

MANAGING NUCLEAR POWER PLANT SAFETY WITH FeCrAl ALLOY FUEL CLADDING

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ABSTRACT

After the tsunami-induced plant black out followed by hydrogen explosions at the Fukushima site, the US Department of Energy (DOE) partnered with fuel vendors to study safer alternatives to the current UO₂ – zirconium alloy system. This proposed accident tolerant fuel (ATF) alternative should better tolerate loss of cooling in the core for a considerably longer time while maintaining or improving the fuel performance during normal operation conditions. General Electric, Oak Ridge National Laboratory, and their partners are proposing to replace zirconium based alloy cladding in current commercial light water power reactors with an iron-chromium-aluminum (FeCrAl) cladding such as APMT. Extensive testing is being conducted to determine the suitability of the FeCrAl concept under normal operation conditions and under severe accident conditions. Results show that FeCrAl has excellent corrosion resistance under normal operation conditions and FeCrAl is several orders of magnitude more resistant than zirconium alloys to degradation by superheated steam under accident conditions, generating less heat of oxidation and lower amount of combustible hydrogen gas. Higher neutron absorption and tritium release effects can be minimized by design. The implementation of FeCrAl cladding is a near term solution to enhance the safety of commercial light water power reactors.

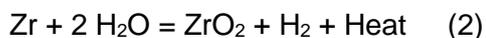
Introduction

Nuclear power plants are one of the most reliable and cleaner ways of producing electricity. Approximately 450 commercial nuclear power plants are used in 30 countries to produce low cost electricity [1]. At least 13 countries use nuclear power to supply about a quarter of their electricity [2]. In the USA alone, the use of nuclear power prevented in 2015 the release of 564 million metric tons of carbon dioxide to the environment [2]. Commercial nuclear power plants (NPP) are designed to be operated without significant effect on the public health and safety and effect on the environment [3]. The operation of NPP energy facilities do not emit greenhouse gases [2]. The main risk of operating a nuclear power plant is the release of radioactive elements into the environment, and for that reason, several barriers are constructed between the fuel containing the radioactive elements and the environment. The first barrier to protect the fuel is the hermetically sealed metallic cladding which envelops the pellets of uranium oxide. That is, maintaining the integrity of the cladding is the first crucial containment for the radioactive material. Further barriers include the reactor pressure vessel, the concrete building structure containing the pressure vessel and abundant amounts of water that remove the heat from the nuclear reaction [3].

The Nuclear Regulatory Commission (NRC) uses probabilistic risk assessment (PRA) methods to assess the likelihood and consequences of severe reactor accidents in accordance with 10 CFR 50.109 [3]. The Risk R is defined as a function of scenarios S_i that can go wrong, of how likely the scenario will happen (frequency f_i), and of the consequence C_i of the scenario S_i (Equation 1) [4].

$$R = \{S_i, f_i, C_i\} \quad (1)$$

The notion of risk includes both opportunities and threats. The basis of managing risk is to build multiple barriers between the threats that can lead to an adverse event of, for example, an operating a nuclear reactor. In the case of the Fukushima disaster of March 2011, the low frequency and high consequence event of the tsunami caused the destruction of the diesel generators that provided the emergency power to pump the water to cool the fuel rods in the reactor and in the cooling pools. Consequently, water and steam reacted rapidly with the zirconium material of the fuel cladding above 400°C producing large amounts of heat and hydrogen (Equation 2) that were vehicles for the release of some radioactivity into the environment.



Once the zirconium metal cladding was consumed by steam, the radioactive fuel was released inside the second barrier, the thick-walled steel reactor pressure vessel. That is, the effect of the tsunami in Fukushima was to destroy the first barrier or the metallic zirconium cladding containing the radioactive elements. To minimize the risk of failure of the operating plant, a stronger first barrier should be constructed between the fuel and the second barrier.

