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# ***SiC cladding R&D execution plan***

**Nuclear Technology  
Research and Development**

***Prepared for  
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## SUMMARY

To advance the development of accident-tolerant fuel cladding for light-water reactors, the Advanced Fuels Campaign actively addresses the R&D gap between the specialized technological progress in SiC-based composite materials, led by industrial partners, and the fundamental scientific understanding of material behavior under reactor operating conditions. The laboratory activities are systematically organized based on the Development Strategy document [1], which outlines critical barriers to the use of SiC composites in nuclear energy applications for the coming decade and beyond. To complement the strategy, this execution plan specifies a detailed year-by-year work package and establishes key milestones for assessing progress in technological advancement. This plan has been formulated in collaboration with principal investigators at national laboratories, stakeholders, and industry partners with the goal of closing technology gaps and readying SiC-based cladding technologies for full-scale commercial testing.

The research conducted at the national laboratories is categorized into three primary subjects: (1) addressing challenges associated with the performance of SiC cladding under normal operating environments, (2) identifying the failure limits of SiC cladding under accident conditions, and (3) modeling fuel performance for SiC cladding systems. Comprehensive laboratory activities integrate the development of advanced modeling tools for SiC-based cladding systems with experimental validation via integrated testing of multiphysics phenomena. This document lays out the laboratory plan to support the development of SiC-based technologies, which have the potential for significant operational and safety benefits for the U.S. nuclear industry. This plan aligns with industry developer needs, relevant Nuclear Energy University Programs, and Nuclear Energy Advanced Modeling and Simulation Programs to ensure SiC cladding technologies are matured as efficiently as possible and will be maintained and updated to accommodate the dynamically evolving progress of development, capability needs, and resource availability.

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## ACRONYMS

AFC	Advanced Fuels Campaign
ASME	American Society of Mechanical Engineers
ATF	accident-tolerant fuel
ATR	Advanced Test Reactor
BWR	boiling water reactor
CMC	ceramic matrix composite
CVD	chemical vapor deposition
dpa	displacements per atom
FEA	finite element analysis
HFIR	High Flux Isotope Reactor
I-FOA	Industry Funding Opportunity Announcement
INL	Idaho National Laboratory
LOCA	loss-of-coolant accident
LWR	light water reactor
NDMAS	Nuclear Data Management and Analysis System
NEAMS	Nuclear Energy Advanced Modeling and Simulation
ORNL	Oak Ridge National Laboratory
PIE	postirradiation examination
PWR	pressurized water reactor
RIA	reactivity insertion accident
SATS	Severe Accident Test Station
SiC/SiC	continuous SiC fiber-reinforced SiC matrix
TREAT	Transient Reactor Test
TWERL	TREAT Water Environment Recirculating Loop
TWIST	Transient Water Irradiation System for TREAT



# SIC CLADDING R&D EXECUTION PLAN

## 1. INTRODUCTION

Continuous SiC fiber-reinforced SiC matrix (SiC/SiC) composite cladding offers potential economic advantages in light-water reactors (LWRs) due to its relatively low neutron capture cross section compared with zirconium alloys [2]. Additionally, it has the capacity to serve as an accident-tolerant fuel (ATF) cladding with enhanced resistance to loss-of-coolant accidents (LOCAs), as evidenced by a series of high-temperature steam oxidation tests [3]. The transition from the current zirconium-based alloys to SiC/SiC composite materials represents a transformative advancement. Given the distinct technological challenges associated with metallic and ceramic systems, successful deployment requires comprehensive advancements across all facets of LWR-specific SiC technology. This includes improving the scientific understanding of material behavior and addressing the existing gap between fundamental research and practical application. The Advanced Fuels Campaign (AFC) is actively working to develop the LWR SiC/SiC composite cladding concept. The goal is to increase the technology readiness level of SiC cladding for LWR applications through a series of separate effects tests, followed by integrated tests, with the aid of computational modeling to design the experiments and interpret the experimental results.

The R&D efforts were initially guided by the Systematic Technology Evaluation Program for SiC/SiC composite-based accident-tolerant LWR fuel cladding and core structures (Figure 1 [4]). This program identified critical feasibility and performance issues that needed to be addressed before integrated tests, such as in-pile testing, could be conducted. The evaluations included manufacturability [5], resistance to hydrothermal corrosion [6] and steam oxidation [3], and leak-tightness without irradiation [5]. As performance data accumulates, the promises and challenges of the current generation of nuclear-grade SiC/SiC composites are becoming increasingly apparent. The current phase of development, referred to as the Technology Implementation Phase (Figure 1), focuses on developing performance enhancement technologies and conducting integrated tests to assess SiC/SiC composite cladding under prototypic operational environments. Key aspects of the technology, such as processing, material performance, and fuel performance modeling, are being integrated to support vendors' lead test rod programs.

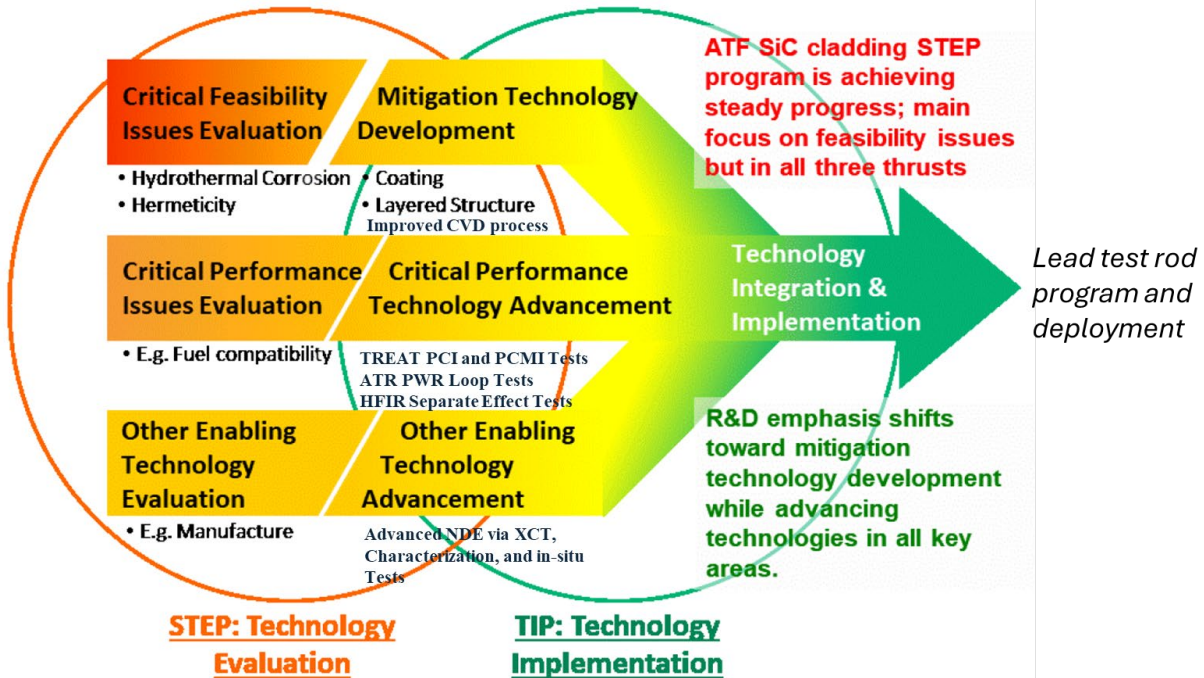


Figure 1. The pathway to the technology integration and implementation phase for SiC/SiC composite-based technologies in LWR applications. This figure has been updated from the original version [4].

The current status of SiC/SiC composite technology for LWR applications has been reviewed, and priority R&D areas have been defined in the SiC/SiC Development Strategy and the 5-Year Execution Plan (2023) [1]. To enhance this strategy, this execution plan document outlines a systematic year-by-year work package, establishes critical milestones for evaluating progress in technological advancements, and specifies the resources necessary to achieve the targeted near-term objectives. This plan has been developed in collaboration with principal investigators from national laboratories, industry stakeholders, and research partners.

## 2. CURRENT STATUS OF SiC/SiC COMPOSITE CLADDING TECHNOLOGY

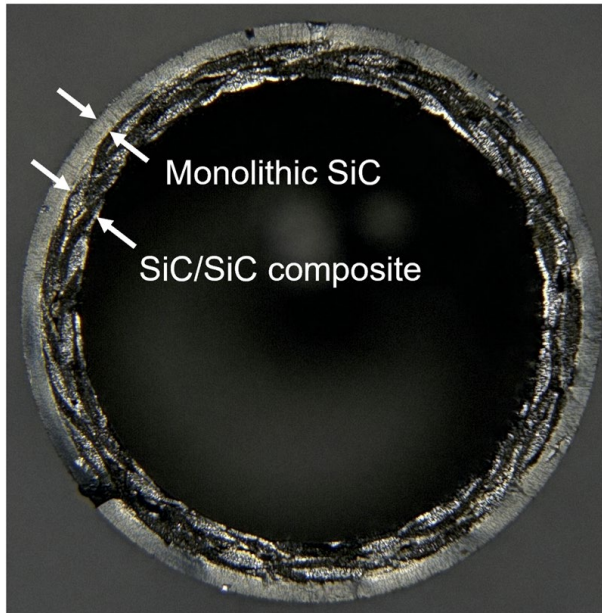
This section provides a concise overview of the critical feasibility and performance issues related to LWR SiC cladding applications, as outlined in the 5-Year Execution Plan [1]. Subsequently, an analysis of the updated technological and knowledge gaps is presented, considering recent advancements in R&D within the relevant domain. The information provided in this section is used to justify research activities under the AFC.

### 2.1 Critical Feasibility and Performance Issues

The following cladding feasibility and performance issues must be addressed to elevate the SiC-based cladding technology suitable for lead test rod insertion.

(1) The failure probability of cladding during normal reactor operations must be maintained at an adequately low level. A full core failure assessment of SiC/SiC composite cladding used the failure rate of Zircaloy cladding as a reference (e.g., a 1 ppm failure rate) [7]. The presence of a network of microcracks in the SiC/SiC composite, resulting in the subsequent release of fission product gases, is classified as a failure, even if the operational stress of the cladding remains below the proportional limit stress at which significant matrix cracking occurs. To reduce failure probability, the statistical reliability of the mechanical properties of SiC/SiC composite materials [8] must be enhanced, and the engineering

design of composite microstructures (e.g., fiber architecture and layered structures) and cladding configurations (e.g., fuel designs and geometries) must be optimized. For example, the duplex SiC/SiC composite tube (Figure 2 [9]), which features an outer monolithic SiC layer, is designed to position the hermetic monolithic layer—susceptible to cracking damage from tensile stresses—in the region where compressive stresses are generated under in-pile conditions [10, 11], thereby avoiding cracking.



