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# A structural model for multi-layered ceramic cylinders and its application to silicon carbide cladding of light water reactor fuel

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ABSTRACT

A thermo-mechanical model for stress distribution and Weibull statistical fracture of a multi-layered SiC cladding for LWR fuel is developed. The model is validated by comparing its results to those of the Finite Element Analysis (FEA) code ANSYS. In steady-state operation, the temperature sensitive swelling may lead to undesirable tensile stresses which is anticipated to challenge the structural integrity of the fission-gas retaining inner layer of CVD-SiC monolith in a triple layer design with the composite being the middle layer. The stress distribution is sensitive to potential differences in the swelling of the monolith from that of the composite layer. The sensitivity is discussed in this work. A double-layered SiC cladding that employs the inner $SiC_f$/SiC composite layer, and the outer CVD-SiC layer has also been analyzed. This SiC cladding design significantly reduces failure probability as it appropriately allocates peak tensile stresses in the inner composite while significantly reducing tensile stress levels of the CVD-SiC monolith.

## 1. Introduction

Silicon Carbide (SiC) is being investigated as a potential alternative for the current zirconium based alloy cladding in light water reactors (LWRs). SiC exhibits several advantages over zirconium based alloys, including excellent high temperature and irradiation tolerance [1–7], and steam oxidation resistance [8–10]. Those features are expected to enhance accident tolerance of the LWR fuel. Even in operation at a similar neutron flux, SiC cladding would absorb fewer neutrons compared to a zirconium based alloy cladding [11,12]. Its generally comparable neutronic performance implies minimal departure from the current LWR reactor core design [11,12].

Thermo-mechanical properties of SiC under irradiation have been well studied, thanks to fusion and high temperature reactor structural applications [4–7,13–16]. Yet, relevant failure mechanisms of SiC cladding should be further examined to determine its design, and operation limitations. Those safety-driven limitations are critical unknowns – at this stage of the concept development – that will determine feasibility of the use of SiC cladding for LWRs. The discussions on SiC cladding oxidation in previous studies [8–10] illuminated that the major failure modes for the SiC cladding would fundamentally depart from the failure modes of zirconium-based cladding, whose primary failure mechanisms are heavily affected by oxidation [17]. Previous SiC structural assessments assume the SiC cladding geometry as a sole composite cylinder [18], and highlight importance of accounting for temperature dependent swelling. The purpose of this study is to lay a foundation for understanding critical structural failure modes for representative multi-layered SiC cladding (as well as the single layer), and discuss their implications for fuel design and reactor operation. Specifically, in this study we develop a model for stress distribution and statistical SiC cladding fracture for multi-layered SiC cladding that can be used to provide the probability of failure of SiC cladding under steady-state operation.

Failures of load bearing structures are either of the yield-dominant or fracture-dominant (fast fracture) types. Yield-dominant strength failures involve dislocation-mediated plasticity in the material, and occur in ductile materials, including zirconium based alloys at room temperature. Unlike dislocation-mediated plasticity, a fracture dominant failure occurs before general yielding through separation of atomic planes which results in the creation of new surfaces, whereas yield-dominant failure leads to shape changes [19]. Generally, no appreciable plasticity, or only highly localized plasticity, is involved in fracture dominant failures. Fracture-dominant failures usually occur for brittle materials that lack the ability to accommodate defects generated during plastic deformation. Fracture-dominant failure is of interest in this study because it is the failure mode of silicon carbide, a brittle ceramic material.

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**Nomenclature**

| | |
|---|---|
| $A$ | *Lamé's* constant (Pa) |
| $\alpha$ | thermal expansion coefficient (1/K) |
| $A_c$ | cross sectional area ($m^2$) |
| $B$ | *Lamé's* constant ($Pa/m^2$) |
| $C$ | constant |
| $\varepsilon$ | Strain (–) |
| E | Young's modulus (Pa) |
| $R$ | radius, fixed (m) |
| $r$ | radius, variable (m) |
| $P$ | pressure (Pa) |
| $P_s$ | survival probability (–) |
| $P_f$ | failure probability (–) |
| $k$ | thermal conductivity (W/m K) |
| $T$ | temperature (K) |
| $V$ | volume ($m^3$) |
| $\sigma$ | stress (Pa) |
| $m$ | Weibull modulus (–) |
| $q'$ | linear heat generation rate (W/m) |
| $\nu$ | Poisson ratio (–) |
| $\Delta$ | difference |
| $S$ | volumetric swelling (%) |

*Subscripts/Superscripts*

| | |
|---|---|
| 0 | characteristic, or fixed |
| *ref* | reference |
| Th | thermal stress |
| s | swelling-induced |
| $u$ | threshold |
| $\theta$ | hoop (tangential) |
| $r$ | radial |
| $z$ | axial |
| 1, 2, 3 | inner monolith, composite, and EBC, respectively. |
| $i, j, k$ | Principal directions |