Risk Management in a Nuclear Power Plant Environment

Benefits from risk management in a nuclear power plant do not only include safety scenarios but also production (operational or engineering) and economics (financial) scenarios [5] (Figure 1). Each one of these risk disciplines will incorporate their own frequencies and consequences. Another discipline or scenario that can be added is the strategic one, which covers things like type of government in the country, nationalization or expropriations, public perception, regulatory and legal framework, etc. (represented as a larger square in Figure 1). It is important to identify all the consequences of an event (e.g. tsunami) to be able to minimize adversarial outcomes and to maximize public response and commercial gains in a cost-efficient manner [5]. The risk management framework is an iterative process in which first the possible risks are identified (together with potential consequences and relative impact of each consequence), then the techniques to manage the risk are identified (e.g. risk reduction or risk transfer), and finally the chosen strategies or techniques are implemented. This process is followed by monitoring and feedback to determine the effectiveness of the solutions and, if necessary, repeat the process with other improved measures. For example, risk reduction can be accomplished by engineering changes, organizational changes, staff training, etc. and risk transfer can be implemented by contracts with suppliers, insurance, regulation, etc.

Following the example from the Fukushima incident, one way of reducing risk in plant operation would be the engineering replacement of zirconium alloys from the nuclear fuel of the power plant with FeCrAl alloys. This is an obvious technical change that would greatly reduce the consequence of the explosion that considerably affected the public perception of safe operation of nuclear power plants. That is, the use of FeCrAl alloys can only produce opportunities to reduce the engineering risk identified in Figure 1. The FeCrAl alloy is the first barrier between the radioactive elements and the biosphere surrounding the NPP. By improving on the performance of the first barrier (cladding of the fuel), the consequence of

combustible hydrogen explosion or release of radioactive elements outside the NPP is greatly minimized.

Accident Tolerant Fuels

Because of the Fukushima accident of March 2011, the US Department of Energy has a mandate from US Congress to develop accident tolerant fuels under cost sharing programs with the nuclear fuel vendors. [6, 7, 8]. A fuel may be defined as having enhanced accident tolerance if, in comparison with the current UO_2 -zirconium alloy system, it can tolerate loss of active light water cooling in the reactor core for a considerably longer time (called coping time) while maintaining or improving fuel performance during normal operations and operational transients, as well as in design basis and beyond design-basis events. The enhanced fuel material should have

- Improved reaction kinetics with steam;
- Slower hydrogen production rate;
- Improved cladding and fuel properties;
- Enhanced retention of fission products.

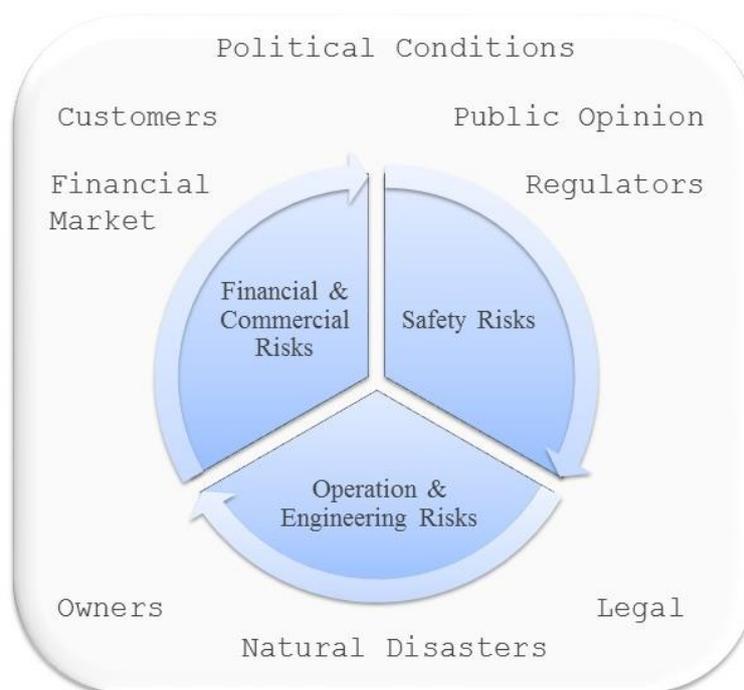


Fig. 1. Risk management environment model for a nuclear power plant operator. The aim of the GE-ORNL team is to minimize engineering risks by using FeCrAl cladding.

