INTERNATIONAL NUCLEAR ENERGY RESEARCH INITIATIVE
Final Report Executive Summary

Advanced Corrosion-Resistant Zirconium Alloys for High Burnup and Generation IV Applications

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Research Objectives

The objective of this collaboration between four institutions in the US and Korea is to demonstrate a technical basis for the improvement of the corrosion resistance of zirconium-based alloys in more extreme operating environments (such as those present in severe fuel duty cycles (high burnup, boiling, aggressive chemistry) and to investigate the feasibility (from the point of view of corrosion rate) of using advanced zirconium-based alloys in a supercritical water environment. This technical basis is to be obtained through the comparison of the corrosion kinetics and the examination of the fine structure of oxide layers formed in model alloys. These model alloys are designed to isolate specific features of the microstructure thought to affect the formation of the protective oxide layer so that their effect on the corrosion rate can be studied individually. The key aspect of the program is to rationalize the differences in corrosion kinetics between alloys through the differences in the structure and evolution of the protective oxide formed on each alloy. The structural differences in the oxides were studies using advanced characterization techniques (including submicron-beam synchrotron radiation diffraction and fluorescence, cross-sectional transmission electron microscopy (TEM), transmitted light optical microscopy, and nano-indentation) to characterize both the metal and the oxide so that we can also relate these differences in oxide structure to the original microstructure of the alloy.

Results and Conclusions

A detailed study has been conducted to address the issue of susceptibility of model Zr alloys to uniform corrosion in the proposed supercritical water reactor and of the specific role of alloying elements. Thirty model alloys were corrosion-tested for periods over 400 days in 360ºC water (as well as limited testing in lithiated water) and from 150 to over 300 days in 500ºC supercritical water. The corrosion results show a wide range of corrosion behavior with the data included in Appendices A, B, and C and discussed in Tasks 2 and 3.

The general agreement between the three different tests performed at 500°C was quite good. In particular, little difference was seen between the results from static and dynamic autoclave testing. The results from lower pressure steam testing agreed with the supercritical water results but showed slightly less oxide growth. Since the rankings of the alloys were preserved from test to test, it is possible the steam test could serve as a preliminary screening test for supercritical water behavior.

1. Corrosion tests for the model Zr alloys showed a wide variety of corrosion resistance depending on the alloy composition during both 360ºC and at 500º testing. These differences manifested themselves in the difference in pre-transition kinetics (as characterized by values of A and n) and in the different tendencies for breakaway.

2. In comparison with other alloys being considered for the SCWR, the Zr alloys showed higher corrosion rates than austenitic alloys and lower corrosion rates than ferritic-martensitic and 12Cr steels.

3. Significant concerns exist in terms of creep rates, and other properties. However, this research indicates that proper alloying additions induce protective oxide growth in model Zr alloys, such that from the corrosion point of view, Zr alloys should be considered as possible candidate materials for application in the supercritical water reactor.

The oxides were also characterized to determine the oxide structures associated with protective and non-protective behavior. These characterization efforts are discussed in Task 4 and rationalized in terms of corrosion behavior in Task 5. Additional results are included in Appendices D, E and F. The main conclusions are:

4. Characteristic differences exist in the oxide-metal interface regions of protective and non-protective oxides. In particular, the presence of two interfacial oxide phases, a highly oriented tetragonal phase and a sub-oxide phase were associated with protective behavior uniform corrosion???.

5. The overall crystallographic texture of oxides also showed clear differences between protective and non-protective oxides. The growth direction of the oxides was similar but the pole figures were considerably more anisotropic in the non-protective oxides than in the protective ones.

6. The protection mechanisms and the mechanisms of transition/breakaway were discussed and the differences between alloys are rationalized in terms of mechanistic models.

Benefits of this research

As a result of this program, it has been shown that some Zr alloys can withstand the high temperature corrosion of a supercritical water reactor. The mechanisms of alloy protection have been studied in detail and rationalized in terms of the oxide structure and its influence on breakaway. This will allow better fuel cladding alloy design for both low and high temperature applications, based on mechanistic concepts.

As a result of this research program, collaborations were established between Penn State, KAERI U. of Michigan, and Westinghouse which proved to be very fruitful. The results of the research have so far been published in three journal publications and two conference proceedings. One more journal publication and two conference proceedings are scheduled for publication in the near term. Additionally this research supported the graduate thesis work of two Ph.D. students at Penn State, one M.Sc. student at Michigan, as well as post-doctoral researchers at both institutions. Graduate students were also supported in KAERI and Hanyang University.