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Updated Probabilistic Failure Analysis for Wound Composite Ceramic Cladding Assembly

J. G. Hemrick and E. Lara-Curzio

March 2013

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J. G. Hemrick
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Materials Science and Technology Division

UPDATED PROBABILISTIC FAILURE ANALYSIS FOR WOUND COMPOSITE CERAMIC CLADDING ASSEMBLY

J. G. Hemrick
E. Lara-Curzio

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1. INTRODUCTION

There is sustained interest in advanced ceramics and ceramic matrix composite assemblies based on silicon carbide (SiC) for nuclear fuel cladding applications in light water reactors (LWRs). SiC is known to possess high strength, reasonable thermal conductivity, and low chemical reactivity at high temperatures. These combined good properties are especially attractive when compared to those of traditionally used zirconium alloys such as Zircaloy^{TM} for the aforementioned applications. It is therefore expected that based on these properties, SiC composite assemblies could act as nuclear fuel cladding which would remain intact and safe during and after long periods of time at very high temperatures, such as what is seen in loss-of-cooling accident (LOCA) events at nuclear reactors or spent fuel pools. Additionally, the low chemical reactivity of SiC is expected to mitigate oxidizing reactions that break down water molecules producing free hydrogen gas that is not only potentially explosive, but may embrittle tubes (such as the formation of zirconium oxide and hydride in zirconium alloys).

Proposed concepts for SiC-based fuel cladding include a monolithic SiC cylinder surrounded by carbon-coated SiC fibers woven into a tubular form and infiltrated (by chemical vapor deposition) with SiC, infiltrated tubular woven carbon-coated SiC fibers surrounded by thin monolithic layers of SiC on both sides, and hybrid assemblies consisting of both metallic elements and ceramic matrix composite elements potentially containing a monolithic SiC layer. Additionally SiC coatings on the outermost surface of these assemblies are also being considered to prevent hydrothermal corrosion of the fibrous structure [1]. For any of these concepts, there is a need to gain understanding of microcracking/failure behavior and an adequate method to evaluate the probability of failure. Thus, such an approach offers the promise of higher burn-up rates and safer behavior in the case of LOCA events, the reliability of such ceramic-based structures still needs to be critically examined, in particular its ability to reliably retain fission products under normal operation. Therefore, probability failure analysis studies are needed to prove the feasibility of these design concepts.

2. BACKGROUND

As reported previously [2], the aforementioned approaches offer the promise of higher burn-up rates and safer behavior in the case of LOCA events, but the reliability of such ceramic-based structures needs to be demonstrated in advance. Specifically, an underlying assumption is that SiC-based cladding should not fail at a greater rate than present-day zircaloy-based cladding (approximately one per million tubes.) Failure in this context is defined as loss of fission products from the cladding tube to the reactor environment. Therefore, it was previously proposed to perform a probability failure analysis study of such monolithic-composite hybrid structures to determine the feasibility of these design concepts followed by probability failure analysis to predict the performance of candidate materials and systems in an effort to determine the feasibility of these design concepts and to make future recommendations regarding materials selections.

Based on the results obtained under the original effort, several additional tasks were identified for completion under continuation of this project. These included:

1. The evaluation of a greater number of test specimens in hopes of improving the confidence bounds on the Weibull statistics generated under the project.
2. Performance of fractography on additional plug specimens from tests carried out under a revised protocol to improve retention of test specimen fragments after failure in a more complete manner and fractographic analysis of diametral compression specimens.
3. Additional Weibull analyses carried out using multiple flaw populations identified though fractographic analysis.
4. Mechanical testing of β-SiC tubes for comparison to the previously evaluated α-SiC materials.
5. Evaluation of additional SiC composite system tubular materials including newly identified materials and additional samples of the previously studied Ceramic Tubular Products Triplex Composite SiC material for improvement of the statistics and evaluation of this material.
6. Finite Element Analysis (FEA) performed based on previously computed stress states for the monolithic inner cylinder of a hybrid monolithic-composite SiC fuel cladding system using the range of values of characteristic strength and Weibull modulus of materials experimentally determined under this project to identify properties needed to meet allowable determined failure rates.

3. APPROACH

3.1 PREVIOUS WORK

The initial efforts [2] resulted in the determination of strength estimates and Weibull statistics for α-SiC tubular material (Saint-Gobain Hexoloy SE SiC Tube, 2012 Vintage) and SiC composite system tubular material received from Ceramic Tubular Products, LLC (Rockville, MD). The experimentally generated α-SiC data was also compared to previous results generated on Saint-Gobain Enhanced Hexoloy SA (2001 Vintage) material. Evaluation of α-SiC materials was carried out based on tensile, expanded plug, and flexure test data while only expanded plug testing was carried out on the composite material.

Existing tensile test data previously generated at ORNL for Saint-Gobain Enhanced Hexoloy SA (2001 Vintage) material was used as baseline data for this study [3]. Tensile properties and Weibull statistics for this material were generated based on a twenty test specimen sample resulting in a characteristic strength of 320 MPa and a Weibull Modulus of 10.0.

Experimental test data generated on 17 test specimens (average calculated circumferential stress of 121.71 MPa with a 24.90 standard deviation) was used to generate Weibull statistics for α-SiC tubular material (Saint-Gobain Hexoloy SE SiC Tube, 2012 Vintage) under internal pressurization conditions. A characteristic strength of 132 MPa and a Weibull Modulus of 5.3 were determined for this material under these loading conditions as shown in Fig. 1.