Tube outer diameter: 10mm

Figure 2. Cross-sectional view of SiC/SiC composite tube. The tube has a duplex structure with monolithic SiC layer deposited on the outer surface [9].

(2) LWR utilities require enhanced fuel economics before a new cladding or fuel concept can be implemented. Core design restrictions imposed by fuel safety limits significantly limit fuel economics; consequently, any new fuel or cladding concept must demonstrate improved performance in normal operating and accident conditions to gain sufficient margin to yield a positive economic return. Although SiC offers intrinsic advantages in low neutron absorption that contribute to better fuel economy, the manufacturing costs and cost required for addressing regulation and plant requirements for nuclear-grade SiC/SiC composite cladding must remain competitive to realize the economic advantages of this new fuel form. Moreover, solutions addressing material performance issues, such as metallic environmental barrier coatings (Figure 3), that could compromise fuel economy should be assessed to confirm the benefits of deploying SiC-based fuel cladding.

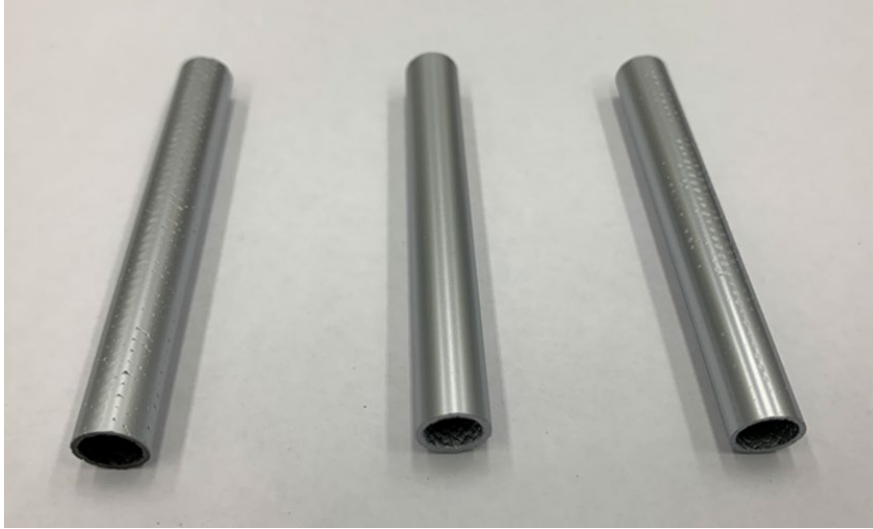


Figure 3. SiC/SiC composite tubes coated with a chromium mitigation coating. Each tube is 75 mm long. Details of the processing have been reported elsewhere [12].

(3) Hydrothermal corrosion of cladding must be low. The recession of cladding must not compromise the integrity of the fuel assembly or reactor components at any point during normal or extended operation. Assessing coolant corrosion requires in-pile testing because the interactions between radiolysis products in the coolant and irradiation-induced defects in the material accelerate the corrosion processes [13]. Therefore, a conventional autoclave corrosion test that does not include irradiation is inadequate for evaluating this feasibility issue. Furthermore, in addition to the corrosion-induced recession, the dissolution of corrosion products (e.g.,  $\text{SiO}_2$  [6]) into the reactor coolant must not adversely affect reactor performance or chemistry.

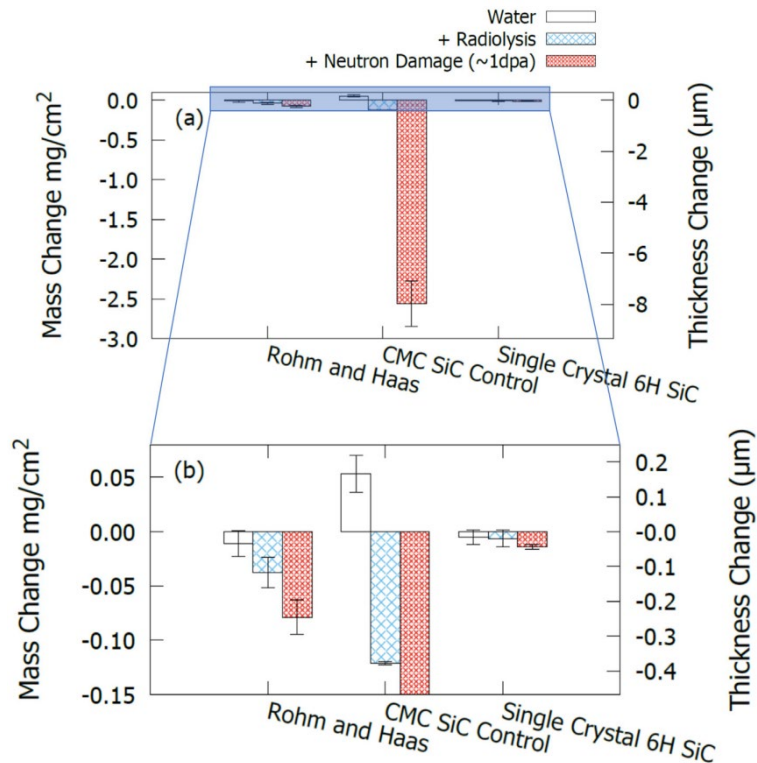


Figure 4. Mass change of Rhom and Haas high-purity polycrystalline 3C SiC, SiC ceramic matrix composite (CMC), and single-crystal 6H SiC specimens under three different flowing coolant environments at the MIT Reactor: without irradiation, with radiolysis products without neutron flux, and with radiolysis products and neutron irradiation damage. The figure has been reprinted from the reference [13].

**(4) Irradiation-induced deformation of cladding under normal operation should not interfere with reactor operation.** Due to their extended lengths and high aspect ratios, LWR fuel rods and core structures, including channel box assemblies, are susceptible to lateral displacements, such as bowing. This phenomenon is a consequence of thermomechanical and irradiation-induced loads that are distributed nonuniformly in axial and azimuthal directions during normal operation. Such loading is also anticipated to occur during power changes that may exceed the plant's acceptance criteria. The presence of these nonuniform loads can significantly distort the fuel assembly, thereby affecting the thermal-hydraulic and neutronic behavior of the reactor. Notably, if the distortion reaches a critical threshold, it may present safety concerns, particularly if the proper insertion of control rods or blades for reactor shutdown is impeded. The deformation behavior is expected to be primarily driven by irradiation-induced swelling and irradiation creep of SiC, both of which are influenced by temperature and dose (Figure 5 [14]).

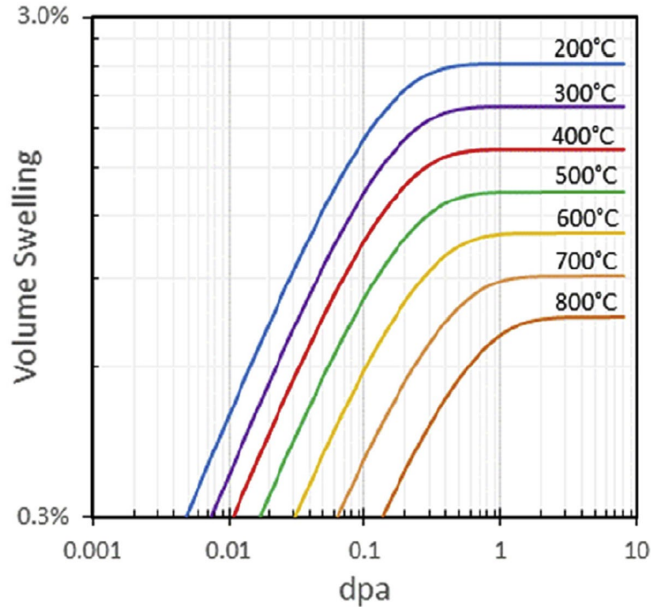


Figure 5. Irradiation temperature and neutron dose dependence of swelling in SiC [14]. Gradients and nonuniform distributions of temperature and neutron flux within the SiC component can cause differential swelling, consequently generating strains.

(5) The safety of SiC/SiC composite cladding must be improved for accident scenarios. The incidents at the Fukushima Daiichi nuclear power plant motivated the development of ATF cladding and core structures. ATFs are specifically engineered to enhance coping time following a beyond-design-basis accident while ensuring compliance with all current technical licensing requirements pertinent to design-basis accident scenarios, including LOCAs and reactivity insertion accidents (RIAs). Current SiC/SiC composite cladding designs include an outer monolithic SiC layer, in part to increase resistance to steam oxidation in a LOCA scenario. A series of steam oxidation tests suggest that high-purity SiC monoliths exhibit significantly lower oxidation kinetics than zirconium alloys (at least two orders of magnitude under atmospheric pressure conditions, as shown in Figure 6 [3]), which could enhance safety margins under severe accident conditions.

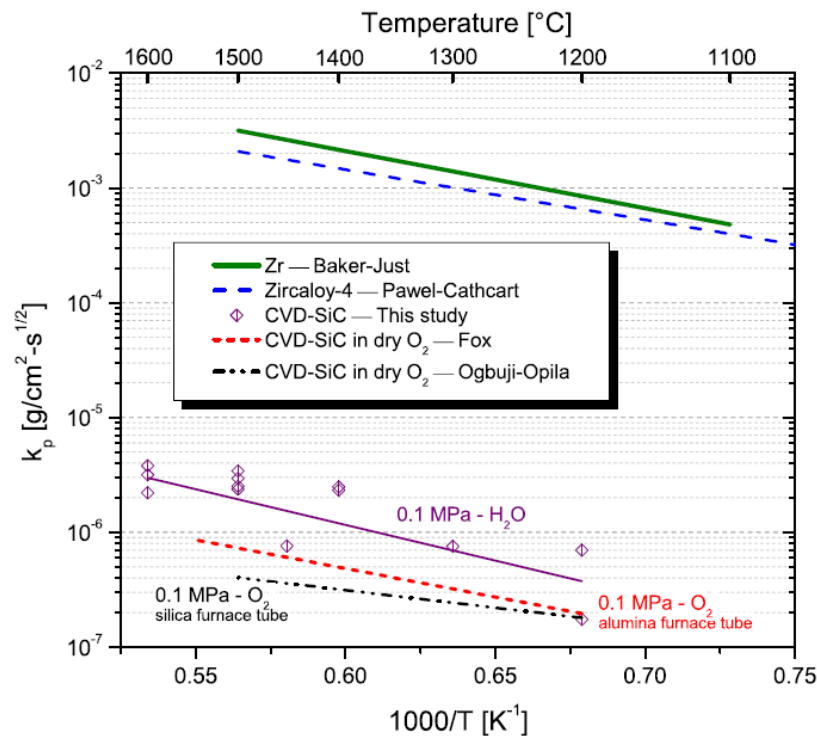


Figure 6. Comparison of the parabolic oxidation rate constants ( $k_p$ ) of zirconium and SiC in steam, highlighting that SiC exhibits significantly lower oxidation kinetics than zirconium. The figure is reproduced from the reference [3].

