Preliminary Evaluation of FeCrAl Performance as Fuel Rod Cladding

Shixin Gao[1], Hui Wang[2], Yi Zhou[1], Wenjie Li[2], Ping Chen[1], Liang Chen[1]

[1] Science and Technology on Reactor System Design Technology Laboratory and [2] Nuclear Power Institute of China, No.328 Section 1, Changshun Road, Shuangliu County, Chengdu, China 610213, gsx5@163.com

ABSTRACT: *In China, NPIC plays the most important role in the CNNC's Accident Tolerant Fuel (ATF) Program, which is aimed to develop advanced fuels and cladding with improved performance, reliability and safety characteristics during normal conditions, design basis accidents (DBA) and beyond design basis accidents (BDBA). After the Fukushima Daiichi accident, accident-tolerant-fuel (ATF) development has been conducted by many institutions in the world. Due to excellent anti-corrosion performance of FeCrAl stainless steel, it has become one of the most important and leading cladding options as ATF cladding material. When compared to the traditional zircalloy-based cladding, the FeCrAl concept provides a few extra hours of time for operators to take mitigating actions and/or for evacuations to take place. FeCrAl is one of the advanced cladding materials in NPIC ATF campaign. NPIC has developed a number of FeCrAl stainless steels with varied chemical composition. And since fabrication of thin walled tubing of FeCrAl alloys is critical to its success as a candidate enhanced accident tolerant fuel cladding material, NPIC is developing thin walled FeCrAl tubes. There were an amount of tests performed in the last 2 years. Out-of-pile test showed that FeCrAl have much lower reaction kinetics with steam compared with zirconium alloys. Besides, FeCrAl showed a higher strength than zirconium alloys. Not only does FeCrAl alloy cladding generate less heat and combustible hydrogen gas, but also would keep the integrity of the coolable geometry for longer periods of time. This paper focuses on both out-of pile property results of FeCrAl material and in-pile performance analysis of fuel rod with FeCrAl cladding, so as to make suggestions for future FeCrAl research, preparation and application. This paper uses FUPAC code to make analysis on in-pile performance. The simulations utilize the most recently known material properties. The results show that some issues should be considered during future fuel rod parameters design.*

KEYWORDS: *ATF, FeCrAl, performance, fuel rod cladding*

I. INTRODUCTION

Fukushima accident exposed the shortcomings of the existing UO_2 zircalloy fuel system performance in terms of resistance to severe accidents. In the absence of effective cooling during severe accident conditions, chemical reaction between the zircalloy cladding and water vapor produced hydrogen. Hydrogen caused explosions and lead serious radioactive hazards. Compared with conventional UO_2 zircalloy fuels, on one hand, accident tolerant fuel (ATF) should tolerate such accidents to a certain extent in the event of loss of effective cooling. On the other hand, ATF concepts should have equivalent or better fuel performance under normal operating conditions, transient conditions, DBA and BDBA.

Stainless steel was successfully used as a fuel rod cladding in fast reactor and PWR. As early as 1960s, ferrite / martensitic steel HT-9 was applied to the fuel rod cladding of fast reactor. Afterwards HT-9 has been developed as the second generation, or more advanced ferrite/martensite steel to get better in-pile performance . For the PWR, austenitic stainless steel 348 was chosen as fuel rod cladding material in Yankee Rowe in the 1960s. Although stainless steel has decades of research and application experience in nuclear industry, in fact researchers started reconsidering stainless steel as one of the potential fuel cladding concepts for LWR after the Fukushima accident. There are two driving reasons for stainless steel considered as fuel cladding. First, there are limitations of zircalloy cladding in DBA and BDBA, so researchers tend to find out a substitute cladding material which has lower water reaction rate, generates less hydrogen when accidents happen, so that the fuel can have a certain degree of accident tolerance. Second, some international companies have developed several advanced commercial ferrite stainless steels, with the main component of FeCrAl, such as APMT and MA956. These commercial FeCrAl alloys has much improved properties compared with the austenitic stainless steel early used last century, so as to meet the current requirements of commercial water reactor(Ref. 1).