The DOE provided a five-step guideline or metrics to assess the behavior of the ATF concept (Figure 2) [9]. That is, the concept for accident tolerant fuel rods must be able to perform as well as the current system under normal operation conditions in the order of 300-400°C cladding temperature (Step 1). This includes low corrosion rates in both boiling water reactors (BWR) and pressurized water reactor (PWR) environments, no environmental assisted cracking, no shadow corrosion, no hydriding that will render the rod brittle, no fretting or debris damage, etc. (Step 1). Also in Step 1, it needs to be demonstrated that the new fuel will be compatible with the thermal and hydraulic flow inside of the reactor. Step 2 requires that the ATF fuel rod would be better than the current zirconium – uranium dioxide system under design basis accidents including the temperature range between 400°C to 1200°C of the cladding temperature in contact with the coolant. Step 3 requires that under

severe accident conditions ($T > 1200^{\circ}\text{C}$), the cladding would be superior to the current system, for example by tolerating reaction with steam to produce lower amounts of heat and explosive hydrogen gas [10]. Step 4 requires that the new ATF fuel rod can be manufactured easily using economical and standard procedures such as tube fabrication and hermetical welding or sealing. Moreover, Step 4 covers the changes that are required in the regulators or licensing specifications (e.g. Nuclear Regulatory Commission in the US) that would allow for the new ATF rod to be deployed into a commercial light water reactor. Step 5 is concerned about the condition of the fuel rods after their useful life in the reactor, if the bundles can be safely and integrally removed from the reactor to be securely stored in cooling pools for a period of 5 years or more, and how the rods will perform under dry cask storage for periods in the order of 100 years, before final disposition in a nuclear waste repository or reprocessing of the used fuel [9].

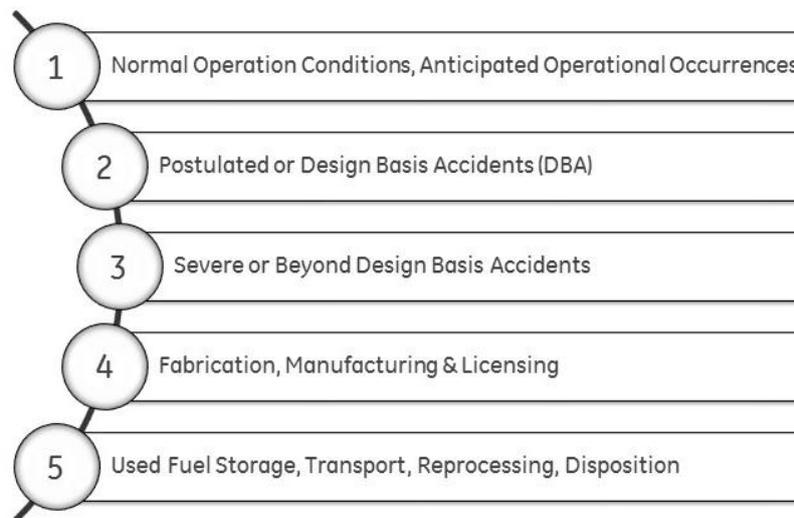


Fig. 2. Five metric Areas Provided by DOE to Evaluate ATF [9].

The objective of the GE project is to develop an iron-chromium-aluminum (FeCrAl) fuel cladding for current design light water power reactors. The idea of using FeCrAl alloys as cladding for current UO_2 fuel is also supported by Oak Ridge National Laboratory (ORNL). Besides Fe, Cr, and Al, the cladding may contain other elements such as molybdenum, yttrium, hafnium, zirconium, etc. The composition of choice is Fe + (10 to 22) Cr + (4 to 6) Al + (2 to 3) Mo + traces of Y, Hf, Zr, etc. The FeCrAl cladding concept is a near term solution for providing enhanced safety to light water reactors. The main reason FeCrAl has been selected is because it has superior oxidation resistance in the event of a severe accident. Figure 3 shows the process of how this alloy resists attack by superheated steam. Under normal operation conditions and up to 1000°C the protection to the alloy is given by the formation of a chromium rich oxide on the surface. However, as the temperature increases beyond 1000°C , an aluminum oxide layer (alumina) forms between the metal and the chromium oxide layer. Eventually, in the presence of steam, the chromium oxide layer volatilizes and the alumina layer remains on the surface protecting the alloy from further oxidation up to its melting point ($\sim 1500^{\circ}\text{C}$). Figure 4 shows the presence of a one micron thick layer of alumina on the surface of APMT coupon after exposure for 2 h at 1200°C in 100% steam.