(6) For accelerated deployment and licensing, the performance of fuel and cladding must be predictable. Advanced fuel performance modeling tools must be capable of predicting and interpreting the response of SiC-based fuel cladding under normal and off-normal operating conditions. A comprehensive set of multiphysics models will be essential to fully capture the range of fuel responses. The phenomena of interest include fuel burnup in SiC cladding, fuel-cladding interactions (Figure 7 [10]), thermo-mechanical responses of the cladding, and corrosion behavior in normal and accident scenarios. The existing modeling framework for zirconium-based cladding must be updated, and new modeling tools for SiC systems must be developed to accurately account for anisotropic properties attributed to fiber architecture and layer structure, stochastic mechanical behavior, and unique failure criteria inherent to SiC/SiC composite materials. The modeling tools are useful for optimizing the engineering design of the cladding, providing material property solutions, and supporting reactor experiments to accelerate the qualification process.

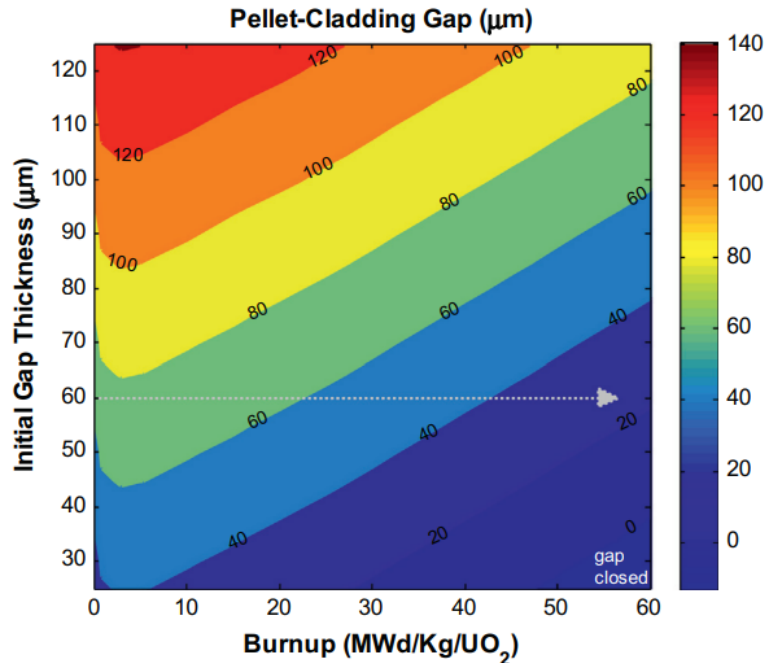


Figure 7. Parametric numerical analysis of fuel-cladding interaction: evolution of pellet-cladding gap size as a function of initial gap size and fuel burnup for SiC/SiC composite cladding. The figure is reproduced from the reference [10].

## 2.2 Remaining Technology and Knowledge Gaps

The technology and knowledge gaps related to the feasibility and performance issues identified in the previous section are summarized below. These gaps drive the structure of this SiC R&D execution plan.

(1) Maintaining the hermeticity of SiC-based cladding under normal operating conditions requires demonstration. A loss of hermeticity is regarded as a failure of the cladding. This issue must be addressed before lead test rod insertions can be considered. The design-limiting factor for SiC/SiC composite-based fuel cladding concepts is probabilistic matrix cracking, which is caused by the complex interplay between neutron irradiation and the radial high heat flux generated by the fuel pellet [10]. Although SiC/SiC composites may contain microcracks due to the nature of the processing [14], crack growth resulting in leakage must be prevented by the crack resistance of the material and/or the engineering design of the cladding. The combination of a large through-thickness temperature variation and the strong temperature dependence of SiC results in significant differential swelling strains across the cladding thickness. A loss of hermeticity due to differential swelling-induced strain has been identified as a serious threat to SiC-based fuel cladding, and the significant temperature gradient that develops across the tube wall is inevitable because of the radial heat flux.

Recent irradiation testing at the High Flux Isotope Reactor (HFIR) at Oak Ridge National Laboratory (ORNL) revealed challenges as well as promises regarding the hermeticity issue. Microstructural and hermeticity characterizations of miniature SiC/SiC composite tubes irradiated with an internal molybdenum gamma-absorbing heater found leaks in the composite tubes after irradiation (Figure 8) [15, 16]. The results and analysis suggest that high-density, high-thermal-conductivity SiC/SiC composites and SiC cladding with hermetic coatings could be potential solutions. The tubes evaluated were fabricated several years prior; fabrication technologies within the industry have since advanced, and various mitigation strategies, including the implementation of hermetic internal liners [17], have been proposed. These engineering solutions need to be tested and analyzed. Given that the degradation mechanisms are

unique to irradiation under a through-thickness temperature gradient, reactor experiments are essential to address this technology gap.

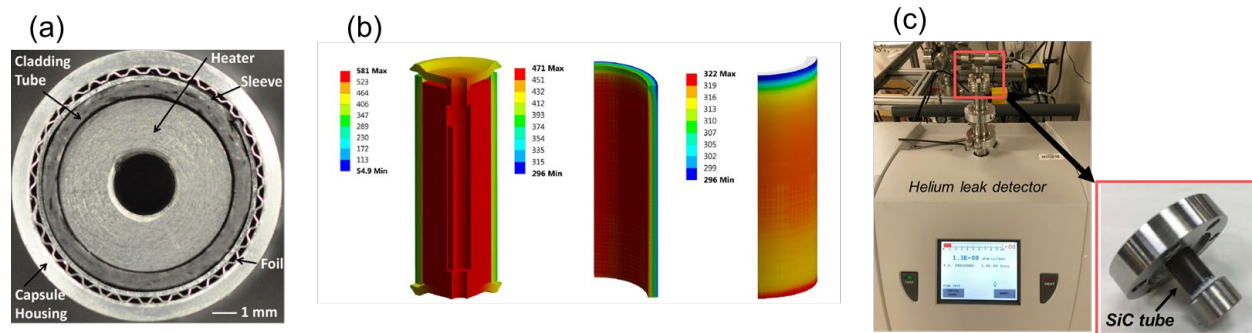


Figure 8. Simulating the irradiation temperature condition of fueled SiC/SiC composite cladding [15, 16]. (a) Cross section of an assembled rabbit capsule for SiC/SiC composite tube specimen, (b) Temperature ( $^{\circ}\text{C}$ ) contours showing composite tube and capsule components during irradiation obtained from 3D simulation, and (c) leak test of SiC tube specimens using a mobile helium leak detector.

Gas leak-tightness is also required for the end plug. Prior neutron irradiation experiments conducted on SiC plate joints demonstrated that the selection of the interlayer significantly influences both mechanical and microstructural stability [18, 19]. The predominant degradation mechanism identified was irradiation-induced cracking, which is associated with differential swelling between the SiC substrate and the bonding layer. The issue of differential swelling was mitigated by the joining methods that form a SiC-based bonding layer. The follow-up irradiation campaign in HFIR tested a miniature SiC composite tube with end-plug joints [20]. The SiC-based bonding layer fabricated using General Atomics' hybrid SiC demonstrated geometrical stability, and some of the end-plug specimens showed gas leak-tightness following irradiation at temperatures ranging from around  $300^{\circ}\text{C}$  to around  $800^{\circ}\text{C}$  and at about 2 displacements per atom (dpa). Nevertheless, the material behavior was not uniform; certain irradiated end-plug specimens displayed a degradation in leak-tightness after irradiation. These findings underscore the necessity for a more comprehensive understanding of the performance of end-plug joints, particularly concerning the effects of irradiation and processing conditions.

(2) The development of an economically viable manufacturing process for nuclear-grade SiC/SiC composite cladding and core structures represents a significant technology gap. Current nuclear-grade SiC/SiC composites consist of fully crystalline, near-stoichiometric, high-purity SiC phases that possess exceptional high-temperature strength, chemical compatibility with coolant and fuel, neutron transparency, and resilience under accident conditions [21, 22]. However, the fiber materials and matrix densification processes for fabricating such high-quality materials are expensive [17, 23]. A challenge in this area is that traditional and more affordable materials, such as reaction-bonded SiC with free Si, are susceptible to irradiation-induced degradation of strength [24].

Innovations across all aspects of composite manufacturing—fiber preforming, fiber production, interphase deposition, matrix densification, and end-plug joining—would help improve the economic competitiveness of SiC-based cladding systems. Enhancing the longevity of SiC-based cladding, predicated on the improved structural reliability of the SiC/SiC composite—specifically the Weibull modulus rather than solely strength—has the potential to broaden the design margin [25], thereby contributing to enhanced fuel efficiency. Recently, more options for SiC fibers have become available on the market (Figure 9) [26]. This trend could yield better and more cost-effective fibers.

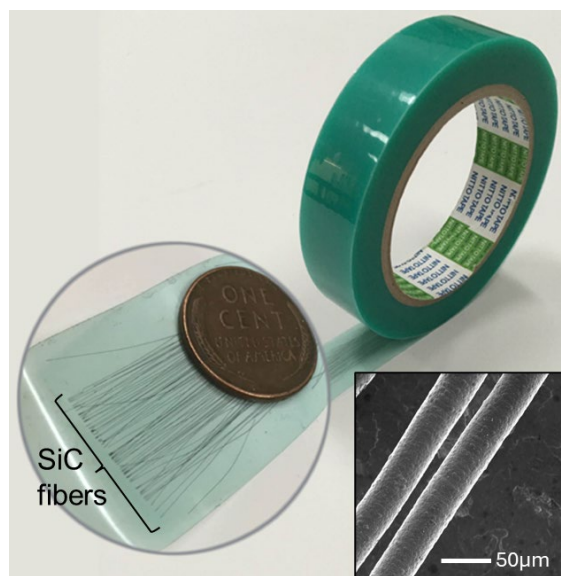


Figure 9. Laser chemical vapor deposited SiC fibers fabricated by Free Form Fibers. The process uses an innovative approach based on additive manufacturing for fiber production. This new fiber demonstrates high strength [26]. The deployment of this fiber for nuclear applications requires nuclear testing to demonstrate its dimensional and mechanical stability under irradiation. The figure is reproduced from the reference [27].