Ferritic FeCrAl has a body-centered cubic structure with excellent resistance to high temperature oxidation and good mechanical properties(Ref. 2, 3). Especially at high temperature during accidents, FeCrAl has much anti-oxidation performance compared with zircalloy cladding. In addition, as a kind of metal, FeCrAl can be used in replacement of zircalloy cladding without major changes of the current PWR core and fuel assembly structure. Therefore, FeCrAl has become one of the most promising concepts among ATF cladding technology solutions. However, the greatest disadvantage of stainless steel as LWR fuel cladding is that the cross-section of FeCrAl thermal neutron absorption is over ten times that of zirconium compared to zirconium alloy, which increases the cost of power generation.

II. FeCrAl PROPERTIES

Before the research focused on the tube manufacturing technology, NPIC started with screening of different compositions through high temperature oxidation test and tensile test by the preparation of the FeCrAl plate. The team prepared FeCrAl plate material with over ten different compositions by vacuum induction smelting. Al content was 3.5-5.0% and Cr content was 13-16%. After 4 h, 1200°C, all the FeCrAl samples show very similar oxidation performance within these compositions, whose mass gain is much lower compared with Zr-4 as the reference sample. It seems Al has a limited influence on FeCrAl tensile properties, as shown in Fig.1a. While FeCrAl samples with different Cr contents show different tensile results, as shown in Fig.1b, elongation is lower with higher Cr content. Higher elongation is preferred in terms of tolerance of fuel rod failure.

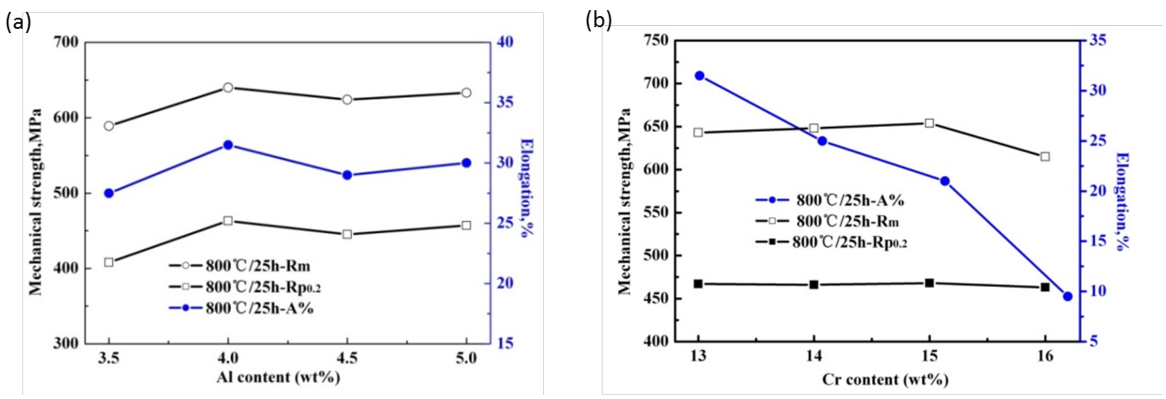

Fig.1. FeCrAl tensile performance versus Al and Cr content

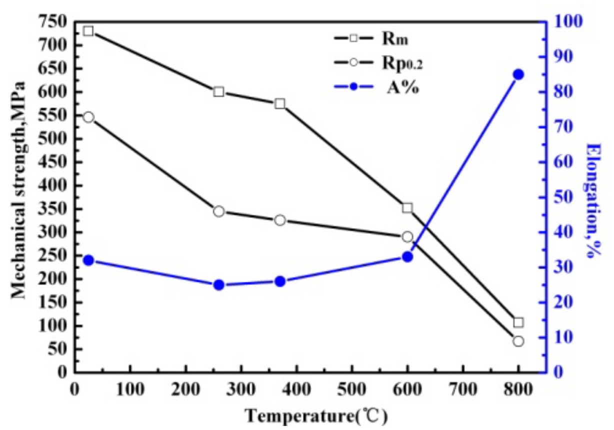

Fig.2. Tensile performance of FeCrAl plates at different temperatures

By different heat treatment means and parameters, mechanical properties can be varied a lot. FeCrAl maintains a high tensile strength above 290MPa from room temperature to 600°C, and tensile strength can be higher than Fig.2 by modifying rolling and heat treatment parameters. But as the temperature increases, tensile strength of the material decreases rapidly, as shown in Fig.2, and at 800°C the yielding strength is below 100 MPa.

