL) will be reduced compared to the Zr-based cladding.

In the case of buckling of the cladding tube, the density of the Mo-UO2 pellet is the same or can be manufactured up to 97.5% [8], so the possibility of densification of the Mo-UO2 pellet is expected to be reduced compared to that of the conventional pellet. In addition, as shown in Fig. 4, the creep deformation amount of ODS treated cladding is reduced compared to conventional cladding. In particular, when CrAl coating is additionally applied to the ODS cladding, the amount of creep strain rapidly decreases to 1/10 of the creep strain rate [9]. Therefore, it is expected that the creep phenomenon of ODS-Mo ATF fuel cladding due to high pressure and temperature of reactor coolant and high-speed neutron irradiation is reduced during operation, and the possibility of cladding buckling is expected to be reduced.

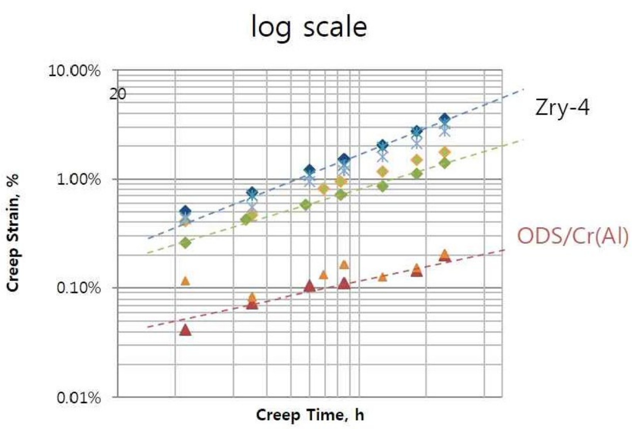

Fig. 4 Tube creep test results [9]

4.2 SAFDLs of cladding collapse

It is judged that the critical collapse pressure of the ODS-Mo ATF fuel cladding is larger than that of the Zr-based cladding and the creep deformation amount is small. In addition, the density of the Mo-UO2 pellet is the same or greater than that of the conventional pellet, so the currently licensed cladding collapse limits for free standing and buckling can be used sufficiently.

5. Design basis for overheating of cladding

5.1 Overheating assessment of ATF fuel cladding

Since the surface in contact with the coolant is replaced by the coated surface of the ODS-Mo ATF fuel cladding, the roughness change of the surface and the decrease in the hydraulic diameter of subchannel are considered to have the greatest effect on the critical heat flux (CHF). Several experiments on the CHF as a factor related to cladding overheating have shown that the coating layer enhances the CHF. In addition, it is judged that the effect of the increase of the heated diameter by the coating is also not large. However, it is necessary to acquire out-of-pile test data under reactor conditions because there is insufficient experience using the coating cladding in the reactor and the critical heat flux has a large effect on the safety analysis.

5.2 SAFDLs of overheating of cladding

DNBR as a SAFDL for cladding overheating has presented improved characteristics of critical heat flux for coated cladding in some critical heat flux experiments. Therefore, if the same surface conditions as that of the commercial cladding are applied to the coated cladding, it is judged that the conservatism of the currently used DNBR correlation equation will be secured. However, considering of the importance of the DNBR as a criterion for nuclear fuel failure, the verification process through test is necessary. If the diameter change due to coating layer occurs, additional evaluation of the thermal margin of the core is necessary in consideration of the reduction of the coolant flow area and the increase in pressure drop.

6. Design basis for overheating of fuel pellets

6.1 Overheating assessment of ATF fuel

It is judged that the overheating of the Mo-UO2 pellet will be reduced compared to the conventional UO2 due to its high thermal conductivity. In the case of the thermal conductivity model, it is necessary to apply the effective thermal conductivity model of the composite material including the anisotropy of Mo thermal conductivity. The UO2 melting temperature is applied as the limiting value for overheating of fuel pellet. In the Mo-UO2 pellet, the melting temperature of Mo is about 240 ℃ lower than that of UO2, so it may be decreased margin of design basis.

6.2 SAFDLs of overheating of fuel pellets

Since the melting temperature of Mo is lower than UO2 in the Mo-UO2 pellet, the overheat limit should be applied based on the melting temperature of Mo and a verification process through test is necessary.

4. Results and Discussion

Accident tolerant fuel composed of CrAl-ODS-Zry4 cladding and 5% Mo microcell pellet with previous design basis such as stress and strain, fatigue, oxidation and hydriding and CRUD, irradiation growth, rod internal pressure, cladding collapse, cladding overheating, pellet overheating is evaluated and new SAFDLs are needed to develop in the case of stress and strain, overheating of fuel pellets.

Table 1 shows the importance level according to the margin of each design basis and the knowledge level according to the possessed data.