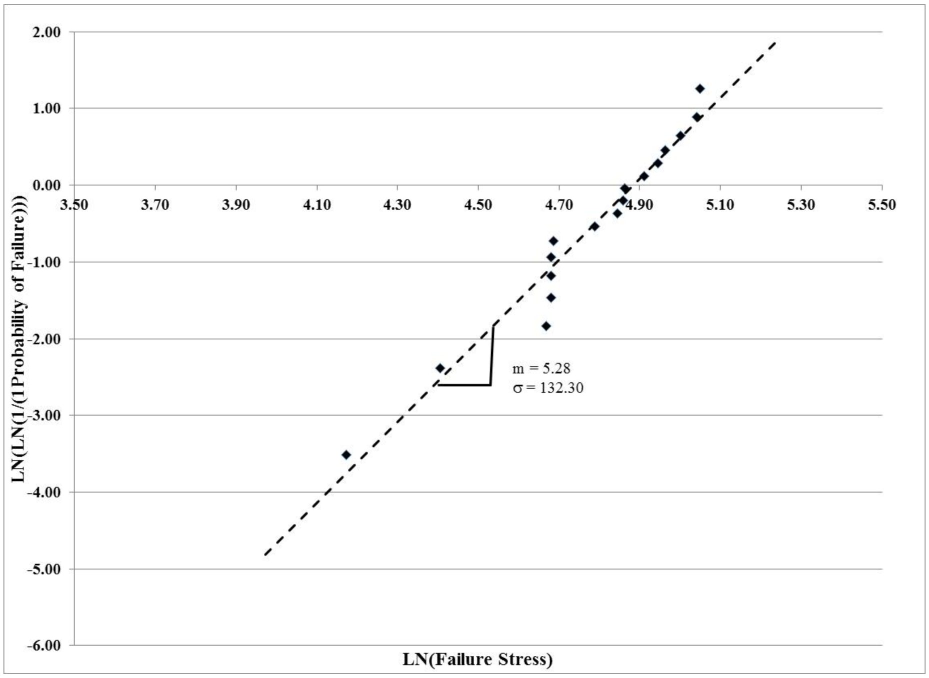

Fig. 1. Weibull Plot for Hexoloy α-SiC Under Internal Pressurization Conditions.

Experimental test data generated on five test specimens (average calculated failure stress of 249.42 MPa with a 7.52 standard deviation) was used to generate Weibull statistics under diametral compression flexure testing for the same α-SiC tubular material tested under internal pressurization conditions. A characteristic strength of 253 MPa and a Weibull Modulus of 31.7 was determined for this material under these loading conditions as shown in Fig. 2. It should be noted that these statistics were generated based on only five tests leading to an upper bound of 46.4 and lower bound of 11.4 on the Weibull Modulus estimate calculated (90% confidence interval).

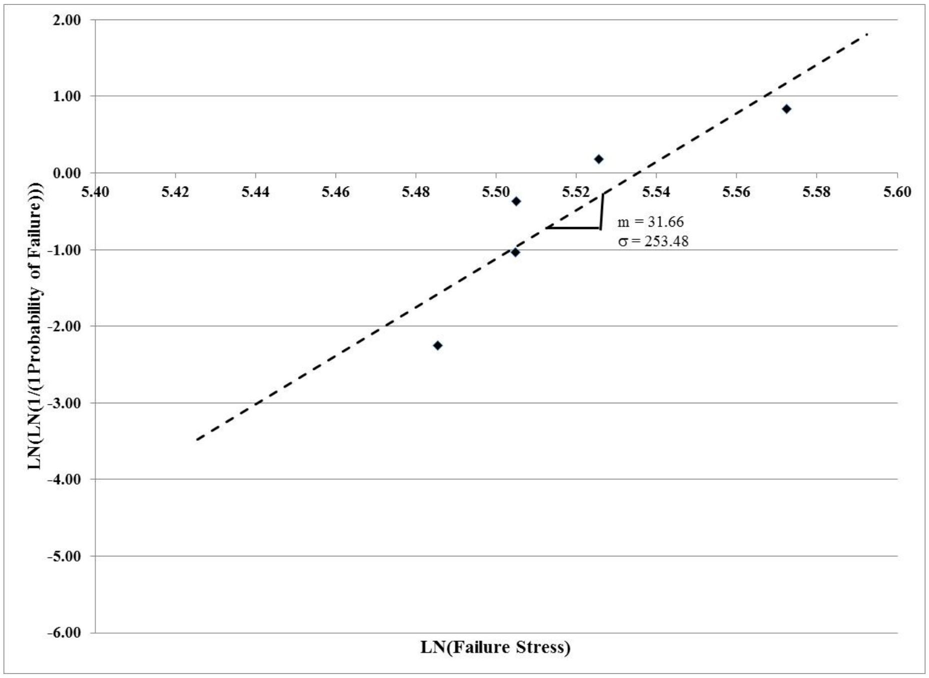

Fig. 2. Weibull Plot for Hexoloy α-SiC in Diametral Compression Flexure.

Experimentally generated data were also compared with previous strength data generated on Saint-Gobain Enhanced Hexoloy SA (2001 Vintage) material in flexure using both a c-ring and sectored flexure test methodology [3]. C-ring testing of 18 test specimens resulted in a characteristic strength of 299 MPa and Weibull modulus of 4.6. Sectored flexure testing of 20 test specimens resulted in a characteristic strength of 192 MPa and Weibull modulus of 5.5. These values bracket the diametral flexure test results generated under this project**.**

A summary of test results from the initial experimental work is shown in Table 1, along with the expected flaw population sampled by each test method.