(3) Mitigation strategies for hydrothermal corrosion under specific material systems and water chemistry are required. The recession of high-purity SiC due to in-pile hydrothermal corrosion was less than  $1 \mu\text{m}/\text{year}$  in simulated pressurized water reactor (PWR) chemistry, and the recession rate may be within acceptable limits for LWR applications [13, 28]. However, the dissolution limit of SiC corrosion product has not been determined. Additionally, corrosion under boiling water reactor (BWR) water chemistry remains unresolved; the dissolved oxygen activity in the water can significantly increase SiC recession [6, 28].

The accumulation of comprehensive in-pile and out-of-pile corrosion data for high-purity, crystalline SiC materials fabricated by chemical vapor deposition (CVD) has enabled the development of hydrothermal corrosion kinetics models [6, 28, 29]. A recent investigation conducted by Seshadri et al. has refined the existing corrosion model and provided interpretations of results obtained from in-pile corrosion tests performed at the MIT Reactor [28]. Applying these corrosion models to engineered SiC/SiC composite cladding remains a challenge. The actual microstructure of SiC/SiC composite materials may differ from that of reference-grade materials (Figure 10 [30]), and hydrothermal corrosion of SiC is known to be sensitive to microstructural variations, particularly those related to grain structure [29]. Further material development and validation are necessary for the creation of hydrothermal corrosion-resistant end-plug joints, as well as for effective corrosion mitigation in BWR coolant environments.

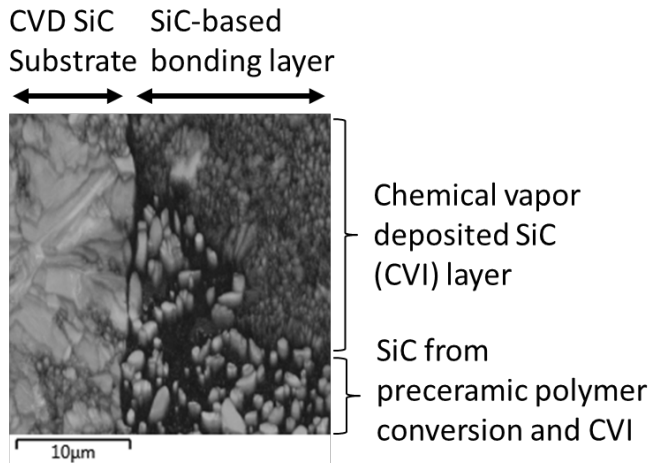


Figure 10. Band contrast map of the SiC joint obtained via backscattered diffraction analysis, highlighting the differences between SiC grain structures in the substrate and the bonding layer [30].

(4) An experimentally validated deformation model needs to be developed to assess the bowing of SiC/SiC composite cladding and core structures. Comprehensive modeling studies of SiC/SiC composite cladding, with and without spacer grids, predict that the lateral displacement of SiC/SiC composite materials induced by their intrinsic irradiation-induced swelling behavior is a concern. Therefore, realistic testing is required to validate and refine these models. The deformation prediction tool can be used to assess whether the deformation of SiC cladding exceeds the limit for the safe operation of LWRs.

To address the required data needs, an irradiation experiment was conducted at HFIR to evaluate SiC/SiC composite tubes and a miniature channel box (Figure 11a) [31]. The primary objective of the irradiation was to evaluate the bowing effects under a fast neutron flux gradient (Figure 11b) at a coolant temperature of approximately 60°C. This novel experiment successfully captured the occurrence of irradiation-induced bowing in the SiC specimens, motivating further investigation into the irradiation-induced bowing behavior of advanced-grade materials under conditions that more accurately simulate prototypic environments. Future work will be essential to expand the irradiation design to evaluate bowing effects under LWR coolant temperatures.

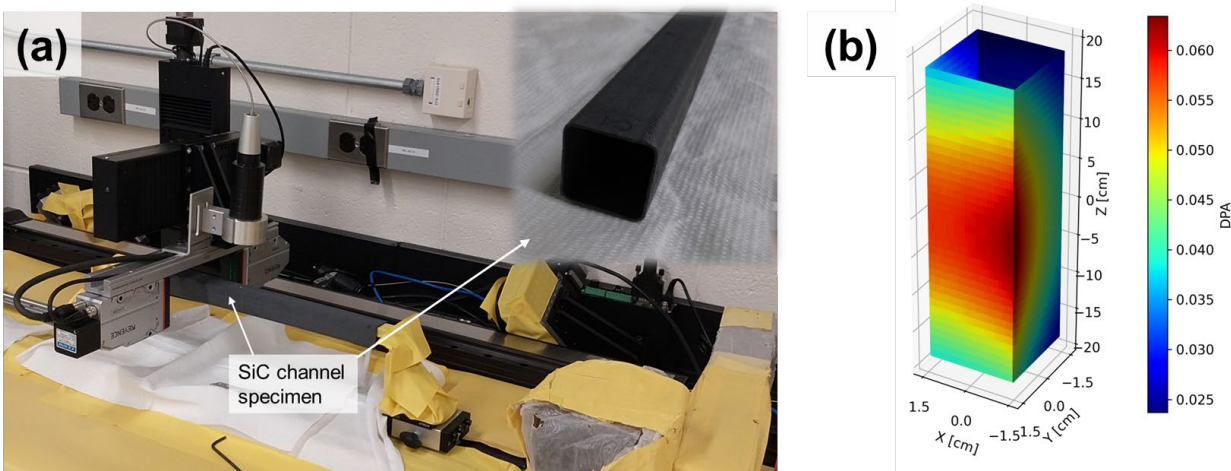


Figure 11. (a) The irradiated channel specimen installed within the profilometry system for dimensional inspections, and (b) distribution of calculated cumulative displacement damage in DPA in SiC channel specimen. The nominal dimensions of the channel specimen are 30 mm × 30 mm × 380 mm, with a 1.25 mm wall thickness. The SiC/SiC composite miniature channel was fabricated by General Atomics [31].

(5) Elucidating the damage processes associated with SiC/SiC composite cladding under LOCA and RIA conditions is necessary to support comprehensive safety analyses. Physics-based models describing material degradation, accompanied by a definition of failure, are employed in the evaluation of accident scenarios. Recent advancements have refined the steam oxidation kinetics model for SiC, accounting for variations in steam pressure, temperature, and flow rate [32]. Furthermore, experimental investigations and analyses of stress rupture tests conducted on SiC/SiC composite tubes under steam at 1000°C have yielded a foundational model that describes the stress corrosion cracking lifetime of the SiC/SiC composite (Figure 12) [9]. The work identified a failure criterion in an accident involving thermo-mechanical loading that exceeds the proportional limit stress in steam oxidation environments.

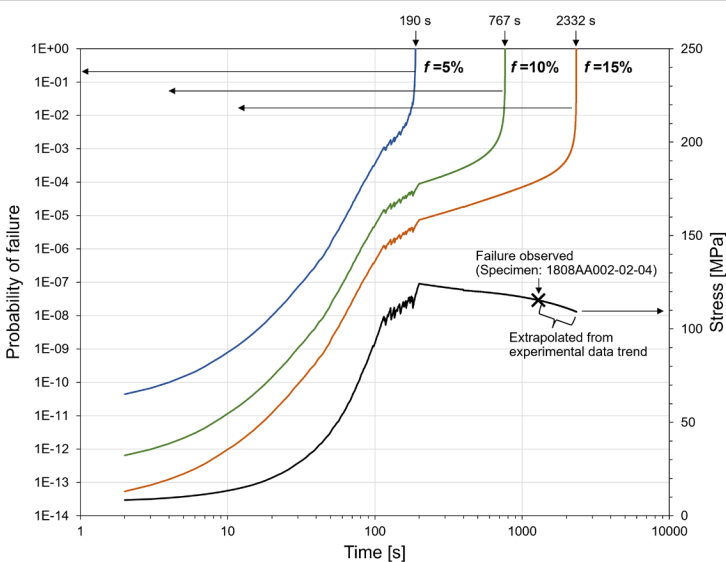


Figure 12. Calculated failure probability of the fiber bundle in a model SiC/SiC composite at a given stress level under steam at 1000°C. Fiber volume fractions ( $f$ ) of 5%, 10%, and 15% were considered. The figure has been reproduced from the literature [9].

Knowledge gaps exist regarding the quenching behavior expected under LOCA conditions and the pellet-cladding interaction behavior during RIA conditions. The pioneering LOCA quench test conducted at the Karlsruhe Institute of Technology [33] and the RIA test performed at the Transient Reactor Test (TREAT) facility at Idaho National Laboratory (INL) [34, 35], using unirradiated SiC/SiC composite tubes, both demonstrated encouraging results, indicating that the tube specimens maintained their geometrical integrity (Figure 13). The next step in the accident tests involves testing engineered SiC/SiC composite cladding under more realistic accident conditions to advance knowledge regarding the relevant phenomena and to develop mechanistic models based on composite fracture mechanics that can reproduce the quench and RIA test results.

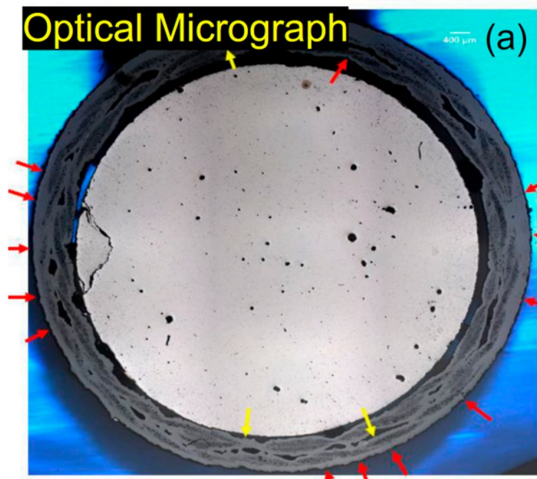


Figure 13. Cross-sectional optical micrograph of the SiC/SiC composite tube after TREAT irradiation tests using an unirradiated tube and fresh uranium silicide fuel [35].