FeCrAl has excellent environmental resistance characteristics under normal operation both for boiling and pressurized water reactors (BWR & PWR) coolants. There is no need to change the water chemistry of the coolants since FeCrAl is compatible with the current water chemistries. The use of FeCrAl would eliminate common/current fuel failure mechanisms such as fretting and shadow corrosion. There is no change in fuel type since it

utilizes the current UO₂ fuel. The current FeCrAl alloy candidate is APMT, but optimization alloy composition and fabrication studies continue at ORNL. ORNL and GE have been conducting research in the five areas listed in Figure 2 since 2012. The aim of this document is to describe the maturity of the concept and the overall feasibility on the use of ferritic FeCrAl alloys as cladding for nuclear fuel in commercial light water reactors. GE and ORNL are following a methodical approach to evaluate metrics or performance attributes outlined by Bragg Sitton et al. [9].

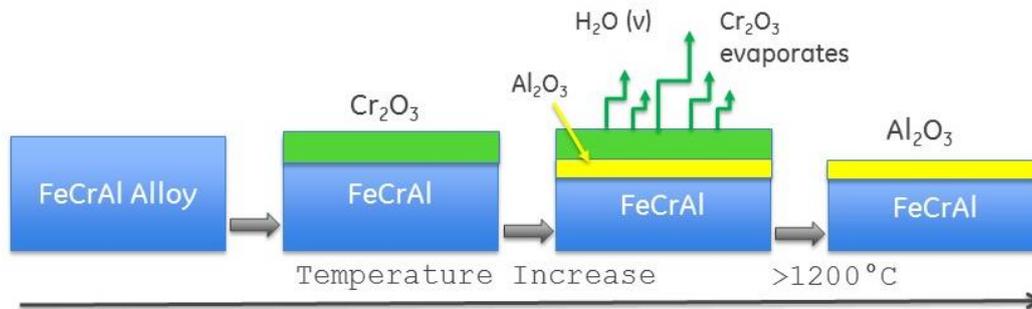


Fig. 3. Oxidation Behavior of FeCrAl in Super-Heated Steam.

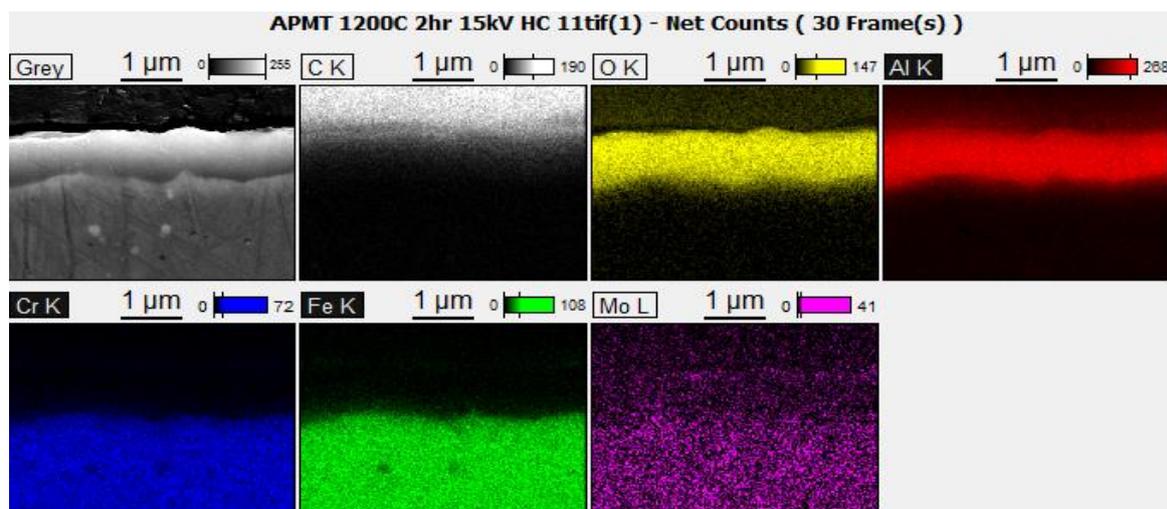


Fig. 4. Coupon of APMT exposed to 100% steam for 2 h at 1200°C. A 1µm thick alumina layer is observed on it surface.