Table 1. Experimentally Determined Mechanical Properties for α-SiC

Test Method	Characteristic Strength (MPA)	Weibull Modulus	Expected Flaw Population Sampled
Axial Tensile	320	10.0	Volume
Internal Pressurization	132	5.3	Both Volume and Surface
Diametral Compression	253	31.7	Surface
C-Ring Flexure	299	4.6	Surface Perpendicular to Circumferential Direction
Sectored Flexure	192	5.5	Surface Parallel to Circumferential Direction

It was concluded that axial tensile testing resulted in a much higher failure stress estimate than plug or flexure testing due to the direction of loading introduced by each test method, the effective surfaces/volumes present in the associated test specimens, and the inherent flaw populations in these materials that lead to failure. Additionally, it was noted that the Weibull analyses performed assume only a single flaw population dictates failure in these materials which is expected to be a false assumption. Therefore, fractography is an important tool that needs to be incorporated into this analysis. Finally, since tensile hoop data from this type of testing may be more directly comparable and characteristic of the expected failure mode inherent in failed clad tubing due to service operation loading, it was also noted that this test method yields the lowest predicted strength for this material although it is believed that a greater number of test specimens may need to be evaluated to improve the generated Weibull statistics.

For the composite testing, two tube types were received and evaluated. The first were composite tubes composed of SiC fibers and a single layer SiC matrix (nominal OD = 10.3 mm and a wall thickness = 1.0 mm). The second sample of specimens was composite tubes composed of SiC fibers and a double layer SiC matrix (nominal OD = 10.8 mm and a wall thickness = 1.2 mm).

Expanding plug testing was successfully performed on three specimens each from both the single layer and double layer samples with an average strength of 138 MPa and a standard deviation of 3.3 MPa determined for the single layer material and an average strength of 172 MPa and a standard deviation of 52 MPa determined for the double layer material. Weibul statistics for these materials were not generated due to the limited number of specimens. It was noted that brittle fracture occurred in these specimens similar to that seen in the testing of monolithic SiC specimens. Additionally, the estimated strength value for the single layer composite material compared well with that experimentally measured for monolithic SiC under internal pressurization (132 MPa) indicating that the strength of this composite material may be controlled by the inner monolithic layer and is not enhanced by the fiber reinforcement (assuming the inner layer material is a similar material to monolithic SiC material tested). This hypothesis would be further supported by the observation of brittle fracture in these materials as opposed to graceful failure as seen in many fiber composite materials. An increase in strength is calculated for the double layer composite material, although this value has a high standard deviation due to the low number of test samples and wide scatter of measured values.

3.2 NEW WORK

Under the current effort, the following work was completed:

- Based on the opinion that a greater number of test specimens needed to be evaluated to improve the confidence bounds on the estimates of the parameters of the strength distribution previously generated under this project, additional plug tests were performed on specimens prepared from the original α-SiC tube material (Saint-Gobain Hexoloy SE SiC Tube, 2012 Vintage). Although it was not possible to state a set number of specimens that would need to be tested to accurately estimate the parameters of the Weibull distribution which characterizes candidate ceramic fuel cladding materials, it was felt that this number would be dependent on the individual candidate material system tested and would be further complicated by the complex interaction of the ceramic matrix and fiber reinforcement that make up candidate composite SiC cladding systems. In theory you need to test every specimen in the population to determine the actual parameters of the distribution. However, this is impossible and therefore we are limited with testing a set number of specimens and as the number of test specimens increases, our ability to estimate the parameters of the distribution increases and the confidence bounds on our estimate get tighter. It was therefore anticipated that larger sample populations than those used in the past effort would be needed. Based on the guidance found in ASTM C 1239, sample populations on the order of at least (50-100) were expected to be required. This amount of testing and characterization was not able to be carried out under the current effort, but work was performed to evaluate the effect of additional test data and more in depth analysis of fracture origin.

- As previously noted, fractography is vital in the analysis of strength data generated for candidate materials and must be incorporated into the analysis as originally proposed. Therefore, the additional plug testing that was carried out incorporated steps into the test protocol to improve retention of fragments from failed test specimens in a more complete manner to aid in the fractographic analysis. Additionally, fractographic analysis of the original diametral compression samples was also carried out. Using such information, additional Weibull analyses was carried out assuming multiple flaw populations (as identified) which lead to failure in these materials.

- Tubes of β-SiC, which is under consideration for use in some nuclear fuel cladding applications, were obtained and evaluated using test methods identified during this project for comparison to the currently evaluated α-SiC materials.

- Finite Element Analysis was performed based on previously computed stress states for the monolithic inner cylinder of a hybrid monolithic-composite SiC fuel cladding system using the range of values of characteristic strength and Weibull modulus of materials experimentally determined under this project to identify properties needed to meet allowable determined failure rates.

4. RESULTS

4.1 ALPHA-SIC TESTING

Specimens were prepared using additional random tubes of α-SiC tubular material (Hexoloy SE SiC Tube with nominal outer diameter (OD) = 14 mm, inner diameter (ID) = 11, wall thickness = 1.5 mm, length = 254 mm) previously obtained from Saint-Gobain Ceramic Materials Structural Ceramics Division (Niagara Falls, NY). This was off the shelf stock material characteristic of commercially available α-SiC tubing. New specimens are shown in Table 2.