(6) Advancing fuel performance models for SiC cladding systems is crucial for accelerating their development and deployment. Most finite element analysis (FEA) models treat the SiC/SiC composite tube as a uniform bulk and do not account for any nonuniformities in the cladding tube, such as pores and fiber bundles [10, 36]. Nevertheless, these models have proven useful for identifying critical feasibility issues, such as loss of hermeticity due to irradiation-induced strain [10] and bowing [36] and for directing the R&D of SiC cladding. Enhancing the FEA models will be important for accurately assessing cladding performance and optimizing the SiC/SiC composite architecture. Additionally, experimentally validated fuel performance models are considered a key element in accelerating fuel qualification and licensing [37].

The development of fuel performance models is intrinsically linked to separate effects tests and integrated tests because experimental validation of these models is critical. Comprehensive models are required for normal and accident environments involving multiphysics phenomena. Updating the material property handbook [38] will facilitate the advancement of model development. Test method standardization and code design must occur in parallel with data acquisition. A recent accomplishment in this area includes the first publication of ceramic composite design rules applicable to SiC/SiC composite core components and assemblies in high-temperature reactors, released in the 2019 edition of the American Society of Mechanical Engineers (ASME) Boiler Pressure Vessel Code Section III Division 5 [39]. Standardization of test methods for destructive and nondestructive tests, along with code development and analysis methodologies, is critical for supporting the qualification of SiC-based claddings.

Constructing high-fidelity models for SiC systems requires incorporation of the heterogeneous microstructure of SiC/SiC composites into the modeling framework while establishing connections between microscopic and macroscopic scale models. The current state of the art encompasses simulations

of material behavior under testing conditions, employing FEA models that are informed by the actual microstructure of the specimens (Figure 14) [40]. Additionally, constitutive modeling at multiple scales has been demonstrated to be effective for the thermo-physical and mechanical modeling of ceramic matrix composites. An initial attempt has been made to apply this approach to the SiC/SiC composite system (Figure 15) [41].

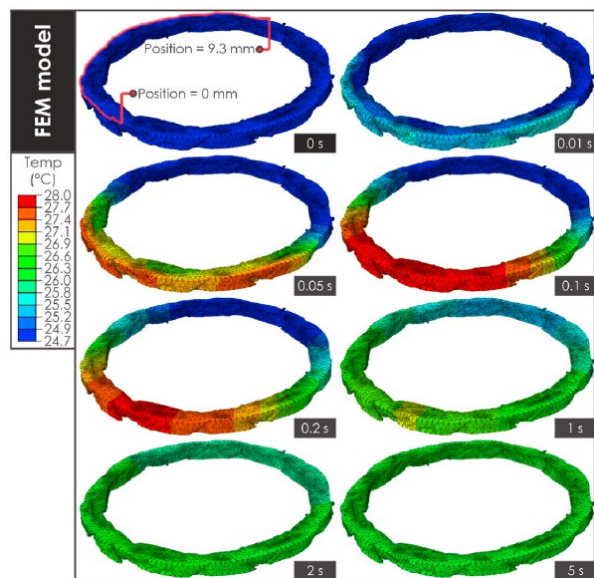


Figure 14. Image-based FEA simulation of thermal transport in a SiC/SiC composite tube. The X-ray computed tomography microstructure of the material was converted into the mesh structure used for modeling. The figure is reproduced from the literature [40].

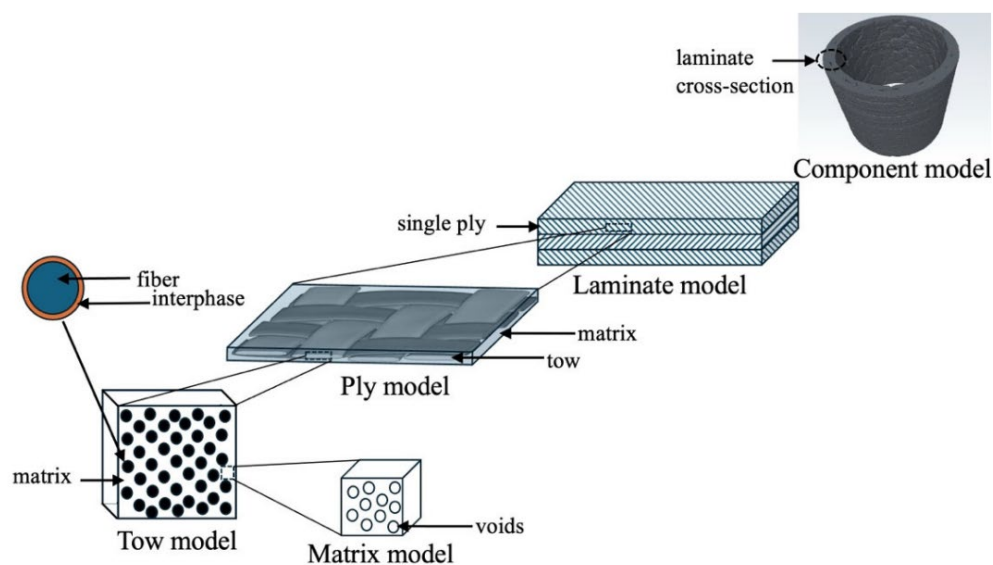


Figure 15. Hierarchical multiscale constitutive modeling approach for the SiC composite cladding system. The figure is reproduced from the literature [41].

### 3. R&D EXECUTION PLAN

This section delineates an R&D execution plan for SiC that is intended to complement the existing 5-year R&D strategy. The overarching goal of the 5-year project is to resolve key SiC technological issues preventing lead test rod deployment. The roles of the national laboratories encompass the following key responsibilities: (1) the development and maintenance of infrastructure necessary for fuel testing and qualification, (2) the execution of uniform and independent assessments of industry concepts, (3) the establishment of experimental and computational analysis methodologies, and (4) the exploration of engineering solutions aimed at mitigating key technical challenges and minimizing development risks. In this way, the labs are playing a critical role in supporting industry efforts to bring SiC/SiC composite technologies to the U.S. reactor fleet.

#### 3.1 Priority Activities and Expected Outcomes

The technical scope of the R&D at national laboratories under different frameworks directly or indirectly covers all key technology and knowledge gaps outlined in Section 2.2: (1) maintaining gas leak-tightness, (2) cost-effective manufacturing solutions, (3) hydrothermal corrosion mitigation, (4) predicting deformation behavior, (5) identifying failure limits under accidents, and (6) advancing fuel performance modeling tools.

The AFC laboratory activities rely on the unique expertise and capabilities at the national laboratories, which will take a scientific approach to experimentally and numerically analyze the technology gaps. The findings from the laboratory activities are feedback to the industry developments. Although these activities focus on all the identified gap areas, the testing and characterization tasks prioritize gaps (4) to (6), while considering other ongoing activities. The Industry ATF Funding Opportunity Announcement (I-ATF-FOA) programs address gaps (1) and (2) by conducting fueled irradiation of industry-specific concepts and relevant separate effects tests as well as by advancing manufacturability. To tackle gap (3), the in-pile corrosion testing facility at the MIT Reactor serves as key infrastructure for the community to address near-term corrosion challenges. The AFC laboratory activities involve the development of testing and analysis capabilities for I-ATF-FOA programs. Furthermore, these activities align with the technology hurdles that industry is currently facing. The following summarizes the high-level objectives of AFC laboratory activities and the expected outcomes to measure the progress and success of the R&D activities.

##### **Objective 1: Address challenges in SiC-based cladding performance under normal operating conditions.**

The work includes conducting nuclear testing to provide material data to advance the predictive capability of models of SiC-based cladding behavior. Based on the separate effects tests previously conducted, reactor testing will be advanced to investigate the interplay of individual material degradation mechanisms and generate the data necessary to investigate cladding damage processes and evaluate the failure probabilities of SiC/SiC composite cladding. Maintaining relevant infrastructure and developing new irradiation vehicles will be required. The expected outcomes will be (1) the development of irradiation and postirradiation examination (PIE) capabilities to support the evaluations of SiC/SiC composite materials and (2) the execution of targeted irradiation experiments in multiphysics environments to validate material properties and degradation models used for integrated fuel performance modeling. The proposed activities include updating and upgrading irradiation and PIE infrastructure for the Advanced Test Reactor (ATR) and the hot-cell facility at INL. For HFIR irradiation, a passive creep capsule and bowing test vehicle will be developed to address the data gap related to irradiation-enhanced slow crack growth and deformation under neutron flux gradients at LWR coolant temperatures.

**Objective 2: Identify the failure limit of SiC-based cladding under accident conditions.**

Failure limits under simulated LOCA and RIA conditions will be investigated. A significant knowledge gap exists regarding the resistance of SiC/SiC composite cladding to LOCA quench and pellet-cladding mechanical interaction under RIA conditions. To advance the current state of knowledge, the specific goal of this task is to assess the accident resistance of neutron-irradiated SiC/SiC composite tubes, informing the test matrix and parameters for fully integrated accident tests in the TREAT facility with irradiated fuel and cladding. The activities include the necessary capability development for the TREAT facility and the Severe Accident Test Station (SATS) at ORNL to enable testing of irradiated SiC rods under simulated accident conditions. Coordination will also be necessary to generate irradiated SiC tube specimens. Additionally, the development of a data analysis methodology will be necessary to capture material deformation and damage processes at multiple length scales to help establish mechanistic models for accident analysis. Accident tests using irradiated SiC tubes, such as those assessing LOCA versus RIA, will be prioritized based on an evaluation of technological challenges, the readiness of testing and analysis tools, and the potential benefits for qualification activities.

**Objective 3: Advance and Validate Fuel Performance Model.**

Advancing the thermo-physical and mechanical cladding behavior models will be important for accurately assessing cladding performance (e.g., failure probability), interpreting nuclear testing results, and optimizing the SiC/SiC composite design and architecture. This work will focus on accounting for the heterogeneity of the SiC/SiC composite microstructure and the anisotropic physical and mechanical properties of the composite materials to develop high-fidelity material behavior models. For comprehensive fuel performance modeling, BISON and its capabilities are critical for successfully conducting large-scale integrated fuel performance simulations to assess SiC/SiC composite materials as a viable LWR cladding concept as well as for deriving solutions that assist in deployment. Therefore, the BISON code will receive upgrades applicable to the SiC-based cladding system. The deliverables supporting the modeling activities include an updated material property handbook along with a database management plan. Currently, the Nuclear Data Management and Analysis System (NDMAS) is planned to serve as a framework to manage and preserve data collected from SiC R&D activities.

These three objectives are connected, as shown in Figure 16. The advanced fuel performance capabilities will be used to assess cladding performance and optimize composite microstructure and fuel rod design. Integrated tests and updates to the material property handbook for the latest grade of cladding are essential to ensure the applicability of the material models. Integrated tests are defined as a type of test in which specimens are exposed to an LWR application-relevant environment that involves the interplay of multiphysics phenomena. For example, pellet-cladding interactions may involve chemical and mechanical interactions as well as synergistic effects (e.g., stress corrosion cracking).

