INTRODUCTION

The TerraPower Traveling Wave Reactor (TWR) envisions a fast reactor breed-and-burn core that initially starts on a combination of low-enriched uranium and depleted uranium, and then operates with additions of depleted uranium by in-situ breeding of its own fuel. TWRs can utilize depleted uranium stockpiles for fuel and produce significantly less spent-fuel waste than LWRs without reprocessing and with reduced enrichment. However, the TWR requires very high burnups and high irradiation doses on fuel components in order to reach equilibrium for a breed-and-burn reactor.

One of the most significant constraints in TWR development, then, is the performance of the fuel cladding and fuel assembly duct material. Irradiation creep and swelling result in distortion and dimensional changes. The threat to the cladding is the closure of coolant channels, resulting in unacceptable local temperature increase. For fuel assemblies, distortion beyond design limits could result in stuck fuel assemblies, preventing fuel shuffling. In addition, thermal creep strain may be design limiting at the hot end of the fuel for long fuel lifetimes.

HT9 is a 12Cr-1Mo-VW steel with demonstrated performance in fast reactors as fuel cladding and duct material. The primary advantage of HT9 is its excellent swelling resistance to doses above 200 dpa, and a substantial irradiation effects database on mechanical properties. The steel does not, however, have the same thermal creep strength as more advanced ferritic/martensitic steels. Moreover, HT9 is not commercially available and must therefore be developed by a commercial supplier.

DESCRIPTION OF THE ACTUAL WORK

Current development efforts are focused on fabrication of HT9 tube and duct material, which is challenging due to the length requirements, tight tolerances, thin wall for fuel pins, and the material's high hardness. Moreover, details on HT9 fabrication are complicated by the variability in swelling behavior observed during irradiations in the Fast Flux Test Facility. Figure 1 is a plot of density change measurements for five separate heat/heat treatment combinations of HT9 irradiated at 400°C. Despite the almost identical compositions, the changes in swelling behavior vary widely, at least in part due to differences in final heat treatment, which are listed in the legend next to the HT9 heat number. After initial incubation doses ranging from 50 - 100 dpa, the measurements show rather linear swelling behavior through to 165 dpa. Additional swelling data is shown at 208 dpa, but without any dose history.

One of the major development efforts will be in producing an optimized microstructure that eliminates delta ferrite and contains a fine carbide distribution. Delta ferrite grains that do not transform to martensite after normalization are thought to have less swelling resistance than tempered martensite grains. Optimization is being accomplished through a combination of refinement of the composition specification through a balance of the austenite and ferrite formers and thermo-mechanical processing to optimize the final normalizing and tempering heat treatment to minimize delta ferrite and prevent over-tempering of the martensite. Using the optimized HT9 material, neutron irradiations of creep tube specimens are planned to qualify the HT9 swelling and irradiation creep behavior up to high doses. The neutron irradiations will be conducted over many years in the future in order to obtain the high irradiation doses required. In addition to verifying the irradiation performance of the HT9, thermal creep performance must also be examined to qualify design models for thermal creep strain limits.

RESULTS

A significant assumption currently made for HT9 creep and swelling modeling is that linear swelling rates persist up to high doses. From Figure 1, heat 84425 showed a swelling rate of ~0.002% / dpa and heat 91353 swelled at ~0.01% dpa, a range of 5X. Even assuming the higher swelling rate may not necessarily be conservative since swelling rates may well increase beyond 0.01% / dpa at higher doses. At the least, a swelling rate 0.01% / dpa for heat 91353 out to 165 dpa is consistent with irradiation data for heat 9607R2 out to 208 dpa. Lacking any insight for the reasons of swelling variability, the highest rate of swelling is used for modeling.

While neutron irradiation swelling data to high doses (e.g. 500 dpa) will not be available for many years, heavy
ion irradiations can easily achieve these doses to give some understanding of the swelling behavior that can be expected at such high doses. Although the swelling rates cannot give an absolute measure of the expected swelling from neutrons, it does provide guidance. Extensive work on a neutron-to-heavy-ion irradiation correlation regarding swelling behavior is being developed for HT9. The correlation seems to indicate little-to-no temperature shift required to match swelling behavior for the different dose rates between neutrons and heavy ions. The correlation adds confidence that swelling behavior with heavy ion irradiation can be understood sufficiently to high doses.

The heavy ion irradiation results at very high doses are expected to provide insight in the swelling trends, as depicted in Figure 2. While Figure 2 indicates an upper range in the swelling rate, the actual swelling rate beyond 200 dpa is unknown and could well be even higher than depicted. The ion irradiation study will be performed on different heats HT9 and be utilized as one tool in down-selecting the final heat treatment for HT9 cladding and duct material.

Another significant development effort involves understanding the thermal creep behavior of HT9. The transition between low-stress and high-stress thermal creep behavior is not well defined. HT9 thermal creep models have been developed, and the strain rates for HT9 have typically been modeled with some form of the equation,

$$\dot{\varepsilon}^{th} = \dot{\gamma} \cdot \sigma^n \cdot \exp \left( \frac{-Q}{R_{gas}T} \right)$$  \hspace{1cm} (1)

where $\dot{\gamma}$ is a pre-exponential, $\sigma$ is the effective stress, $n$ is the stress exponent, $Q$ is the activation energy, $R_{gas}$ is the gas constant, and $T$ is the temperature. The equation above implies only a single stress exponent for the entire thermal creep regime. But looking at thermal creep data in Figure 3 from Toloczko et al. and Sandvik, there are clearly two thermal creep regimes with different stress exponents. Consequently, current creep and swelling modeling of HT9 incorporates two separate regimes with different stress exponents.

Since the optimized heat treatment developed for the TWR duct and cladding is likely to affect the thermal creep performance, extensive thermal creep testing is needed to understand long-term performance, as well as a better understanding of the transition from a low stress exponent to high stress exponent as a function of temperature. This program is examining several different optimized heat treatments for insight on the effects of heat treatment to thermal creep strength.

Figure 1. Density measurements of HT9 creep pressure tube samples irradiated at 400°C in FFTF.

Figure 2. Depiction of potential swelling rates up to high irradiation doses, to be examined with heavy ion irradiation.

Figure 3. Steady-state thermal creep rate data as a function of stress showing a change in stress exponent from low to high effective stress levels [6, 8]

REFERENCES

[8] Sandvik thermal creep data. Private communication