III. MATERIAL MODELS AND ANALYSIS INPUTS

FUPAC code was used to make analysis on FeCrAl cladding fuel rod in-pile performance compared with Zr-4 cladding. FUPAC is a self-developed code by NPIC for the performance analysis of fuel rods in LWR. Based on the international tests results of FeCrAl stainless steel, the team added FeCrAl properties codes into FUPAC to be able to study the irradiation behavior of FeCrAl rodlet. These models include density, melting point, yield stress, ultimate tensile strength, uniform elongation, thermal expansion, thermal conductivity, specific heat, Poisson's ratio, elastic modulus, irradiation swelling, creep, etc. Density is 7.1g/cm^3 and melting point is considered as 1490°C. Yield stress, ultimate tensile strength and uniform elongation are shown Fig.2. Poisson's ratio, elastic modulus, thermal expansion, thermal conductivity, specific heat models are from the reference paper (Ref. 4). Irradiation swelling model is given from the paper (Ref. 5).

Creep strain ($\dot{\varepsilon}_c$) is divided into two distinct contributions for thermal ($\dot{\varepsilon}_{c,th}$) and irradiation ($\dot{\varepsilon}_{c,\mathrm{irr}}$) creep, and $\dot{\varepsilon}_{c,th}$ is iven from the paper(Ref. 6). Since Ref. 7 mentions the irradiation creep coefficient can be varied in the range of $0.5\text{-}5\times10^{-6}$MPa^{-1}dpa^{-1}, this paper uses a high and a low creep model with the coefficient 5×10^{-6} MPa^{-1}dpa^{-1} and 0.5×10^{-6} MPa^{-1}dpa^{-1} respectively, to further illustrate irradiation creep sensitivity to fuel rod performance.

Fuel rod power history and axial power distribution is used from Qinshan2 Unit highest burnup fuel rod as a target. This paper also uses a simplified fuel rod power history and axial power distribution, to further show a clearly different fuel rod behavior caused by varied properties of material instead of complex fuel rod power history or different burnup. The inputs are listed in TABLE I. A thinner FeCrAl cladding is considered to balance large neutron absorption cross section to some extent. Nuclear design analysis results show that the 0.35mm thickness FeCrAl cladding fuel rod should use 4.6% enrichment UO_2 fuel to maintain an approximately equivalent cycle length with the zircalloy cladding fuel rod using 4.45% enrichment fuel.

TABLE I. Fuel Rod Analysis Input Parameters

	Zr-4	FeCrAl
Enrichment	4.45%	4.6%
Cladding thickness（mm）	0.57	0.35
Pellet diameter(mm)	8.192	8.632
Pellet-cladding gap (mm)	0.084	
Cladding out diameter(mm)	9.5	

IV. NORMAL OPERATING CONDITIONS

Since both the power history and the axial power distribution are the same for the FeCrAl and Zr-4 rodlets, and a FeCrAl rodlet has more U load, so the burnup of FeCrAl rodlet is lower than that of Zr when the same irradiation time.

IV.A. QINSHAN2 POWER OPERATION

At the end of the lifetime, the fuel burnup of FeCrAl rodlet is 53963MWd/tU, and 59999MWd/tU for Zr-4. Fig.3 shows the fuel rod performance at the middle axial position of FeCrAl cladding and Zr-4 cladding. During a short period of the beginning of the cycle, the gap between the pellets and the cladding increases due to the pellets densification, as seen in Fig.3a. As irradiation time is longer, the gap is reduced under combined effects of pellets irradiation swelling and cladding creep. Due to a much smaller creep strain rate of FeCrAl compared with Zr-4, gap closure of FeCrAl rodlet happens until over 20000h even with the low creep strain rate, which increases greatly compared with Zr-4 cladding. This means that the time when FeCrAl rodlet has a risk of pellet clad mechanical interaction (PCMI) at normal conditions is significantly delayed compared to Zr-4 rodlet.