It is noted that austenitic stainless steel (SS) materials were used for fuel rod cladding in the past both for US commercial plants and overseas NPP [11]. Preliminary studies on FeCrAl alloy materials indicate sufficient strength and ductility to perform acceptably as cladding alloy, like past use of austenitic SS cladding. FeCrAl alloys also do not contain nickel, which is a more expensive and higher neutron absorption element than Fe, Cr or Al. However, compared to experience with austenitic SS cladding, extensive crack propagation studies show that ferritic FeCrAl proved to be several orders of magnitude more resistance to environmentally-assisted cracking than modern type 304 SS [7]. Because of its ferritic or bcc structure, FeCrAl alloys are also more resistant to irradiation degradation than prior versions of austenitic SS cladding materials. Proton irradiation studies performed at the U. of Michigan showed that FeCrAl materials may be resistant to proton irradiation induced cracking providing additional confirmation of the potential acceptability of FeCrAl

materials for fuel rod cladding [12]. Although there may be nominal changes in fuel rod geometry (e.g. clad OD and thickness) for lead rod assembly designs and in fuel assembly designs (e.g. fuel channels design) to accommodate differences in material performance in future fuel designs, such changes are expected to be incremental to existing fuel rod and assembly designs, significantly leveraging the knowledge base for current fuel designs for the new concept. Simulation studies performed at Brookhaven National Laboratory showed that there is little or no impact on the thermal-hydraulic properties of the system by using a fuel rod clad with a FeCrAl alloy [12]. It is expected that a FeCrAl alloy clad fuel rod can be designed with minimal thermal-hydraulic design changes. FeCrAl alloy cladding is completely compatible with the current coolant chemistries used in either BWR or PWR reactors, that is, significant coolant chemistry changes are not expected because of FeCrAl implementation. Extensive immersion studies with chemistries typically observed in both BWR and PWR reactors showed excellent corrosion resistance of the FeCrAl alloys both under hydrogen and oxygen atmospheres [13]. Figure 5 shows a protective Cr rich layer protecting the surface of APMT while exposed for a year in PWR type environments containing dissolved hydrogen. This is the same behavior observed for other current structural reactor internal materials such as type 316 SS [14, 15].

Electrochemical studies in high temperature water showed that FeCrAl has a behavior like traditional reactor alloys such as type 304 SS and nickel based alloy X-750. Electrochemical studies performed at GE Global Research showed that FeCrAl rods in contact with a separator grid of alloy X-750 would not experience galvanic corrosion under irradiation conditions [16], allowing utilization of current existing grid/spacer designs.