Table 2. Additional Hexoloy SE α-SiC Test Sample Dimensions

Plug Specimen	OD (mm)	Wall (mm)	ID (mm)	Length (mm)	Status
21	13.99	1.53	10.94	10.23	Not Tested
22	14.01	1.54	10.92	10.23	Not Tested
23	14.00	1.53	10.93	10.19	Not Tested
24	13.97	1.55	10.88	10.20	Tested
25	13.99	1.55	10.90	10.20	Tested
26	14.00	1.56	10.87	10.19	Tested
27	13.99	1.54	10.92	10.21	Tested
28	14.00	1.52	10.96	10.21	Not Tested
29	14.01	1.54	10.93	10.21	Tested
30	14.02	1.56	10.89	10.20	Tested
31	14.00	1.54	10.91	10.23	Not Tested
32	14.00	1.53	10.94	10.23	Tested
33	13.99	1.54	10.92	10.22	Tested
34	14.01	1.55	10.90	10.22	Not Tested
35	14.03	1.55	10.93	10.22	Tested
36	14.00	1.55	10.90	10.21	Not Tested
37	13.99	1.55	10.89	10.22	Not Tested
38	13.99	1.54	10.92	10.21	Not Tested
39	14.03	1.55	10.93	10.21	Tested
40	14.03	1.54	10.96	10.21	Not Tested

Expanding plug testing was successfully performed on 10 of the 20 additional specimens as shown in Table 2. The remaining ten specimens were retained for future testing or validation efforts. Results of the additional testing are shown in Table 3 with failure loads converted to circumferential stresses based on sample dimensions and previously given equations [2]. This test sample was then used in conjunction with the previous experimental data to generate updated Weibul statistics for this material under internal pressurization conditions. A revised Weibull plot considering only a single flaw population is shown in Fig. 3 with a resulting new characteristic strength of 137 MPa and a Weibull Modulus of 5.8. For reference, an original characteristic strength of 132 MPa and Weibull Modlus of 5.3 was estimated for this material under these loading conditions using only the previous data.

Table 3. Additional Expanding Plug Test Results for Hexoloy SE α-SiC

Specimen	Failure Load (kN)	Circumferential Stress (MPa)
24	3.274	114.21
25	5.242	182.78
26	4.235	146.16
27	2.990	104.87
29	3.810	132.91
30	4.230	145.89
32	4.025	141.47
33	3.348	117.29
35	4.315	149.96
39	3.534	122.77

Avg: 135.83, Stdev: 22.59 MPa

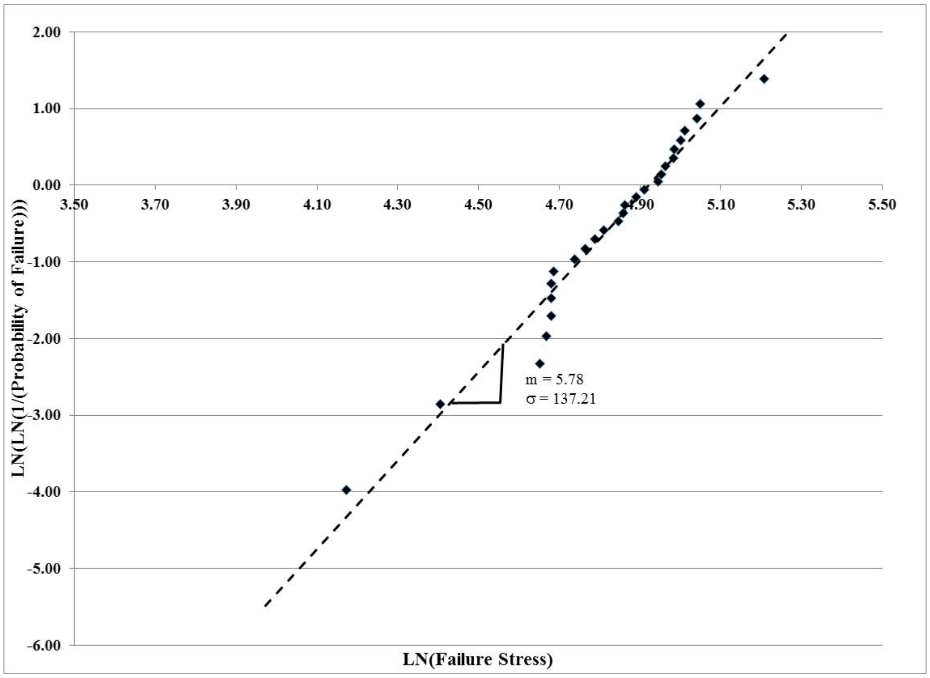

Fig. 3. Revised Weibull Plot for Hexoloy α-SiC Under Internal Pressurization Conditions.

Fractography was performed on the failed specimens from the current and previous round of expanding plug testing. Three flaw populations were identified through this analysis. The first was failure due to large surface flaws that are expected to have been inflicted during machining and handling of the samples. This type of flaw was identified for the two low strength outliers as identified in Fig. 4 and is shown graphically in Fig. 5a . The next flaw population consisted of smaller surface flaws which are expected to be inherent to the material. This flaw population was identified in specimens all exhibiting a calculated circumferential stress in the range of 105-110 MPa (LN(Failure Stress) values on the order of 4.65-4.69 in Fig. 4). This flaw type is shown graphically in Fig. 5b. The final flaw population identified consisted of volume flaws which are also expected to be inherent in the material. This flaw population was identified in specimens exhibiting a calculated circumferential stress greater than 114 MPa (LN(Failure Stress) greater than 4.74 in Fig. 4). This flaw type is shown graphically in Fig. 5c.

