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Silicon Carbide TRIPLEX™ Fuel Clad and SiC Channel Boxes for Accident Resistance and Durability

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ABSTRACT

The behavior of zircaloy cladding during the loss of coolant accidents at Three Mile Island (TMI) in the US and the Fukushima reactors in Japan was the major cause of overheating and hydrogen release. An alternate cladding material, consisting of multiple layers of silicon carbide fiber matrix composite and silicon carbide high density monolith, (called SiC TRIPLEX cladding) is being developed in the US that offers reliable service during normal reactor operation, and a very large reduction in the exothermic reaction and hydrogen generation that occurred in these accidents. Should another loss of coolant accident occur in a power reactor somewhere in the world, as it surely will someday, use of this cladding would avoid the severe core damage and allow recovery of the plant without total core destruction as occurred at Fukushima and TMI. The status of development and testing of this TRIPLEX cladding is described, as are the plans for future development and testing in preparation for licensing and use. A separate program for replacement of zircaloy channel boxes in BWRs with a unique form of SiC-SiC composite, is also described.

KEYWORDS

Fuel cladding, hydrogen generation. loss of coolant accident, silicon carbide

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1. Introduction

Based on the evidence from both Fukushima and TMI-2, the key to achieving accident resistance in commercial nuclear fuel is the fuel cladding, which is intended to contain the fuel and the fission products as the first line of defense against release of fission products to the environment during accidents. This fission product containment capability of the cladding was lost in both accidents because (1) zircaloy lost all of its strength upon heating above 500 ^{o}C and ballooned, blocking flow to the core interior, (2) zircaloy reacted with water releasing large quantities of flammable hydrogen gas, and (3) zircaloy reacted exothermically with water during the accident releasing a large amount of heat. As long as zircaloy is used as a cladding material, with its inherent poor properties above normal operating temperatures, it will continue to be the root cause of fission product release during loss of coolant or other core overheating accidents. For Boiling Water Reactors, an additional root cause of the excessive heat and hydrogen release during the accident at Fukushima was the zircaloy channel boxes which comprise about half the volume of zircaloy in the core, and hence released about half the heat and hydrogen during the hours following the accidental core uncovery.

An alternative to zircaloy that does not react exothermically with water, or release hydrogen when quenched with water at high temperatures, is the ceramic material silicon carbide. Over several decades of research for fusion reactor materials in Japan and the US, it was learned that some forms of silicon carbide are radiation resistant and hence may be usable in fission reactors. [1] However, some research in the last ten years to evaluate use of silicon carbide composites as a replacement for zircaloy in water reactors has proved unsuccessful. For example, an advanced form of SiC-SiC fiber matrix composite fabricated in Japan was tested in the MIT research reactor at normal operating temperatures and found to have excessive corrosion in PWR coolant. Other forms of SiC-SiC had acceptable behavior. A careful evaluation of these experiments has led to a unique form of multilayered SiC that overcomes these difficulties and offers the prospects of high durability during

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normal operation, and a high degree of stability and fuel containment during severe accidents. This paper describes the unique features in this SiC TRIPLEX^{TM} cladding, including the results of recent testing during both normal and accident conditions. It also summarizes the development work that remains as needed to prove the technical and commercial viability of this new fuel cladding.

2. Summary of SiC TRIPLEX Cladding and SiC Channel Box Technology

The CTP TRIPLEX^{TM} cladding is a three layer, all silicon carbide, tube that has the same dimensions as zircaloy cladding in current LWRs. It retains its strength to temperatures above 1400 ^{o}C [1]. As shown in Table 1, it has at least 700 times slower reaction rate than does zircaloy at design basis accident conditions (1200 ^{o}C), and reduces the amount of hydrogen released during such accidents by at least a factor of 600. The CTP TRIPLEX cladding design is illustrated in Figure 1 below. In recent fabrication trials, the outside diameter of the TRIPLEX clad tube retains the same diameter as the current 17 x 17 commercial PWR fuel, thus allowing direct replacement of zircaloy clad fuel rods with SiC TRIPLEX clad fuel rods.