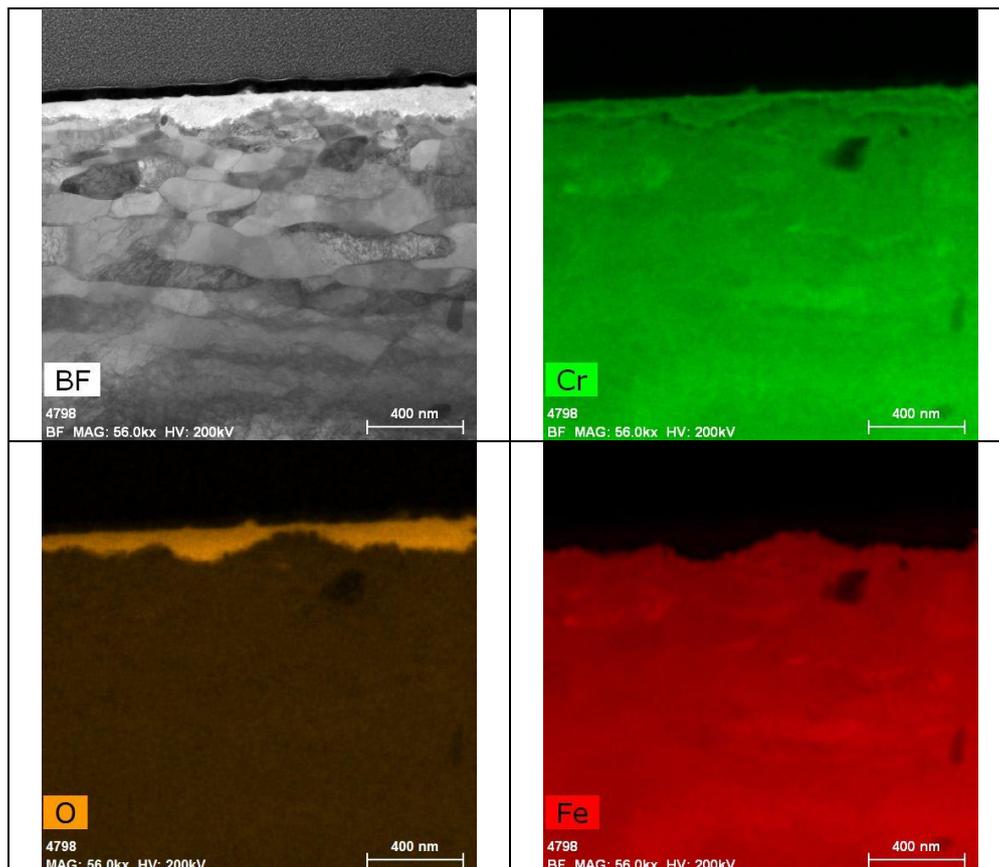


Fig. 5. Coupon of APMT exposed to PWR type water pure water + 3.75 ppm hydrogen at 330°C for one year. A ~150 nm oxide layer rich in Cr is observed on its surface.

Fabrication, Manufacturing and Licensing

The FeCrAl/ UO_2 fuel rod is compatible with current large-scale production technology. Uranium dioxide (UO_2) pellet fabrication would remain the same as in the current process. Currently, tube fabrication trials are being conducted to demonstrate that FeCrAl alloys can be produced as long, thin walled tubes for fuel rod assemblies. Although the cladding fabrication process is yet untested for large scale production, there does not appear to be a significant barrier for production quantities of the cladding. Preliminary studies demonstrated FeCrAl compatibility with existing welding, manufacturing, and quality practices used with current Zircaloy based rod assembly systems. The fabrication processes for the FeCrAl/ UO_2 system will be very like current LWR fuel fabrication processes (pilgering/extruding, heat treatments, welding, NDE techniques, etc.) which are mature and well understood. No issues are anticipated complying with current nuclear industry quality and performance standards.

FeCrAl/ UO_2 fuel rod systems will have minimal or no impact in the handling of the fuel, shipping requirements and/or plant operations. It is expected that standard analyses techniques applied to zirconium alloy systems may be used substituting FeCrAl-specific properties to demonstrate acceptable performance under shipping and handling conditions, although licensing for shipping of the LFR/LFAs will need to be completed as well as in-core licensing.

Currently the GE team is working with the US Nuclear Regulatory Commission as a first step to request an exception to insert a lead fuel assembly (LFA) made with FeCrAl segments in a commercial power reactor to determine the behavior of FeCrAl alloys under typical operation conditions. Originally the deadline for insertion of a LFA given by DOE was 2022 [9] but the GE team believes that inserting components made with FeCrAl can be earlier.

Mitigation measures to neutron absorption and tritium release

By its own nature, FeCrAl alloys offer a larger parasitic neutron absorption compared to zirconium alloys [6, 7, 17]. Because FeCrAl alloys such as APMT are stronger than zirconium alloys at near 400°C , the FeCrAl material for the cladding can be made approximately half the thickness of the current zirconium alloys (Figure 6). The thinning of the wall will increase the volume of the uranium dioxide pellet inside the rod.