Fig.3b illustrates the evolution of fuel centerline temperature as a function of time. As irradiation burnup goes higher, pellet radius increases because of swelling, and the creep of the cladding leads to a decrease in diameter. The gap between the pellets and the cladding is reduced, so thermal resistance becomes lower and the central temperature of the pellets decreases, which is shown in Fig.3b. Sudden rises at temperature when about 12000h and 23000h are due to fluctuations in power history. Compared with Zr-4 rodlet, at the same irradiation time, the gap between pellets and FeCrAl cladding is larger, so the pellet temperature is higher until the time gap closure happens. After gap closure, thermal conductivity difference of the material is the main reason for the difference of the pellet temperature. Although the FeCrAl thermal conductivity is close to Zr-4, thermal conductivity of the pellets of the two fuel rods is different. Thermal conductivity of the pellets decreases with the increase of the fuel burnup, and because the fuel with Zr-4 has higher burnup at the same irradiation time, so thermal conductivity of the pellet with Zr-4 is lower than FeCrAl. Besides, radius of pellet with Zr-4 is smaller too, so thermal resistance is lower. These explain why fuel rod with FeCrAl has lower temperature of pellet center after gap closure happens.

Fission gas release comparisons between the rodlets are shown in Fig.3c. Before 20000h, fission gas release of FeCrAl and Zr-4 rodlets is basically similar, as shown in Figure 4. But after 20000h, Zr-4 rodlet has higher fission gas release than FeCrAl, which has two reasons. On the one hand, the fission gas release increases with higher burnup, and the burnup of Zr-4 rodlet is higher than that of FeCrAl. On the other hand, the fission gas release increases with higher temperature and the pellet temperature of Zr-4 rodlet is higher when high burup, as shown in Fig.3b.

The change of fuel rod internal pressure is shown Fig.3d. Although internal pressure of the FeCrAl rodlet is lower than that of Zr-4 throughout the lifetime, the main reason for the difference in internal pressure is different at varied stages. Before pellet and cladding gap closure, as FeCrAl creep rate is lower and the gap change is smaller, so the internal pressure of FeCrAl rodlet is smaller. After gap closure, because the FeCrAl rodlet fission gas release is lower compared with the Zr-4 rodlet, so FeCrAl rodlet has lower internal pressure.

The evolution of the hoop stress and hoop strain is shown in Fig.3e and Fig.3f. High hoop stress of FeCrAl rodlet at the beginning of lifetime is due to a high thermal expansion. After gap closure, hoop stress turns from compressive stress to tensile stress due to fuel swelling. It should be noted that the tensile stress at the end of the lifetime for low-creep FeCrAl rodlet is continuously increased due to the low creep rate of FeCrAl, and the cladding does not release the stress effectively due to insufficient creep. If the FeCrAl rod design burnup was higher, whether or not the stress would be higher than yield stress and cause fuel rod failure should be fully considered.

IV.B. SIMPLIFIED POWER OPERATION

For this analysis, except the bottom and the top, the fuel rods are ramped to a linear heat rate of 22.18kW/m and held at this power to a time of 34726h, the same irradiation time as Qinshan2 power operation. Burnup of FeCrAl rodlet is 50621MWd/tU and 562830MWd/tU for Zr-4 rodlet. The difference between FeCrAl and Zr-4 rodlet can be seen clearly, so as to the difference between low creep rate and high rate, as shown in Fig.4. The trend is similar as Qinshan2 power operation and some conclusions in IV.A can be verified here. Gap closure of the low creep rate FeCrAl rodlet happens when burnup is 40000MWd/tU while 30000MWd/tU for high creep rate, as shown in Fig.4a, and Zr-4 rodlet gap closure happens below 10000MWd/tU.