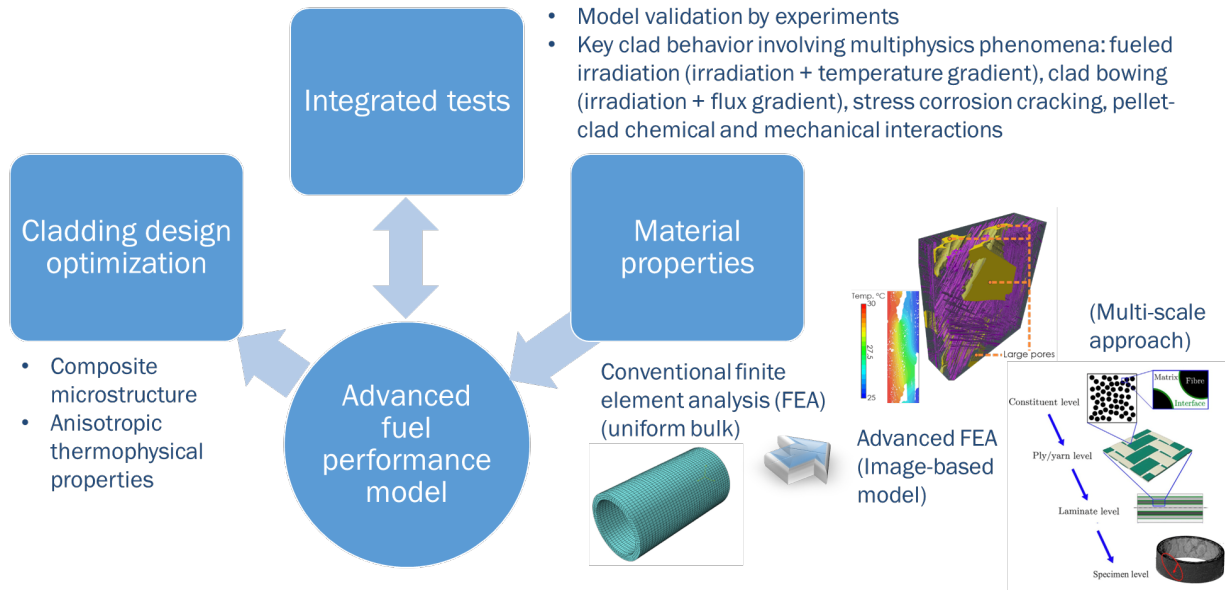


Figure 16. A schematic of the high-level structure of the ATF SiC development activities.

## 3.2 Proposed Work Packages and Milestones

### 3.2.1 Work Package Category

The laboratory R&D for SiC-based cladding development is covered under two types of work packages: “Cross-cutting SiC R&D,” which focuses on material testing and model development, and “Experimental Capabilities for SiC,” which supports the development of the necessary test capabilities and infrastructure to aid both national laboratory and industry efforts. The scope and description are provided below.

#### Cross-cutting SiC R&D

The SiC cladding R&D efforts will concentrate on the cross-cutting development of SiC/SiC composites for ATF applications. The primary focus will be on evaluating and enhancing the R&D capabilities necessary for the continued progression of this technology.

Targeted technical R&D activities will commence at the national laboratories to complement the industry-led programs. These activities will address current opportunities and work toward resolving the most pressing cross-cutting technical challenges. Specifically, the initiatives will focus on advancing fuel performance modeling and experimental validation. The capabilities developed in advanced fuel performance prediction will be instrumental in evaluating cladding performance, optimizing composite microstructures, refining fuel rod design, and supporting design optimization for emerging applications.

The testing and development of SiC/SiC technology for specific ATF applications will be supported through direct work packages under the industry-led FOA funding.

#### Experimental Capabilities for SiC

The scope of this activity covers the development of fabrication, characterization, irradiation testing, and PIE capabilities specific to the testing of integral (rod-like) SiC/SiC composite cladding test pins developed by industry-leading teams in the SiC area. Due to the nature of the ceramic cladding, these pins often require special handling procedures and may necessitate a different focus in testing objectives than their metallic cladding counterparts. Specific work packages will concentrate on the development of capabilities for testing SiC/SiC composite rodlets in the ATR, at the TREAT reactor, in HFIR, and at the SATS facility.

Work at ATR will include the development of a test plan that allows for the testing of fuel pins with a higher risk of gap fraction leakage than traditional metallic-clad pins. At TREAT, the current water capsule, Transient Water Irradiation System for TREAT (TWIST), will be modified with a heater, and the safety basis will be updated so that testing can occur in a hot zero-power condition, enabling SiC cladding concepts with liquid metal backfill to be tested under realistic conditions. Modifications at SATS will include the development of pin handling and feedthroughs to allow for testing the pins in prototypical LOCA conditions.

Following the closure of the Halden Reactor and the subsequent end to the Halden Reactor Project, significant new irradiation testing infrastructure was deemed necessary to support, in the near term, the ATF program objectives and, in the long term, the sustainability of LWRs. The community identified that the US LWR Testbed for irradiation of fuels and materials required the following: (1) expanded water loop facilities for irradiation testing, (2) LOCA testing capability, (3) access to modern in-pile instrumentation capabilities for fueled experiments, and (4) refabrication and instrumentation capabilities for previously irradiated fuel samples. The ATR I-loop concept was developed to satisfy the first need. Two loops are being designed to enable testing under PWR and BWR operating conditions. In-pile instrumented HFIR irradiation for unfueled SiC/SiC composite material testing is being designed to support the third need.

**3.2.2 Work Packages for SiC R&D**

To accomplish the three overarching program objectives discussed in Section 3.1, four distinct work packages have been established. INL and ORNL are each responsible for one work package aligned with the areas of “Cross-cutting SiC R&D” and “Experimental capabilities for SiC,” as outlined in Table 1.

Table 1. Overview of work scope and associated work packages for INL and ORNL.

Scope	Work Package	Work Package ID
Cross-cutting SiC R&D	Experimentally Validated Multiscale Models for SiC – INL	EVMM–INL
	High Performance SiC Cladding Development – ORNL	HPCD–ORNL
Experiment capabilities for SiC	TREAT and ATR capabilities – INL	TA–INL
	SATS and HFIR capabilities – ORNL	SH–ORNL

The following subsections summarize the anticipated Level 2 Milestones (M2) for FY 2026 and subsequent years. Each work package is designated to fulfill at least one M2 per year. Furthermore, activities that support the priority activities and corresponding M2 are also documented. The ID of the corresponding work package in Table 1 is also included. To remain consistent with the 5-year strategy document [1], the planning was conducted through FY 2028. Reaching the proposed milestones outlined in Table 2 will lead to achieving the three main objectives summarized in Section 3.1.

Table 2. Proposed Level 2 milestones for the AFC laboratory activities.

Objectives	FY 2025	FY 2026	FY 2027	FY 2028
Addressing normal operation issues	High-temperature SiC clad bowing test design (ORNL)	HFIR irradiation testing capability development – creep and bowing tests (ORNL)	Evaluation of bowing of SiC tubes (ORNL)	
Failure limit under accidents	SiC in TWIST (INL)  SiC tube fabrication for accident tests (ORNL)	Design package for new TWIST design with steam (INL)	Commissioning RIA test for fresh SiC fuel rod in TREAT (INL)  Quench and modified burst tests of the latest grade SiC tubes (ORNL)	Transient test for irradiated SiC tubes in TREAT and SATS (INL and ORNL)
Advanced fuel performance modeling	Multi-scale modeling status (INL)	Experimental validated multiscale thermal property model for BISON (INL)  Modeling framework for SiC-end plug and PCMI (ORNL)	BISON upgrade for SiC (INL)	NDMAS for SiC (INL)  Updated material handbook (ORNL)

### 3.2.2.1 Cross-Cutting SiC R&D

#### FY 2026

- M2: Experimentally validated multiscale thermal property model for BISON (EVMM–INL)

Accurate predictions of the thermal properties of SiC/SiC composites are critical input for the BISON code. The thermal properties of the composites depend not only on operating temperature and neutron fluence but also on the composite structure, type of fibers, and processing methods. The development of a predictive model needs to be based on multiscale FEA models that can be integrated into BISON. More importantly, the model will be validated first through experiments involving relevant SiC/SiC composite tube materials.

- M2: Modeling framework for SiC end plug and pellet–cladding mechanical interactions (HPCD–ORNL)

Mechanistic models are lacking in the current fuel performance tools used to design the end-plug geometry and joints as well as to predict the response to reactor environments. This milestone aims to present a methodology for conducting numerical analyses of mechanical damage in SiC end plugs subjected to neutron irradiation. Using an image-based modeling approach, the proposed model will account for the heterogeneous microstructure observed in experimental investigations. This approach will facilitate the interpretation of results from fueled irradiation experiments and provide critical input for full-core analysis. Furthermore, by employing a comparable image-based methodology, models of microscopic-scale pellet-cladding mechanical interactions will be developed. The primary focus will be on replicating cladding deformation resulting from hard contact between a surrogate fuel and a representative SiC/SiC composite tube because this significant phenomenon is not currently addressed within the BISON code.

- Activity: Planning accident tests of irradiated SiC tubes under the laboratory work package (EVMM–INL, HPCD–ORNL)

To ensure the most efficient and effective accident tests of irradiated SiC specimens at the TREAT and SATS facilities, we will discuss the potential test matrix and the necessary preirradiation testing needed to inform the experimental plan. The current knowledge gap involves the quenching behavior and RIA-like

pellet–cladding mechanical interactions of SiC cladding systems. This discussion will focus on prioritizing these two tests.

- Activity: Risk-informed modeling, economical and accident analysis for SiC for LWRs (EVMM–INL)

The safety and operational benefits of SiC cladding are not fully understood, hindering its deployment. In collaboration with the iNERI project led by Brookhaven National Laboratory, risk-informed modeling and BISON modeling will be conducted to quantify the safety and operational benefits of SiC for current LWR fleets as well as for LWR-based small modular reactor concepts. This study is critical to the business case for SiC cladding and its economic viability.

#### FY2027

- M2: BISON upgrade for SiC (EVMM–INL)

By taking the building blocks from multiscale models, the SiC BISON code will be upgraded with improved predictive thermal properties. Further enhancements include mechanical properties, failure predictions, and effects of irradiation.