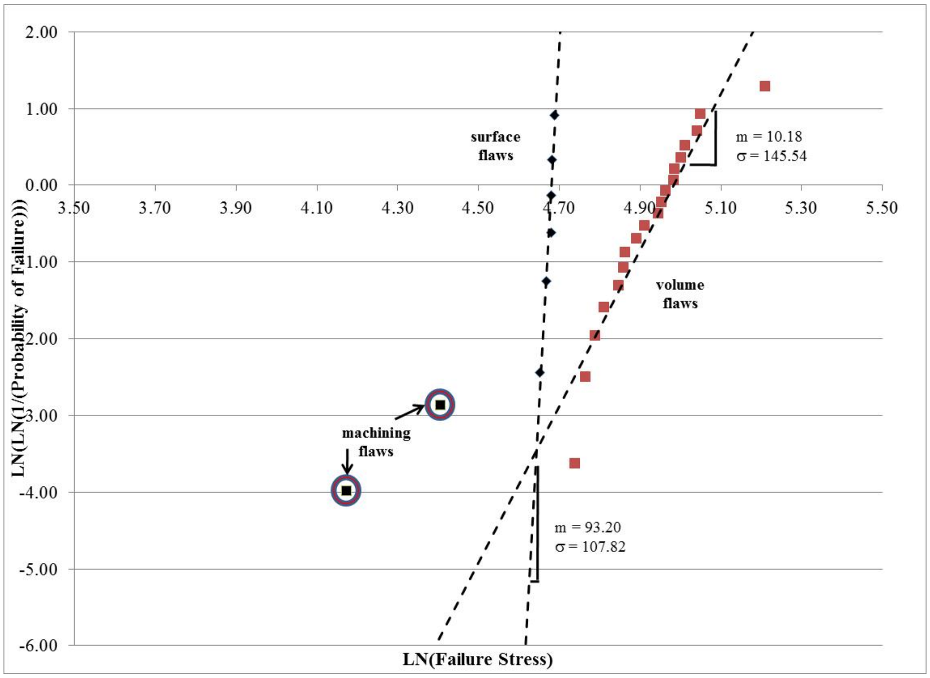

Fig. 4. Weibull Statistics for Hexoloy α-SiC Under Internal Pressurization Conditions Considering Varying Flaw Populations.

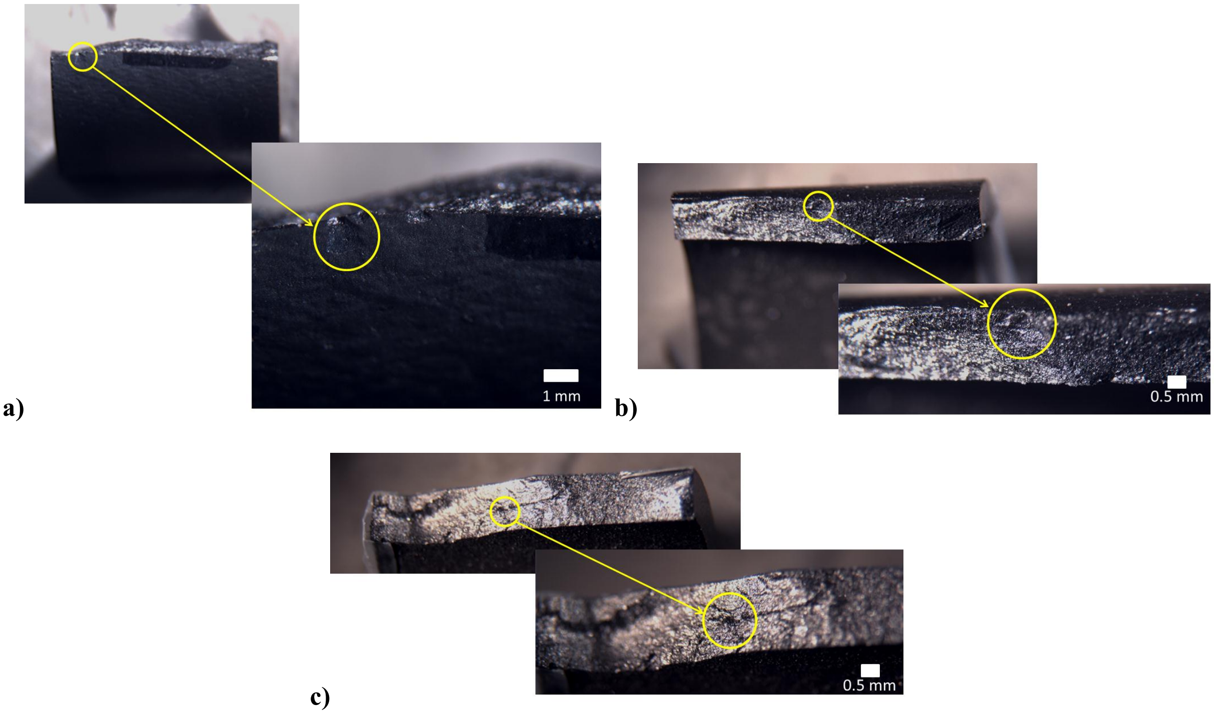

Fig. 5. Flaw Types Identified for Hexoloy α-SiC Under Internal Pressurization Conditions. (a-Machining Surface Flaw, b-Inherent Surface Flaw, c-Inherent Volume Flaw)

Following identification of multiple flaw populations through fractography, the Weibull analysis was repeated for the α-SiC test sample assuming concurrent flaw populations (considering the failure due to the inherent surface and volume flaws separately). Such an analysis (as shown in Fig. 4) resulted in a characteristic strength of 108 MPa and a Weibull Modulus of 93.20 for the surface flaws and a characteristic strength of 146 MPa and a Weibull Modulus of 10.2 for the volume flaws. The extremely high Weibull Modulus found for the surface flaw population indicates that the strength of the specimens which failed from these flaws showed little variation (ranging from 105-110 MPa). This may be explained by the fact that the surface flaws were large in size and led to low strength failure compared to the volume flaws which were smaller in size, led to higher strength failure, and showed a larger distribution of failure strengths (114-182 MPa). Additional fractography may be necessary to fully understand these flaw populations and their effect on the strength of this material.