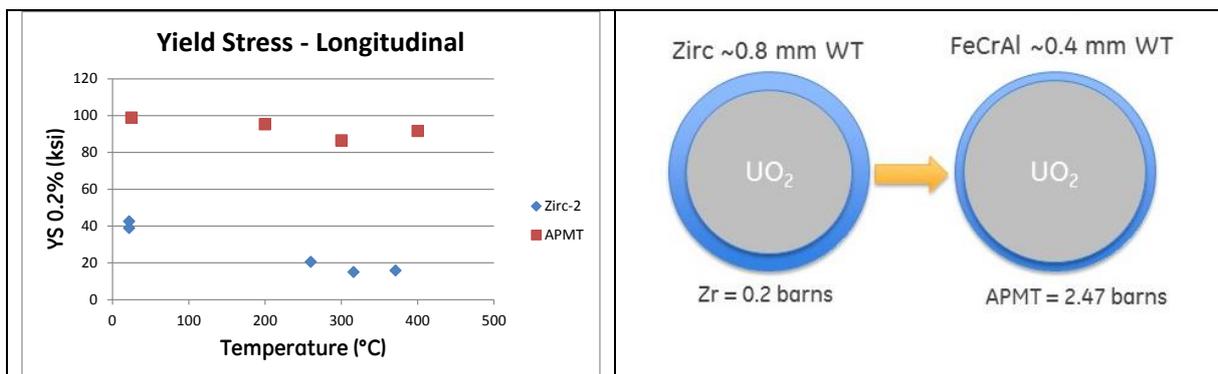


Fig. 6. Mechanical and neutron absorption properties of APMT and Zircaloy-2.

Additional design changes (such as the fuel channel), may be required to meet bundle design requirements, further impacting fuel cycle economics. However, potential mitigation strategies have been identified that may partially or fully offset these penalties.

Such mitigation strategies include alternate materials (e.g. silicon carbide composite channel materials), higher allowable heat generation rates, as well as relaxation of regulatory requirements due to much improved fuel cladding performance under normal/off-normal, design basis and beyond design basis accident conditions, which in turn will result in improved economics of plant operation.

A second issue that requires resolution is the potential to increase release of tritium into the coolant. EPRI reported that when austenitic stainless steel cladding was used the amount of tritium in the coolant water was approximately 10 times higher than when zirconium cladding was used [18]. Also since FeCrAl are ferritic (bcc) in nature, it can be inferred that the diffusion of tritium through the cladding wall into the coolant could be even higher than when the austenitic (fcc) material was used. One potential mitigation strategy, currently under investigation, is formation of an alumina layer (or other type of permeation barrier) in the ID and/or OD of the cladding [19]. A thin alumina layer (Figure 4) in the ID of the cladding will significantly reduce the hydrogen permeation from the fuel to the coolant [20].

Conclusions

- 1) The General Electric (GE) accident tolerant fuel (ATF) design concept utilizes a FeCrAl alloy material such as APMT as fuel rod cladding in combination with uranium dioxide (UO₂) fuel pellets, resulting in a fuel assembly that leverages the performance of existing/current LWR fuel assembly designs and infrastructure with improved accident tolerance.
- 2) The use of FeCrAl APMT will greatly improve the safety of plant operation by putting a sturdier primary barrier between the radioactive elements in the fuel and the coolant.
- 3) Under accident conditions, FeCrAl alloys are orders of magnitude more resistant to reaction with superheated steam than zirconium, generating less combustible hydrogen and heat of reaction.
- 4) FeCrAl alloys are less transparent to neutrons than zirconium alloys, therefore the cladding wall needs to be thinner. Tritium release into the coolant can be minimized by using an alumina barrier layer in the ID of the cladding.

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References

1. R. B. Rebak, "Nuclear Application of Oxide Dispersion Strengthened and Nano-Featured Alloys: An Introduction, JOM, Vol. 66, No. 12, pp. 2424-2426 (2014)
2. Nuclear Energy Institute (NEI), www.nei.org. Retrieved 20170119.
3. US Nuclear Regulatory Commission, Fact Sheet on Nuclear Reactor Risk, <http://www.nrc.gov/reading-rm/doc-collections/fact-sheets/reactor-risk.html>
4. N. Sridhar, "Risk Assessment of Corrodible Systems—An Overview," Materials Performance, June 2011, p. 32.