The low creep rate FeCrAl rodlet before gap closure, as shown in Fig.4b, but after it the two FeCrAl rodlets have nearly the same fuel center temperature. When burnup is higher than about 45000 MWd/tU, Zr-4 rodlet shows a higher fuel center temperature. This is because in this analysis corrosion is considered for Zr-4, but not yet for FeCrAl. Corrosion product layer is about 30μm at the end of Zr-4 rodlet lifetime and the oxidation layer has very low conductivity. In fact, with a 30μm thick oxidation layer, the temperature at the interface between oxidation layer and zircalloy is about 10°C higher compared the cladding surface temperature without oxidation layer. So the temperature of Zr-4 rodlet pellet out-diameter surface is higher than FeCrAl.

Fission gas release of Zr-4 and FeCrAl rodlet is similar at the same burnup, as shown in Fig.4c, the small difference is due to difference of pellet temperature when high burnup. Besides, gas release of the rodlets is higher than Qinshan2 mainly because pellet temperature is higher than Qinshan2 when high burnup. Fig.4d shows that internal pressure of the rodlets is also higher than Qinshan2 when high burnup due to higher fission gas release.

Fig.4e shows cladding hoop stress versus burnup. Low creep rate FeCrAl rodlet has highest cladding hoop stress above 260MPa when high burnup. Hoop stress of low and high creep rate FeCrAl rodlet could be higher if higher burnup was analyzed.