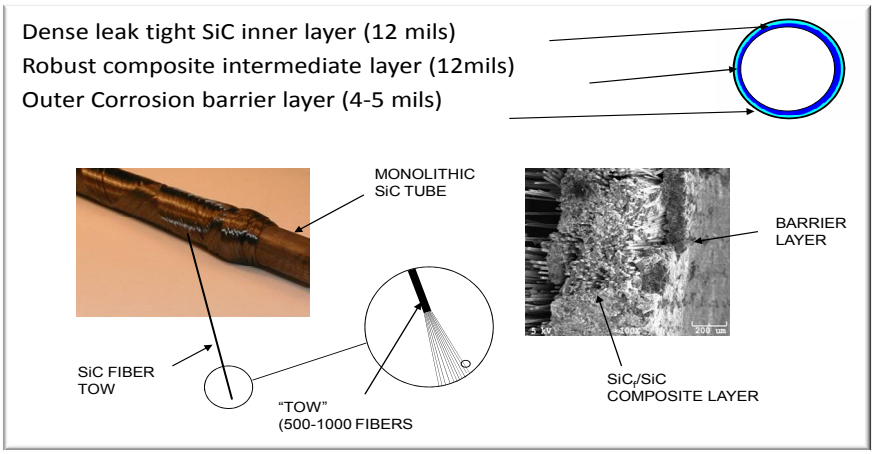

Figure 1 – TRIPLEX^{TM} Fuel Clad Construction

Each of the three layers fulfills a different design requirement. The inner high density monolith layer of stoichiometric beta phase SiC assures hermeticity and fission gas retention during normal operation and reactor transients. The central composite layer is made from stoichiometric beta phase SiC fibers (for example – HiNicalon-S fibers made by Nippon Carbon or special Sylramic fibers made by ATK-COI) and an SiC matrix produced by the Chemical Vapor Infiltration (CVI) process. This central layer assures a graceful failure mode even when the clad is subjected to high external forces during accidents, thus avoiding the brittle failure mode of monolithic ceramics. The central layer assures that the clad tube retains its shape and solid fission product retention capability during severe accidents. Alternative matrix infiltration processes (other than CVI) have been tried and proved unsuccessful during coolant exposure tests in the MIT research reactor.

The outer dense layer of SiC serves as an environmental barrier layer assuring the cladding can achieve at least seven years of exposure to PWR coolant without excessive corrosion. Figure 2 below presents the results of coolant exposure tests after 30 months in PWR coolant temperature and chemistry conditions (e.g. 300 ^{o}C with typical boric acid concentrations) [2] Specimens labeled "F" used HiNicalon-S type fibers, and specimens labeled "H" used Sylramic type fibers.