Fractography was also performed on the failed specimens from the previous diametral compression testing. All flaws were identified as surface flaws through this analysis as shown in Fig. 6.

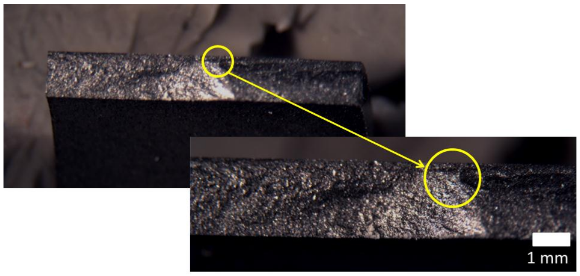

Fig. 6. Example of Surface Flaw Identified for Hexoloy α-SiC Under Diametral Compression Conditions.

An updated summary of test results from all α-SiC experimental work is shown in Table 4, along with the associated flaw population sampled by each test method. As can be seen, the original failure stress estimate for the internal pressurization testing was dominated by the volume flaw population behavior. Additionally, the already low estimated characteristic strength, as determined by the internal pressurization method, is even lower if failure occurs due to surface flaws.

Table 4. Updated Experimentally Determined Mechanical Properties for α-SiC

Test Method	Characteristic Strength (MPA)	Weibull Modulus	Associated Flaw Population Sampled
Axial Tensile	320	10.0	Volume
Internal Pressurization			
Original Estimate	132	5.3	Both Volume and Surface
Revised Estimates	137	5.8	Both Volume and Surface
	108	93.2	Surface
	146	10.2	Volume
Diametral Compression	253	31.7	Surface
C-Ring Flexure	299	4.6	Surface Perpendicular to Circumferential Direction
Sectored Flexure	192	5.5	Surface Parallel to Circumferential Direction

It can be additionally observed that the increased number of specimens tested by internal pressurization (increasing the sample size from 15 to 25 specimens) did not appear to change the characteristic strength and Weibull Modulus estimates drastically. It was originally thought that on the order of (50-100) specimens may need to be tested. This amount of testing and characterization was not able to be carried out under the current effort, but may be considered for follow on efforts.

4.2 BETA-SIC TESTING

Specimens were prepared from seven random tubes of β-SiC material (Crystar® 2000 Slip Cast Recrystallized SiC Tube with nominal outer diameter (OD) = 25 mm, inner diameter (ID) = 12 mm, wall thickness = 6.5 mm, length = 102 mm) obtained from Saint-Gobain Ceramic Materials (Worcester, MA). This was off the shelf stock material characteristic of commercially available β-SiC tubing. Prepared specimens are shown in Table 5.

Table 5. Crystar® 2000 β-SiC Test Sample Dimensions

Plug Specimen	OD (mm)	Wall (mm)	ID (mm)	Length (mm)	Status
1	25.54	6.33	12.87	19.88	Tested
2	25.64	6.45	12.73	20.28	Not Tested
3	25.62	6.75	12.12	19.85	Tested
4	25.53	6.48	12.57	19.59	Not Tested
5	25.51	6.37	12.77	20.22	Not Tested
6	25.67	7.03	11.62	19.38	Tested
7	25.50	6.73	12.05	20.59	Tested
8	25.52	6.73	12.06	19.54	Tested
9	25.61	6.66	12.29	20.01	Tested
10	25.67	6.88	11.90	20.07	Tested
11	25.63	7.08	11.47	20.01	Tested
12	25.60	6.26	13.08	19.50	Not Tested
13	25.56	6.18	13.20	19.65	Not Tested
14	25.57	6.44	12.69	19.74	Tested
15	25.60	6.65	12.29	19.68	Tested

Expanding plug testing was successfully performed on 10 of the 15 prepared specimens as shown in Table 5. The remaining five specimens were retained for future testing or validation efforts. Results of testing are shown in Table 6 with failure loads converted to circumferential stresses based on sample dimensions and previously given equations [2].

Table 6. Expanding Plug Test Results for Crystar® 2000 β-SiC

Specimen	Failure Load (kN)	Circumferential Stress (MPa)
1	5.555	24.26
3	6.418	26.34
6	5.240	21.16
7	6.630	26.33
8	5.385	22.53
9	5.443	22.47
10	6.684	26.61
11	6.099	23.69
14	5.732	24.80
15	7.058	29.64

Avg: 24.78, Stdev: 2.51 MPa

This test sample was then used to generate Weibul statistics for this material under internal pressurization conditions. A Weibull plot is shown in Fig. 7. A characteristic strength of 26 MPa and a Weibull Modulus of 11.7 were determined for this material under these loading conditions. Additionally, fractography was performed on the failed specimens from this testing. All flaws were identified as volume flaws through this analysis as shown in Fig. 8.