## 2. Qualitative understanding of SiC cladding fracture modes

The structure of SiC cladding can be viewed in terms of its response/tolerance to possible fractures under excessive loading. Today, a three-layer laminated structure (that consists of a monolithic SiC layer, SiC–SiC fiber composite layer, and a monolithic environmental barrier coating (EBC) layer) is regarded as a potential candidate for SiC cladding design. Monolithic SiC is well known to undergo fast fracture without a sign of plasticity if stresses are excessive. SiC/SiC fiber composites exhibit rather complex modes of failures that show some degree of pseudo-ductility [14,20], which is sometimes called brittle-like (or quasi-ductile) failure [21]. In SiC–SiC fiber-composite materials, since the CVI (Chemical Vapor Infiltration) matrix is stiffer, the fiber strength is not accessed until significant matrix microcracking occurs [22]. While CVI matrix microcracking basically follows the behavior of monolithic CVD SiC, propagating cracks from the matrix eventually meet the fibers in the composite, experiencing a barrier to the continuity of propagation. At that moment, the strength of the fiber is accessed and the fibers undergo elastic strain. The composite is regarded as essentially "leaky" above the matrix cracking stress although catastrophic fracture does not occur [5]. This crack arresting mechanism by an interaction with fibers renders the SiC composite fracture toughness (~30 MPa $m^{1/2}$) roughly 10 times the monolith (~2.5–3.0 MPa $m^{1/2}$ for CVD SiC) [4,22]. Having said this, the seemingly ductile behavior of the SiC composite due to the fiber strength, in principle, is engineered pseudo-ductility caused by proper juxtaposition of brittle materials. In that regard, it can be inferred that the SiC composites, while possessing decent fracture toughness and engineered graceful failure modes, have essentially no strain tolerance to cracking.

Fracture of the SiC cladding layers (SiC monolith/SiC composite/EBC) can occur either individually for one layer, or in company with neighboring layers. Each layer has a specific significance to performance of the cladding as well as the fuel rod. Fractures in each layer imply degradation of certain performance metrics of the cladding. Fig. 1 illustrates qualitative evaluations for SiC cladding performance with different fracture modes in terms of fission gas retention, prevention of $H_2O$ attack of the carbon coating of the SiC fibers in the composite during steady-states & accidents, and strength margin for accidents. The integrity of SiC monolith has prime importance in fission gas retention and load sharing in SiC cladding. Improving cladding with the addition of pseudo-ductility with additional crack-arresting capability, the SiC composite has prime importance for load sharing and avoiding catastrophic shattering of the cladding. As discussed previously, the SiC composite needs to be protected from $H_2O$ access to the carbon-coated fibers to avoid significant strength degradation of the composite, caused by consumption of part of the carbon coating by the $H_2O$–C reaction [23–25]. Therefore, without the presence of the monolithic SiC overcoat by either EBC or extended CVI overcoat, the SiC composite may undergo strength degradation even at temperatures under normal operating conditions. It is important to note that SiC composite has CVI overcoat extended for a certain thickness on the surface, which can function as an EBC with similar oxidation behavior of CVD SiC [8,10]. Therefore, even with a crack formed on the EBC layer, the composite may still be protected from $H_2O$ access to the fibers by the presence of the CVI overcoat. Microcracks formed in the CVI matrix with cracked EBC would leave the fibers essentially unprotected from $H_2O$ access, resulting in substantial strength degradation. While meeting steady-state performance requirements in terms of fission gas retention, and load sharing, the amount or even presence of allowable cracking in the inner monolith and fiber composite should be evaluated in the context of strength margin for accidents. It is important to note that for the inner most monolithic SiC, it may not be appropriate to think of fracture in terms of amount; being monolithic, it should be viewed in terms of allowing any propagating crack(s) or none. For the composite, the unused strength should be viewed as margin left for CVI matrix cracking to access the SiC fibers' elastic limit. Being considerably thinner in comparison to the inner most monolith and the composite, the influence of EBC on strength safety margin was considered negligible in the qualitative evaluations shown in Fig. 1. Note that the current SiC monolith/SiC–SiC composite/SiC EBC cladding design is a result of a rather qualitative SiC cladding behavior; their relative thicknesses, or perhaps even the need for each layer will be quantitatively questioned by rigorous design studies in following discussions.

## 3. Tensile versus compressive stresses for SiC cladding fracture

The cylindrical fuel rod cladding experiences both tensile and compressive stresses during its life time. It is initially under compression as the operating coolant pressure in the reactor is higher than the internal helium fill gas pressure. As burnup proceeds, fuel