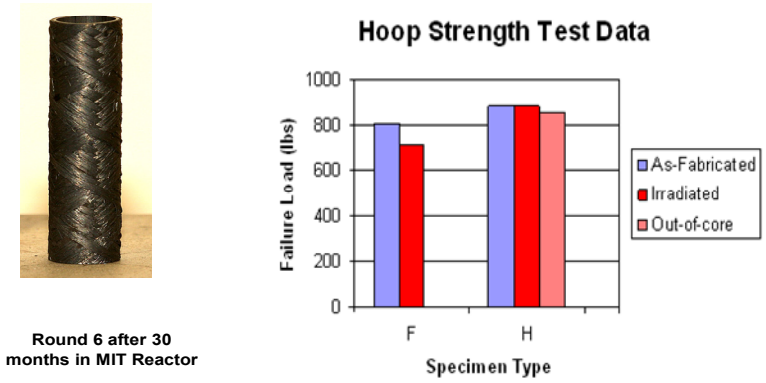

Figure 2 – MIT Reactor PWR Coolant (300 °C) Exposure Test Results

Out-of-pile accident tests have demonstrated the superior behavior of TRIPLEX™ clad during simulated LOCA events. For example, a quench test of SiC TRIPLEX™ clad by emersion of a 1000 °C specimen into a room temperature water pool showed virtually no damage or loss of structure. As illustrated in Table 1, other tests in a 1200 to 1400 °C LOCA steam environment for 6 to 8 hours demonstrated the dramatic reduction in exothermic reaction and hydrogen release cited above.[3] A test of fuel and clad interaction at typical PWR operating temperatures and flux is ongoing in the Oak Ridge High Flux Isotope Reactor.

Table 1 – SiC Accident Simulation (Steam Exposure) Tests at CTP Lynchburg

- **Summary at 1200 C for 6 hours**

Zircaloy-2 values are predictions based on well established data;
SiC values are based on measurements at CTP Lynchburg

Hydrogen released– ml /cm2 -	SiC	0.25
	Zircaloy 2	160.7
Recision in microns	SiC	0.72
	Zircaloy 2	530

- **Summary at 1400 C for 8 hours**

Hydrogen released – ml/cm2	SiC	1.5
	Zircaloy 2	170
Recision in microns	SiC	4.2
	Zircaloy 2	890

Further research to improve the product is nearing completion and has begun to demonstrate (1) a robust, high integrity, hermetic end cap joint, (2) a new "semi-continuous" manufacturing approach

for fabricating 14 foot long clad tubes to precise dimensions, (3) and a factor of two improvement in mechanical fracture resistance of the clad tube. Minor changes to the SiC clad UO_2 fuel pellet design are being examined which appear to reduce the potential for higher fuel temperature with SiC cladding. Such higher fuel temperatures could result from the absence of creep-down of cladding onto the pellet during long term operation. The pellet modifications include the use of a small (< 10% by volume) void, or annulus, in the center of the pellet, providing more room for pellet swelling and reducing the peak fuel temperatures. Such "annular" pellets have been used in commercial LWRs in the past. Other fuel pellet changes to help reduce the fuel temperatures and also allow higher fuel burnup, enabled by the SiC cladding, such as the addition of Beryllia to the UO_2, or the use of thoria plutonia fuel, are also being examined.

With additional investment by the international fuel supply industry, and National governments, this new ceramic fuel clad technology, with its dramatic improvement in reactor safety during severe accidents, could be ready for testing in commercial reactors within five to ten years.

3. BWR Channel Box Application

In a parallel program, sponsored by EPRI (US Electric Power Research Institute), a mechanical shock test of a BWR channel box model (4" x 4" x 24") fabricated from layers of SiC-SiC composite material was performed in March 2012. [4] The test demonstrated acceptable shock resistance for use in commercial BWRs. In the authors view, however, further development and advancement of the basic fiber architecture is needed to assure adequate dimensional stability during irradiation, and the absence of de-lamination. For example, the use of new 3-D fiber architecture, as has been developed and used for ceramic composite aerospace applications, would help assure the absence of de-lamination that is a concern with channel boxes as they are exposed to high gradients of neutron radiation. Once this work is successfully completed, introduction of test units into test reactors and then commercial BWR reactors should be pursued.

4. Conclusions

Although the zircaloy cladding used in commercial water reactors for the last fifty years has proved very reliable during normal operation, it has also been the major contributor to the severity of core overheating accidents such as occurred at Three Mile Island and Fukushima. If the industry and the governments who are dependent on nuclear power, are serious about reducing the consequences of such severe accidents, thereby improving the future safety of commercial nuclear reactor operations, then they should immediately invest in the further development, testing and licensing of alternative, non-reactive, fuel cladding and channel boxes similar to the unique SiC TRIPLEX^{TM} fuel cladding, and dimensionally stable SiC-SiC channel box, described in this paper.

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