- M2: Evaluation of bowing of SiC tubes (HPCD–ORNL)

Based upon the success of the bowing experiment at the HFIR coolant temperature (~60°C), the follow-up PIE will be conducted on bowing behavior of SiC/SiC composite tubes at LWR relevant temperature of about 300°C under neutron flux gradient in HFIR.

#### FY2028

- M2: NDMAS for SiC (EVMM–INL)

The SiC database will be constructed in NDMAS and will consist of all irradiation and PIE data from test reactors such as ATR, HFIR, MIT Reactor, Belgian Reactor 2, commercial reactors, and others. This comprehensive database serves as the foundation for SiC fuel licensing and qualification and is critical for the accelerated fuel qualification effort for SiC.

- M2: Updated material handbook (HPCD–ORNL)

An updated material property handbook for SiC/SiC composite tubes will be produced. This handbook will compile historical and recent thermo-physical and mechanical property data pertaining to relevant SiC/SiC composite materials. Furthermore, mechanistic material property models will be provided as input for BISON fuel performance modeling. Guidance on the appropriate use of the property data will be provided. Bridging the mechanical properties of a segment of tube and a full-length rod will be key.

### **3.2.2.2 Experiment Capabilities for SiC**

#### FY 2026

- M2: Design package for new TWIST design with steam (TA–INL)

Currently, prototypical RIA or LOCA tests cannot be performed in TREAT for fueled SiC rods. To fill this capability gap, the current TWIST design will be upgraded to include a preheating capability, a flowing steam capability, and a quenching capability. The upgraded TWIST design will be finalized in FY 2026, in anticipation of fresh SiC fuel rod tests in FY 2027, followed by preirradiated ATR rods in FY 2028.

- M2: HFIR irradiation testing capability development (SH–ORNL)

Slow crack growth under irradiation is a significant data gap necessary for assessing the failure probability of SiC/SiC composite cladding. A final design of a passive irradiation creep vehicle for irradiation in HFIR will be delivered, and out-of-pile testing will be conducted as part of the approval

process for HFIR insertion. Additionally, the status of the high-temperature bowing experiment in HFIR will be reported. The design of the irradiation vehicle is being developed in FY 2025. This irradiation task is intended not only to evaluate the bowing of SiC/SiC composite tubes but also to provide irradiated specimens for accident tests at the SATS facility.

- Activity: ATR I-loop final design

Because of the lack of BWR loop and ramp testing, the ATR I-loop is highly anticipated by the ATF community. A final design of the I-loop will be delivered.

#### FY2027

- M2: Commissioning transient test for fresh SiC fuel rod in TREAT (TA-INL)

The first SiC fuel rod safety test will be performed at TREAT using the latest grades of SiC rodlet samples. The test conditions will be determined based on inputs from industry partners, results from relevant separate effects tests, and the economic and safety benefit studies from the iNERI project.

- M2: Quench and modified burst tests of the latest grade SiC tubes (SH-ORNL)

As-fabricated engineered SiC/SiC composite tubes will be subjected to LOCA quench and modified burst tests to inform the test matrix and experimental parameters for the accident tests of irradiated SiC/SiC composite tubes in the following year. This activity is tied to the assessment of the model's predictive capability for fracture behavior during the experiments.

- Activity: BWR test at ATR I-loop

Testing of SiC under relevant coolant conditions is crucial for BWR fuel cladding and channel box applications. The first ATR I-loop test is planned to be conducted using SiC provided by the ATF community. Corrosion mitigation for BWR water chemistry is required before the I-loop testing can be conducted.

#### FY2028

- M2: Transient tests for irradiated SiC tubes in TREAT and SATS (TA-INL and SH-ORNL)

This joint milestone aims to facilitate a demonstration of the capability for complementary accident tests involving irradiated SiC/SiC composite tube specimens at the TREAT and SATS facilities. The experimental conditions and test matrix will be informed by findings from the previous year's tests of fresh SiC/SiC composite tubes. The outcomes of this milestone are expected to provide critical feedback to refine the test plan for fully integrated accident tests involving irradiated fuel and SiC/SiC composites as part of the vendors' program.

- Activity: Ramp test at ATR I-loop (TA-INL)

The capability to conduct ramp tests for SiC rodlets will be demonstrated. This activity aims to investigate the effects of various operational offsets, including pellet-cladding chemical and mechanical interactions. The capability will be critical in supporting the industry-led R&D program, and the data will play important roles in licensing and qualifying SiC cladding materials and optimizing fuel rod designs.

### **3.2.2.3 Suggested budget profile**

Continuing funding support will be needed to advance SiC-based cladding technology to facilitate lead test rod insertions and achieve the proposed milestones described above. In FY 2025, a total of \$9 million has been allocated for laboratory research activities and the development of irradiation and PIE capabilities. For planning purposes, an allocation of about 50% of the FY 2025 funding is assumed for the budget of FY 2026 and beyond. With this reduced budget scenario, activities related to both "Cross-cutting SiC R&D" and "Experimental Capabilities for SiC" will be necessary to support priority activities (Table 3).

Table 3. AFC appropriated budget for FY 2025 and future targets for FYs 2026–2028 for SiC R&D laboratory activities. The IDs of the work packages are explained in Table 1.

Work Package	FY 2025	FY 2026	FY 2027	FY 2028
Cross-cutting SiC R&D: EVMM–INL	\$1.3M	\$0.7M	\$0.7M	\$0.7M
Cross-cutting SiC R&D: HPCD–ORNL	\$1.7M	\$0.9M	\$0.9M	\$0.9M
Experiment Capabilities for SiC: TA–INL	\$5M	\$2.5M	\$2.5M	\$2.5M
Experiment Capabilities for SiC: SH–ORNL	\$1M	\$0.5M	\$0.5M	\$0.5M

### 3.2.3 Additional Activities

If additional funding becomes available exceeding the 50% assumption of FY 2025 funds, the R&D of SiC cladding will be expedited. This section describes additional activities that align with the key objectives in Section 3.1 but are not covered by the funding detailed in Table 3. The additional activities are summarized for each category of work package.

#### 3.2.3.1 Cross-Cutting SiC R&D

- PIE of SiC/SiC composite tube specimens irradiated in the MIT Reactor

Additional PIE, particularly advanced microscopy and other microstructural analyses, will be needed to assess the hydrothermal corrosion of SiC and to advance the corrosion models. PIE for the MIT Reactor irradiated specimens is proposed at both INL and ORNL to conduct complementary material characterizations. Specimens irradiated under the vendors’ programs will be subjected to investigation.

- SiC irradiation campaign for the Second Framework for Irradiation Experiments.

A proposal for a HFIR irradiation campaign for SiC cladding concepts is being put forward for the Second Framework for Irradiation Experiments under the coordination of the Nuclear Energy Agency. This activity complements ongoing AFC research. These irradiation experiments will involve screening various engineered SiC materials, which will be provided by international participants, to address the technology challenges outlined in Section 2.2. If the proposal is awarded, then this activity will be elevated to a priority task for the AFC in FYs 2027 and 2028.

- Corrosion mitigation for BWR applications

Hydrothermal corrosion of SiC under BWR water chemistry requires material solutions. Improvement of corrosion and irradiation resistance of the environmental barrier coating on outer surfaces of SiC cladding is proposed. Demonstration of corrosion and irradiation resistance by separate effects experiments will be required before integrated tests in the ATR I-loop can be conducted.

- Test method standard and ASME code development

Test method standards and code design activities will be crucial for generating quality test data for licensing. Test method qualification must be addressed. The methodology development will involve engagement with the ASTM Committee C28 on Advanced Ceramics. Round-robin testing among academic and industrial institutions is a typical activity in the process of developing a test method standard.

### 3.2.3.2 Experiment Capabilities for SiC

- Enhancing capabilities at ATR and the TREAT facility

Establishing an escrow fund for loop cleanup allows ATR to take higher risk of test rod leak and accelerate the irradiation tests for SiC. The TREAT Water Environment Recirculating Loop (TWERL) is a prototypical flowing water loop capability for TREAT, which enables the true representative thermal-hydraulic conditions for SiC rods in accident progression.

- NDMAS database

The funding currently assumed will support only the foundational stages of NDMAS database development. Additional funding will facilitate acceleration of the database development process, enable the incorporation of extended data from a range of test reactors, and demonstrate enhanced data access and analysis capabilities.

- HFIR irradiation capabilities

In-pile irradiation of SiC/SiC composites under applied stress will contribute to the accelerated qualification of the cladding by enabling quicker nuclear data acquisition. To accelerate the development, additional irradiation capability for in-pile pellet-cladding interaction testing with surrogate fuel will be beneficial to support the fueled irradiation in the ATR. Additional funding will support the development of the design, out-of-pile testing, and the irradiation experiments. Furthermore, HFIR can generate long SiC/SiC composite tubes for the accident tests: an existing full-length HFIR irradiation target design for metallic fuel rods can be modified for SiC rods.

- Development of a passive thermometry technique for SiC cladding

The distribution of irradiation temperature within SiC rods in test reactors is critical information for data analysis. This information is particularly important for fueled irradiation, which causes a through-thickness temperature gradient in the rods. This work aims to develop a method for locally probing irradiation temperature using spectroscopic techniques. The foundation for this method has been established [42], but it requires improvements before being applied to engineered SiC/SiC composite tube materials.

## 4. SYNERGISTIC ACTIVITIES

### 4.1 Industry-Led Programs

To ensure timely development of SiC/SiC composite technologies for the U.S. LWR fleet, coordination between lab activities and industry-led technologies is essential. The identified technology gaps, as detailed in Section 3.1, and the execution plan proposed in this document reflect the assessment and prioritization of these gaps as agreed upon by laboratory and industry stakeholders. To ensure ongoing alignment between lab activities and industry needs, the testing and modeling activities will incorporate input and test material from industry-leading SiC/SiC concepts to close technology gaps and help advance SiC/SiC technology toward full-length commercial testing before the end of this 5-year execution plan.

This effort is facilitated through the execution of fueled irradiation experiments of industry-specific concepts, alongside advancements in manufacturability. Fueled irradiation and corresponding separate effects nuclear testing are typically conducted using the LWR testbed at the AFC national laboratories. The results obtained by the AFC during the technology evaluation period (Figure 1) have revealed the technological hurdles that must be addressed by improving material properties and engineering designs, which have stimulated the generation of SiC/SiC composite cladding concepts unique to each individual company. The collaborative activities between the AFC and the industrial sector, particularly among entities participating in the I-ATF-FOA programs, exhibit a synergistic relationship whereby both parties provide reciprocal feedback to ensure concordance regarding the most pressing technological challenges.