Acknowledgement

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REFERENCES

[1] KINS, Safety review guidelines for light water reactors. (Revision 6), KINS/GE-N001

[2] J.-D. Hong, J.Y. Kim, Qualitative approach to understand fatigue behavior of CrAl-ODS-Zr alloy ATF cladding, 2021 KNS spring meeting

[3] J.-D. Hong, J.Y. Kim, Qualitative approach to understand the behavior of oxidation, hydriding, and the buildup of corrosion products (CRUD) for CrAl-ODS-Zr alloy ATF cladding, 2021 KNS spring meeting

[4] Yong Sik Yang, Jong Dae hong, Jae Yong Kim, Qualitative approach to understand irradiation growth behavior of ODS ATF fuel, 2021 KNS spring meeting

[5] D.H. Kim et al., Development of FRACAS-CT module with FRAPCON4.0P01 for simulation mechanical behaviors for accident-tolerant fuel cladding in a reactor, JNST Vol. 56, No. 8, 671-683, 2019

[6] Yang-Hyun Koo et.al., Fission gas release in the micro-cell fuel pellet under normal operating conditions: A simplified approach based on UO2 pellet experience, Journal of Nuclear Materials 527, 151801, 2019

[7] Hyung-Kyu Kim, Design Method to Avoid Elastic Buckling of a Crylindrical Tube Incorporating Ovality, Trans. Korean Soc. Mech. Eng. A, Vol. 42, No. 1, pp. 9~15, 2018
[8] Dong-Joo Kim et al, “Development status of high thermal conductive UO2 pellet as ATF at KAERI,” Top fuel 2019, 2019
[9] Yang-Il Jung et al, “Formation of Surface ODS Layer in Zr Alloys and Their Mechanical Properties,” KAERI/TR-7105/2017, KAERI, 2017.

Table 1 Phenomenon Identification and Ranking Table of ODS-Mo ATF fuel

ID	Damage Mechanism	Comments	Importance Level	Rationale	Knowledge Level	Rationale
1	Cladding stress	- Prevention of cladding damage due to excessive stress	L	- Due to ODS layer, the yield strength ATF fuel cladding may be increased. - So, the stress margin for the design basis may be increased.	L	- It is necessary to develop a methodology to evaluate stress and strain in multi-layer structures. - It is necessary to measure local mechanical properties under various temperature, burn rate, etc.
2	Cladding strain	- Prevention of cladding damage due to excessive strain	L	- Because CrAl coating well resists corrosion and hydrogen absorption, brittleness of cladding may be decreased. - So, the strain margin for design basis may be increased.	L	- Strain measurement of irradiated ATF fuel claddings are required. - It is necessary to measure the properties of the irradiated coating layer and ODS layer.
3	Cladding fatigue	- Repetitive fatigue loading may cause cladding failure	M	- Fatigue characteristics cannot be clearly determined due to limited data and uncertainties such as cracks, but the effect on nuclear fuel performance may be limited.	L	- No fatigue data of ODS, CrAl-coated cladding. - A fatigue design curve using the experimental data of the irradiated ATF fuel cladding is required.
4	Cladding oxidation, hydriding, and CRUD	- Oxidation and hydriding cause material embrittlement, and excessive oxidation causes delamination, leading to the formation of hydride lenses. - Oxidation and CRUD cause temperature rise of the cladding.	L	- Superior than the Zr-based cladding.	M	- LTR/LTA results are required for suggesting regulatory standards. - There is uncertainty about hydrogen uptake and resistance to the deposition of corrosion products.
5	Irradiation growth	- Excessive cladding irradiation growth may cause fuel rod bending.	L	- CrAl and ODS are expected to have smaller irradiation growth compared to the Zr-based cladding.	L	- It must be confirmed through the LTR/LTA test.

6	Fuel rod internal pressure	- Excessive fission gas release can increase the rod inner pressure and cause lift-off of the cladding.	L	- Mo metal microcell pellet has less increase in rod inner pressure due to reduced fission gas release.	L	- It must be confirmed through the LTR/LTA test.
7	Cladding collapse	- Excessive cladding collapse may cause cladding failure.	L	- The critical collapse pressure of the ATF fuel cladding is higher, and the density of the pellet is larger than the Zr-based cladding. - So, the possibility of cladding collapse may be decreased.	H	- The mechanism of the phenomenon is well-known. - The calculation formula of critical collapse pressure and the density of the ATF fuel pellet are well known.
8	Overheating of cladding	- Overheating of the cladding, DNBR limit violation, may cause fuel failure.	M	- Effect of change in fuel rod diameter and surface treatment.	H	- Many studies on forced boiling have been conducted. - Possible with out-of-reactor test results.
9	Overheating of fuel pellet	- Overheating of the pellet may cause fuel failure.	H	- Because Mo metal microcell pellet has a melting temperature of 240℃ lower than that of UO2, the melting margin may be reduced.	L	- A demonstration process through testing is required for the melting temperature of the Mo metal microcell pellet.