5. IAEA, International Atomic Energy Agency, "Risk management: A tool for improving nuclear power plant performance," TECDOC-1209, Vienna, 2001
6. S. J. Zinkle, K. A. Terrani, J. C. Gehin, L. J. Ott, and L. L. Snead, "Accident tolerant fuels for LWRs: A perspective," *Journal of Nuclear Materials*, 448 (2014) 374–379
7. R. B. Rebak, "Alloy Selection for Accident Tolerant Fuel Cladding in Commercial Light Water Reactors," *Metallurgical and Materials Transactions E*, Vol. 2E, 197-207 (December 2015).
8. R. B. Rebak, K. A. Terrani, W. P. Gassmann, J. B. Williams, K. L. Ledford, "Improving Nuclear Power Plant Safety with FeCrAl Alloy Fuel Cladding," *Materials Research Society Fall Meeting 2016*, MRS Advances, pp. 1-8, doi: 10.1557/adv.2017.5.
9. S. M. Bragg-Sitton, M. Todosow, R. Montgomery, C. R. Stanek, R. Montgomery, and W. J. Carmack, Metrics for the Technical Performance Evaluation of Light Water Reactor Accident Tolerant Fuel, *Nuclear Technology*, 195(2), p. 111-123, August 2016.
10. K. R. Robb, "Analysis of the FeCrAl Accident Tolerant Fuel Concept Benefits During BWR Station Blackout Accidents," *Proc. of NURETH-16*, Chicago, IL, USA, August 30-September 4, 2015
11. EPRI, Electric Power Research Institute, Evaluation of Expected Behavior of LWR Stainless Steel-Clad Fuel in Long-Term Dry Storage, EPRI, Palo Alto, CA: 1996. TR-106440
12. R. B. Rebak, N. R. Brown, and K. A. Terrani, "Assessment of Advanced Steels as Accident Tolerant Fuel Cladding for Commercial Light Water Reactors," Paper 227, 17th International Conference on Environmental Degradation of Materials in Nuclear Power Systems – Water Reactors, August 9-12, 2015, Ottawa, Ontario, Canada (Canadian Nuclear Society, Toronto).
13. D. D. Ellis, and R. B. Rebak, "Passivation Characteristics of Ferritic Stainless Materials in Simulated Reactor Environments," Paper C2016-7452, *Corrosion/2016* (NACE International, Houston, TX).
14. T. Terachi and K. Arioka, "Characterization of Oxide Film Behaviors on 316 Stainless Steels in High-Temperature Water - Influence of Hydrogen and Oxygen Considerations for Initiation of SCC," Paper 06608, *Corrosion/2006 Conference and Exposition* (NACE International, Houston, TX).
15. M. Da Cunha Belo, M. Walls, N. E. Hakiki, J. Corset, E. Picquenard, G. Sagon and D. Noel, "Composition, Structure and Properties of the Oxide Films Formed on the Stainless Steel 316L in a Primary Type PWR Environment," *Corrosion Science*, Vol. 40, No. 2/3, pp. 447-463 (1998).
16. Y.-J. Kim, F. Wagenbaugh, T. B. Jurewicz, R. J. Blair, and R. B. Rebak, "Environmental Behavior of Light Water Reactor Accident Tolerant Candidate Cladding Materials under Design Conditions," Paper C2015-5817, *Corrosion/2015* (NACE International, Houston, TX)
17. N. M. George, K. Terrani, J. Powers, A. Worrall, and I. Maldonado, "Neutronic analysis of candidate accident-tolerant cladding concepts in pressurized water reactors," *Annals of Nuclear Energy*, 75 (2015) 703–712
18. EPRI, "An Evaluation of Stainless Steel Cladding for use in Current Design LWRS," Report NP-2642, Section 4 "Tritium Release from Stainless steels," December 1982 (<http://www.epri.com/abstracts/Pages/ProductAbstract.aspx?ProductId=NP-2642>).
19. R. B. Rebak and Y.-J. Kim, "Hydrogen Diffusion in FeCrAl Alloys for Light Water Reactors Cladding Applications" Paper PVP2016-63164, 2016 ASME PVP Conference, MF-7 Materials and Technologies for Nuclear Power Plants, 17-21 July 2016, Vancouver, BC.
20. D. Levchuk, H. Bolt, M. Döbeli, S. Eggenberger, B. Widrig, and J. Ramm, "Al-Cr-O thin films as an efficient hydrogen barrier," *Surface & alumina Coatings Technology* 202 (2008) 5043–5047