Furthermore, capability development under the AFC should be strategically aligned with the I-ATF-FOA irradiation campaign to facilitate the provision of essential characterization tools for irradiation and PIE.

## 4.2 Fuel Performance Modeling Activities

Toward the objective of developing an advanced fuel performance model for SiC-based cladding systems, this section outlines the coordination strategy involving the various modeling efforts. Experimentally validated fuel performance modeling is a crucial component of SiC R&D aimed at providing a tool that delivers material property solutions (Figure 16).

Currently, the modeling activities are directed toward advancing the fuel performance code and associated models to establish a framework for integrating the various elements, thus facilitating model predictions of SiC cladding behavior in reactor environments. The efforts are coordinated synergistically, with each participant fulfilling a distinct role, as schematically illustrated in Figure 17. For instance, the work package under the AFC program at INL undertakes essential modifications and updates to the BISON code to accommodate the SiC-based cladding system. The BISON code has been used by multiple researchers to assess SiC cladding and channel box systems [11, 36] and is continually being enhanced to integrate mechanistic models specifically to SiC/SiC composites. The research conducted by the AFC at ORNL prioritizes the development of lower-scale models that are essential for the integrated fuel performance model and are not adequately captured in the current BISON code. This work involves targeted material testing and irradiation experiments designed to generate mechanistic models of material behavior. For example, the bowing experiment illustrated in Figure 11 was performed to validate the applicability of the dose- and temperature-dependent swelling model to representative SiC/SiC composites, given that the swelling model was derived from data obtained from reference SiC/SiC composites [14]. The material data and property models are compiled and maintained in the SiC-cladding material property handbook [38]. The development activities in industry require thermo-mechanical material behavior models to design cladding and assess industry-specific engineered cladding concepts for targeted applications. The model frameworks documented in the literature address the mechanical behavior of SiC/SiC composite tubes [43-45]. Models that have been validated through mechanical testing have contributed to the optimization of layer design and processing parameters, including fiber architecture and other aspects of composite manufacturing.

Overall, those initial modeling efforts focused mainly on separate effects to advance knowledge of the response of SiC/SiC composite tubes to specific and controlled environments. The modeling activities are associated with relevant experimental material investigations for material development and the elucidation of material damage processes. Therefore, the development and validation of individual physical and chemical models are effective for individual R&D tasks. The modeling activities have been coordinated to ensure that all critical material behaviors are being investigated and modeled within the community. In this coordination, the Nuclear Energy Advanced Modeling and Simulation (NEAMS) program plays a role in providing consultation and resources for the BISON upgrade as well as relevant modeling tools and methodologies that have been developed under the NEAMS program.

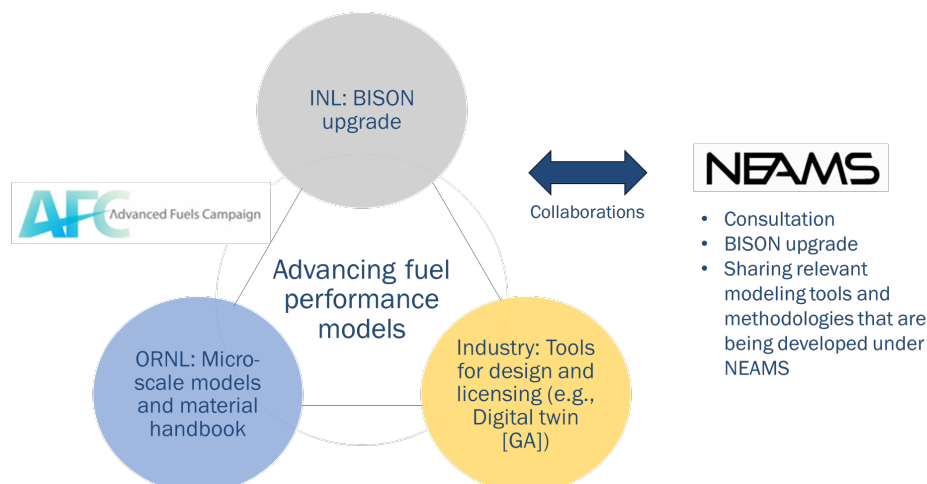


Figure 17. Initial coordination structure for advancing fuel performance models for SiC-based cladding.

As the behavior of SiC/SiC composite materials—including mechanical behavior, fundamental radiation responses, and corrosion—is being understood and reproduced through numerical analysis, the integration of models using BISON codes will become more proactive. Meanwhile, efforts will continue to address the remaining needs for lower-length-scale models, such as those focused on pellet-cladding mechanical interactions. Figure 18 illustrates the proposed coordination for the model integration efforts. In this context, integration refers to upgrading the BISON code and the associated model framework by incorporating individual material behavior models for SiC. A dedicated working group comprising the SiC R&D leadership from both the AFC and NEAMS programs will assume stewardship and be accountable for the development and coordination of research efforts, including obtaining feedback from industry partners. This consolidated resource, characterized by its expertise and advanced modeling tools, will facilitate effective communication and foster collaboration between programs. The anticipated responsibilities of this leadership include assistance with the development of a design and test matrix for nuclear testing, which includes steady-state irradiation in the ATR and HFIR as well as transient tests in the TREAT and SATS facilities, with the objective of acquiring experimental data valuable for the validation of the integrated modeling tool. The leadership within the working group is also tasked with the collection of lower-length-scale models and their adaptation to the BISON code. Furthermore, the most recent iteration of the modeling tool will be made available to industry partners through the leadership team. The mechanisms and leadership for the integrated model development will be pursued in consideration of ongoing progress in the model development and the available resources.

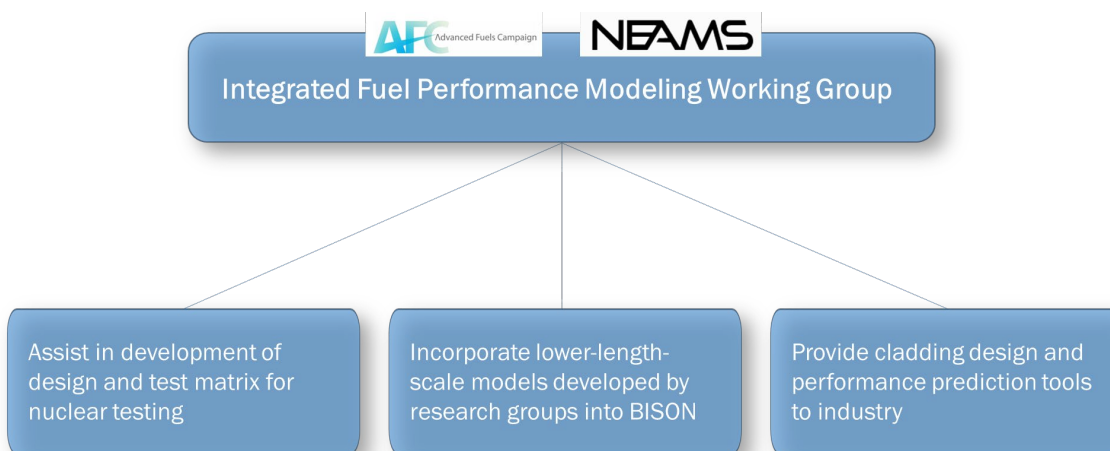


Figure 18 Proposed coordination for the development of integrated fuel performance model for SiC-based cladding.

### 4.3 University-Led Programs

Table 4 summarizes the SiC cladding research currently supported by the Nuclear Energy University Program. This university program complements the national laboratory activities and plays a role in training the next generation of talent. The national laboratory principal investigators will continue to support the projects by providing feedback through quarterly and annual reports and sharing the most up-to-date technological challenges in the area of SiC R&D. When innovative materials and numerical analysis tools are developed, they will be considered for application to nuclear testing under the AFC.

Table 4 List of active university-led programs on SiC-based cladding research.

Project title	Lead institution
(Project 23-29106) Physics-Informed Artificial Intelligence for Non-Destructive Evaluation of Ceramic Composite Cladding by Creating Digital Fingerprints	University of Florida
(Project 23-29826) Facile manufacturing of fiber-reinforced-SiC/SiC composite using aerodynamic fiber deposition (AFD) and metal assisted polymer impregnation and pyrolysis processes (MAPIP)	University of Pittsburgh
(Project 23-29455) Thermal-Hydraulics Assessment of SiC Compared to Other ATF Cladding Materials and its Performance to Mitigate CRUD	University of Wisconsin–Madison
(Project 24-31464) Understanding the Performance of SiC-SiCf Composite Cladding Architectures with Cr Coating in Normal Operating and Accident Conditions in LWRs and Advanced Reactors	University of Wisconsin–Madison

Establishing further capabilities and expertise at universities conducting SiC research would benefit the efficient execution of the SiC development plan. Below are proposed potential university program subjects based on the remaining technology gaps to be addressed through fundamental science.

- Hydrothermal corrosion of SiC under BWR conditions

Dissolution of SiC in operating environments combining oxidative water chemistries and water radiolysis is a critical feasibility issue for SiC-based fuel and core components in LWRs. The current understanding is that corrosion mitigation strategies must be provided for the BWR environment. The corrosion mechanism and the mitigation strategies specific for BWR applications are potential research subjects.

- Cost-effective manufacturing of SiC/SiC composites

An economically viable manufacturing process for nuclear-grade SiC/SiC composite cladding and core structures must be developed. The SiC/SiC composite must be fully crystalline and near stoichiometric to withstand irradiation damage and corrosion attacks. The scope of the processing includes matrix densification, fiber production, interphase deposition, fiber preforming, and end-plug joining.

## 5. SUMMARY OF THE EXECUTION PLAN

The SiC R&D execution plan will guide the AFC laboratory activities to support the industry's lead test rod deployment programs. The project plan prioritizes experimental and modeling activities to address critical limitations of SiC-based cladding technologies and the capability developments needed to support vendors' cladding qualification programs. This execution plan has been crafted with input from the ATF SiC community, including both industry and academia, to address the community's needs and synergize with other relevant programs and projects.

Among several priority R&D subjects, the demonstration of hermetic cladding and its end plug under normal operating conditions is the most critical task before conducting lead test rod insertions. Technological challenges in normal and off-normal operating environments will be addressed using experimentally validated advanced fuel performance modeling tools. This capability will be crucial for designing nuclear tests, interpreting reactor test results, optimizing cladding design, and providing material prosperity solutions.

This execution plan will be maintained and updated to accommodate the dynamically evolving progress of development, capability needs, and resource availability.

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