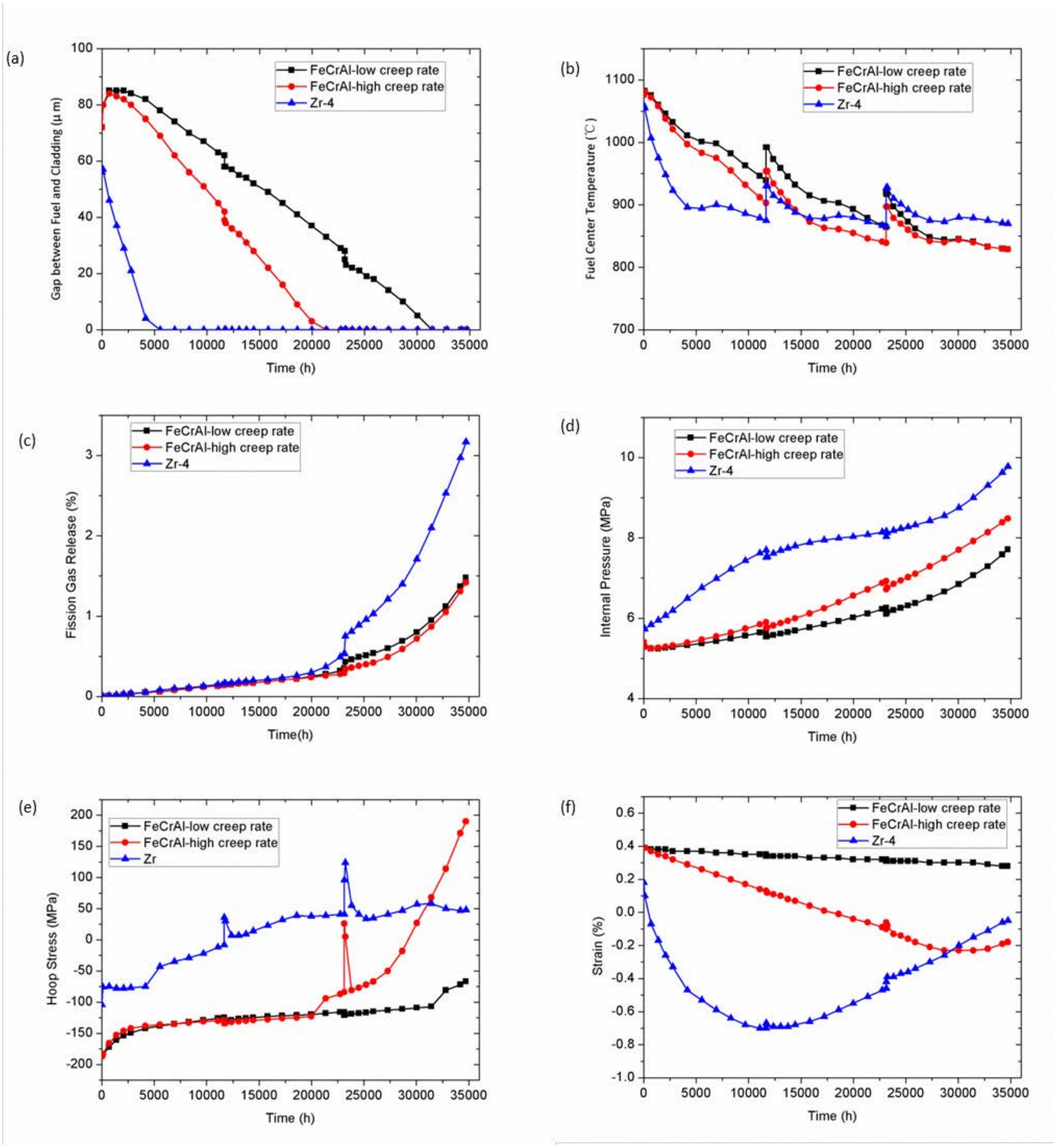

Fig.3. Fuel rod performance of FeCrAl cladding and Zr-4 cladding with Qinshan 2 fuel rod power history and axial power distribution