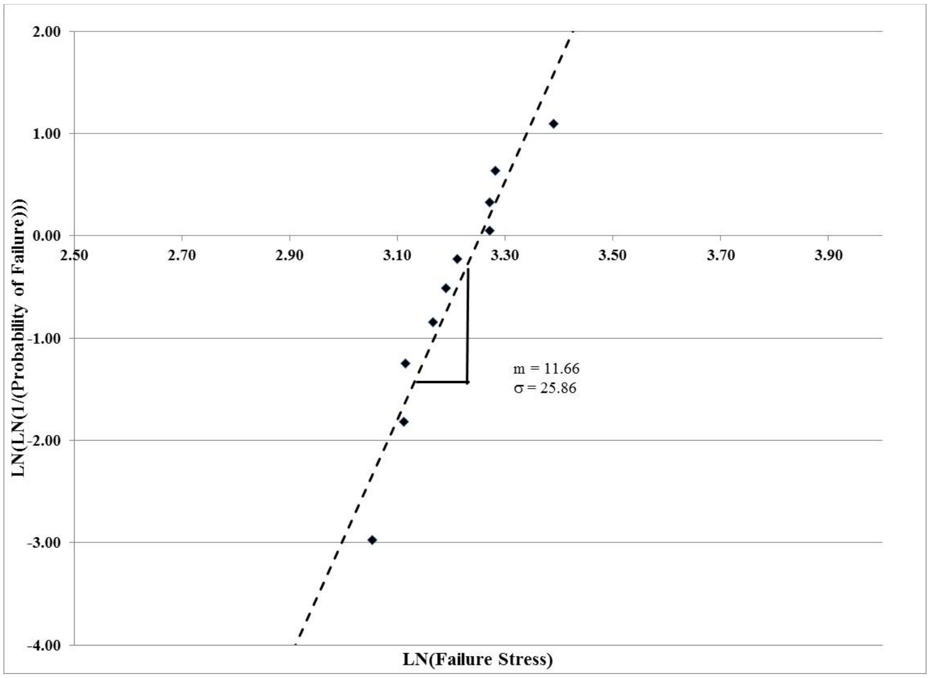

Fig. 7. Weibull Plot for Crystar® 2000 β-SiC Under Internal Pressurization Conditions.

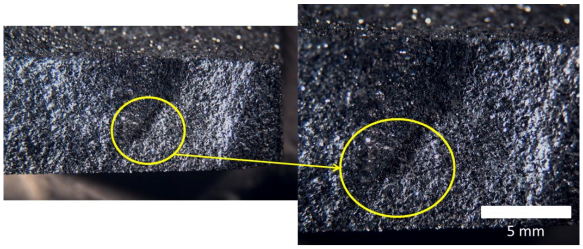

Fig. 8. Example of Volume Flaw Identified for Crystar® 2000 β-SiC Under Internal Pressurization Conditions.

The determined characteristic strength of the β-SiC material was much lower than that of the previously studied α-SiC material (26 MPa as compared to ≈135 MPa). This lower strength is attributed to the larger grain size of the β-SiC material, and the processing methods (recrystallization) used to produce these tubes. This material is also found to be inherently more porous than the α-SiC material studied. Literature values for Crystar® 2000 β-SiC as reported by the manufacturer give a Modulus of Rupture (MOR) value on the order of 80 MPa at room temperature and a bending strength of 90 MPa at 1400°C. It would be expected that our internal pressurization test would yield values lower than these as seen for the α-SiC material testing by various methods.

4.3 FINITE ELEMENT ANALYSIS

In previously published reports [2,9] known conditions of loads due to axial, vibrational, and thermal stress across the thickness of a hybrid ceramic assembly and along its length were used to define a combined hypothetical stress state for a characteristic fuel rod and the associated cladding system. Using this stress state, a probabilistic analysis was performed to determine the reliability of a candidate system and from this analysis, a range of values of characteristic strength and Weibull modulus of materials in such a hybrid structure that are needed to meet allowable failure rates were identified. Additionally, FEA was performed to compute the stress state for the monolithic inner cylinder of a hybrid monolithic-composite SiC fuel cladding system, which is responsible for containing the fuel and fission products. Specifics of this analysis can be found in the previously published report [2].

For the previous analysis, existing monolithic SiC failure data from the literature was used to analyze behavior due to surface and volume flaws using Eq. 1 and the associated Weibull modulus (m) and deterministic stress (σ_o) as determined by the slope of the curve for each data set.

$$P_f = 1 - exp\left[k \int \left(\sum_{i=1}^{3} \sigma_i^{m}\right) dV\right] \qquad (1)$$

Where: P_f = probability of failure defined as ($P_f = 1 - R$),
R = the system reliability composed of the reliabilities of each sub-component ($R = \prod_{i=1}^{n} R_i$),
k = is a function of (V), the characteristic volume (V_o) and the deterministic stress (σ_o)

Using such an approach and the properties shown in Table 7, a ceramic nuclear fuel cladding cylinder was represented by a two-dimensional axi-symmetric model (shown in Fig. 9) in the commercial software package ANSYS to determine a maximum failure stress for each flaw population based on a maximum allowable probability of failure (0.001% in the example case). NASA CARES life code was then used to perform multiple probabilistic analysis which allowed for the definition of the range of Weibull moduli (a unitless measure of the dispersion strength) and characteristic strengths needed to meet allowed failure rates.

Table 7. Thermomechanical Material Properties for Non-Irradiated Monolithic SiC (from literature)

Material	Elastic Modulus (GPa)	Poisson's Ratio ν	CTE (ppm/^{o}C)	Thermal Conductivity (W/mK)
SiC	240*	0.2	4.0	25

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* It should be noted that since this analysis was performed it has been learned that the Young's Modulus for radiation-stable monolithic SiC will be on the order of 450 GPa unless the material is highly porous.