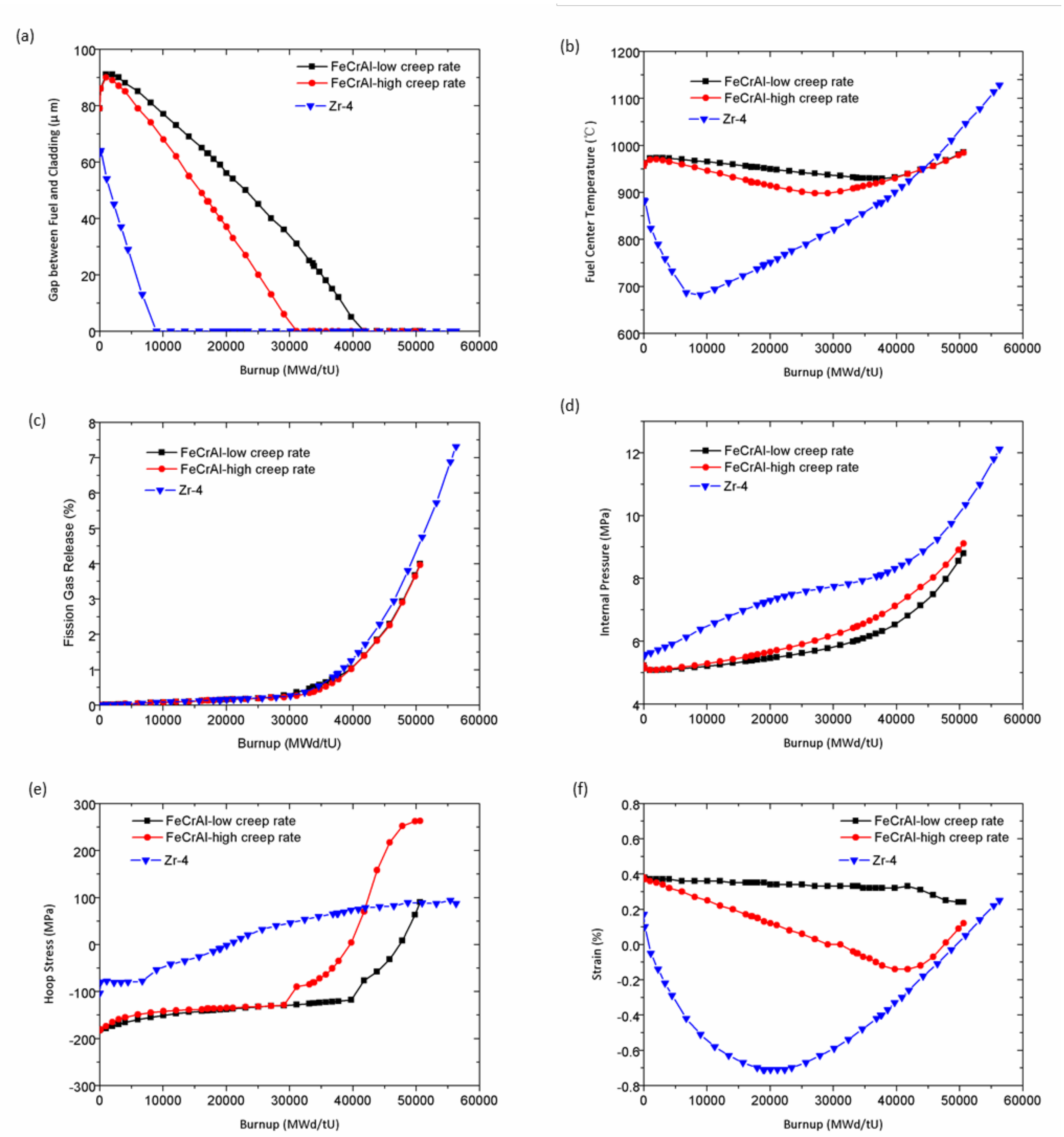

Fig.4. Fuel rod performance of FeCrAl cladding and Zr-4 cladding with simplified power history and axial power distribution

V. SUMMARY

This paper uses FUPAC code to make analysis on in-pile performance of the fuel rod with FeCrAl cladding. Based upon the recently known available experimental data, material models for FeCrAl were added to the FUPAC fuel performance code. Comparisons between FeCrAl and Zr-4 under steady state conditions show some differences including fuel temperature, pellet cladding gap, cladding strain and stress, etc. Creep sensitivity study shows that creep strain rate has a great influence on fuel rod performance. These simulations show large stresses (>200 MPa) forming the in the FeCrAl cladding, which may be larger than the yield strength at these temperatures. These simulations provide information on important parameters for alloy design and fuel modeling.

As higher fuel burnup is the future development trend, next irradiation behavior of FeCrAl rodlet will be evaluated at higher burnup(75000-80000 MWd/tU). In addition, this paper only studies the behavior of fuel rods under the steady state conditions, and behavior of FeCrAl rodlet in transients and even accident conditions should also be evaluated. Besides, FeCrAl properties and irradiation behavior models should be updated through experimental data so as to conduct more precisely prediction of fuel in-pile behavior.

ACKNOWLEDGMENTS

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REFERENCES

1 B. Lori and M. W. Edgar, "ADVANCED FUELS CAMPAIGN FY 2014 ACCOMPLISHMENTS REPORT," DOE,2014.

2 B. A. Pint and K. A. Terrani, "Severe Accident Test Station Activity Report," Oak Ridge National Laboratory (ORNL)2015.

3 Y. Yamamoto, B. A. Pint, K. A. Terrani, K. G. Field, Y. Yang, and L. L. Snead, "Development and property evaluation of nuclear grade wrought FeCrAl fuel cladding for light water reactors," *Journal of Nuclear Materials,* vol. 467, pp. 703-716, 2015.

4 X. Wu, T. Kozlowski, and J. D. Hales, "Neutronics and fuel performance evaluation of accident tolerant FeCrAl cladding under normal operation conditions," *Annals of Nuclear Energy,* vol. 85, pp. 763-775, 2015.

5 J. Bates and J. Straalsund, "An empirical representation of irradiation-induced swelling of solution treated type 304 stainless steel," *Nuclear Technology,* vol. 14, pp. 292-298, 1972.

6 N. M. George, K. A. Terrani, and B. Wirth, "BISON Fuel Performance Analysis of FeCrAl cladding with updated properties," Oak Ridge National Laboratory (ORNL), Oak Ridge, TN (United States)2016.

7 K. A. Terrani and Y. Yamamoto, "Input Correlations for Irradiation Creep of FeCrAl and SiC Based on In-Pile Halden Test Results," Oak Ridge National Laboratory (ORNL), Oak Ridge, TN (United States)2016.