† Original values used were a thermal load of 1600^{o}C applied at the inner surface decaying to 300^{o}C at the outer surface, internal

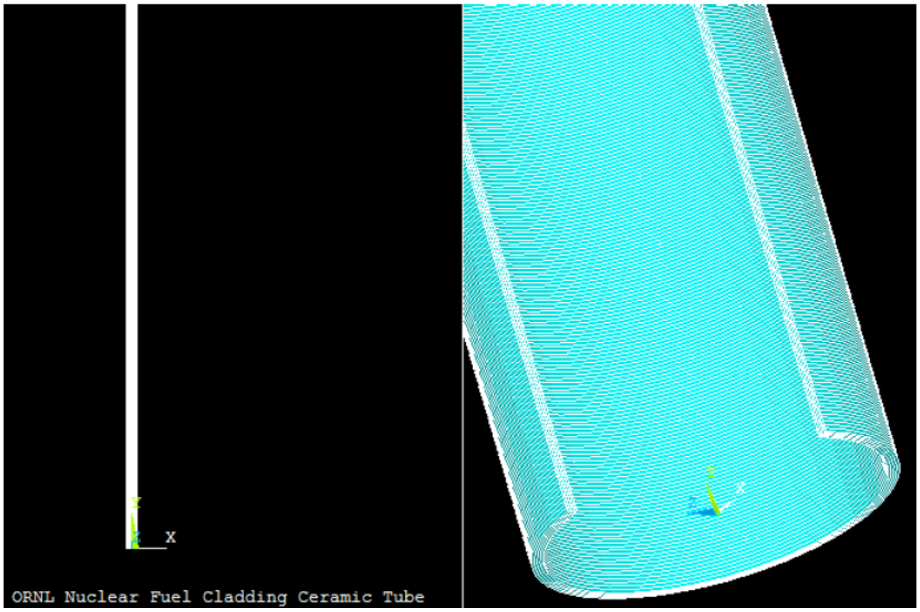

Fig. 9. ¾ expansion view for a nuclear fuel cladding ceramic tube simulated using a two-dimensional axi-symmetric FEA model.

FEA thermal analysis was performed to simulate the temperature distribution throughout the tube due to the thermal loads and properties as specified above. Since it was expected that the thermal load would be the most critical amongst all the applied loads (axial loading due to gravity is almost negligible and loading due to pressures will be compressive and therefore can be ignored when computing the probability of failure for a ceramic material), a thermal stress analysis with the thermal load applied separately was first performed. The computed temperature distribution was also combined with all of the structural loads (internal pressure, external pressure, and gravity) to compute the combined stress states within the tube.

For this initial probability of failure analysis, only volume flaws were used to computer P_f. To predict P_f, the Principal of Independent Action (PIA) theory or Batdorf theory was used which combines the weakest link theory with linear elastic fracture mechanics and includes the calculation of the combined probability of the critical flaw being within a certain size range and being located and oriented so that it may cause fracture. The probabilistic sensitivity analysis was performed assuming materials with characteristic strengths ranging from 200-1000 MPa and Weibull moduli varying between 4-40. As expected, the P_f decreases as the characteristic strength and/or Weibull modulus increase. Results showed that the P_f is unacceptably high for any material with characteristic strength lower than 900 MPa. Additionally, the most favorable case occurs under the prescribed loads and using a ceramic material with characteristic strength of 1 GPa and m=40 where the tube's P_f is 2.4e^{-4} meaning that 2.4 out of 10,000 tubes are predicted to fail. It is also noted that the analysis assumed unrealistically high thermal conductivity (non-irradiated SiC thermal conductivity value used, radiation will reduce thermal conductivity drastically with values of thermal conductivity at 300^{o}C under neutron irradiation generally not exceeding ~10 W/mK [10]), thus failure rates would likely be more severe (possibly by as much as 5X stress).

The current effort aimed to apply the same FEA performed based on previously computed stress states for the monolithic inner cylinder of a hybrid monolithic-composite SiC fuel cladding system using the range of values of characteristic strength and Weibull modulus of materials experimentally determined under this project to identify properties needed to meet allowable determined failure rates. If the same maximum allowable probability of failure (0.001%) is assumed, then the result of P_f being unacceptably high for any material with characteristic strength lower than 900 MPa still must be met. The strength values measured by internal pressurization for both the α-SiC and β-SiC materials are well below this value. Even the strength of the α-SiC material evaluated in tension is significantly lower than this threshold value. Subsequent work is proposed to repeat the previous probability failure and FEA analysis using revised estimates for thermal and mechanical loads[†] and experimentally determined SiC failure data in place of literature data.

[†] Original values used were a thermal load of 1600^{o}C applied at the inner surface decaying to 300^{o}C at the outer surface, internal pressure of 1.8 MPa and external pressure equal to 10.34 MPa, and weight due to gravity.

FUTURE WORK TO BE PERFORMED UNDER PROJECT

Based on the results to date obtained under the current project, several additional tasks are proposed for consideration.

- Subsequent work is proposed to repeat the previous probability failure and FEA analysis using revised estimates for thermal and mechanical loads, as previously described, and experimentally determined SiC failure data in place of literature data. Such probability failure analysis of monolithic and monolithic-composite hybrid structures would allow for a range of values of characteristic strength and Weibull modulus of materials in such a hybrid structure to be identified to meet allowable determined failure rates.

- Based on the current experimental results, additional internal pressurization testing and the associated fractographic analysis should be conducted on α-SiC Hexoloy SE SiC tube specimens to determine if the Weibull statistics for this material can be improved upon. Additionally, further fractographic analysis should be performed on previously tested internal pressurization specimens to further characterize the failure mechanisms and critical flaw populations.

- It would benefit the program to obtain additional SiC composite system tubular materials for testing and evaluation under this project. Additionally, evaluation of additional specimens of previously evaluated composite materials would greatly improve the statistics and evaluation of these materials.

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