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Multilayer Silicon Carbide Composite Material Technology for High-Temperature Concentrated Solar-Thermal Power Components

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Abstract. In 2012, the U.S Department of Energy defined aggressive targets to achieve lower component costs and higher system efficiencies for concentrated solar-thermal power (CSP), and this, in turn, has led to the exploration of technology options that can operate at higher temperatures [1]. These next-generation CSP options, referred to as Generation 3 (a.k.a. Gen3), are targeting temperatures at or above 700 ºC for the energy being delivered to the power cycle, and the more challenging plant conditions have necessitated a review and selection of alternative receiver heat transfer fluids as well as a search for materials that can meet the associated high-temperature component requirements. Nickel-based alloys are currently being considered, but these generally experience a significant drop in strength at temperatures > 775 ˚C [2] and may not be able to achieve corrosion and other lifetime requirements. Furthermore, these alloys are expensive, frequently have cost and schedule volatility, and offer little potential for lower cost at high production volumes. As an alternative, Ceramic Tubular Products, LLC (CTP) has developed a multilayer silicon carbide composite that can complement or replace alloys currently being considered for these Gen3 CSP applications.

Keywords: Gen3 CSP, Silicon Carbide, Fiber Composite, High-Temperature Components

1. Company and technology overview

1.1 Company background

Ceramic Tubular Products, LLC (CTP), a registered small business formed in 2006 and located in Rustburg, Virginia, is currently developing multilayer silicon carbide (SiC) ceramic matrix composite (CMC) tubes and complex shapes. These, in turn, enable components for use in various high-temperature, harsh environments. Markets of interest include: 1) Generation 3 (Gen3) concentrated solar-thermal power (CSP); 2) super-critical carbon dioxide (sCO_2) Brayton cycle systems; and 3) industrial process heat applications.

CTP's primary area of technical expertise is in ceramic materials manufacturing technology with specific multi-year experience in the development and production of SiC_f/SiC composites. Since its inception, the company has successfully completed multiple projects funded by DOE and has achieved significant advancements in its technology. In 2021, CTP completed a Phase II Small Business Innovation Research (SBIR) contract (DE-SC0018733) entitled "Multilayer SiC Piping for 900 ºC Brayton Cycle", and it has recently completed the development of a Gen3 CSP molten salt receiver (DE-EE-0008995), the subject of this paper.

1.2 CTP's technology and CSP market interest

Although the use of ceramic materials for extreme environments has been broadly investigated due to its desirable strength, the brittle failure nature generally associated with ceramics has led to a perception that using this material for such applications will be challenging. To address this, CTP's technology consists of an inner monolithic SiC tube, overwrapped with a SiC_f/SiC composite. (See Figures 1 and 2.) This allows for a strong, hermetic seal with the benefit of having the composite layer provide additional strength and toughness, thereby providing significant thermal and mechanical shock resistance for CTP's multilayer tubular products. There is significant design flexibility whereby the monolith dimensions and the CMC layer characteristics can be adjusted as needed for a specified application. The following are key capabilities that have been demonstrated to date and support CTP's component development activities: 1) ability to manufacture very thin wall (i.e., < 0.016") SiC monolithic tubes; 2) ability to manufacture SiC monolithic tube walls > 0.25"; 3) ability to produce multilayer SiC CMC thin-walled tubes up to 5 feet in length; and 4) ability to join multilayer SiC components.

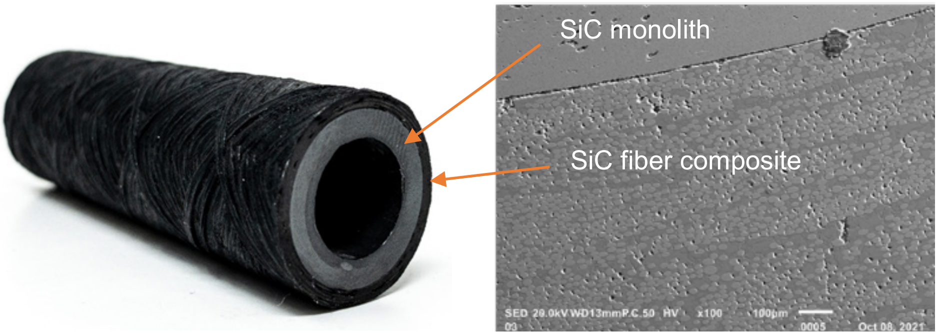

***Figure 1**. CTP multilayer technology.*

***Figure 2**. Silicon carbide-wound tubes.*

Key attributes associated with the CTP multilayer tubular technology are listed below,.

- Inner tube hermiticity (high pressure liquids and gases)
- High strength at high temperature
- Temperature capability in excess of 1000 °C
- Harsh environment corrosion resistance including liquid metal, molten salt, and sCO_2
- Very high wear resistance
- Mechanical and thermal shock protection (enabled by CMC overwrap)
- Strength maintained when heated to > 1100 °C and quenched in water
- Heating rates > 200 °C / minute accommodated without detrimental effects
- Absorptance, for CSP receiver applications, in excess of 97% (for four layers of CMC) of incident sunlight energy with no degradation in performance over time

For the emerging Gen3 CSP market opportunity, these next-generation technology options are generally categorized by the solar receiver technology (i.e., either solid particle, liquid, or gaseous medium receivers). Current global development and demonstration activities are primarily focused on component-level and small-scale integrated system testing. Given that plant-level commercial readiness will likely not occur until the latter part of this decade [1], [3], CTP considers it premature to focus its near-term efforts on any one Gen3 CSP tower technology option. Instead, it is advancing its technology and further characterizing its material for a range of plant conditions while using various heat transfer fluids.

2. 200 kWt molten chloride salt receiver development

For CTP's recently completed DOE SETO contract (i.e., DE-EE0008995, initiated in 2020), a key objective was to demonstrate the feasibility of using its material technology in high-temperature CSP components. This included the development of manufacturing technologies required to apply CTP's multilayer ceramic tubes to a complete receiver assembly (including flow headers, piping, and joining techniques). The initial task was the development of a conceptual design for a 2 MWt SiC-based receiver that, in turn, provided the bases for the development of a 200 kWt prototype receiver. Receiver parts were fabricated, and final assembly and hydrostatic testing were completed in June 2023.

2.1 Material technology advancements and characterization

Testing was performed on material and components throughout the program to begin to mitigate performance risks and perceptions associated with the use of ceramics in CSP applications. Solar performance, material strength, thermal and mechanical shock, and corrosion testing were performed. In addition, joining development and testing were performed prior to the manufacturing of the SiC receiver.

2.1.1 Optical & thermomechanical performance

Solar optical performance was evaluated using the High Flux Solar Simulator with Automated Sample Handling & Exposure System (ASHES) at the Sandia National Laboratories. The emittance was measured using a Surface Optics ET100 Emissometer using the integrated surface reflectance at 20° and 60° incident angles for size discrete wavelength bands between 1.9 and 20 µm at room temperature. Absorptance and emittance were measured on samples prior to the exposure and after every 100 cycles. During the high flux accelerated aging, samples were subjected to high heating and cooling rates, which did not produce any visual damage to the samples (Figure 3a). The absorptance of the multilayer tube samples at a peak temperature of 800 ^{o}C up to 1000 cycles is shown in Figure3b. The absorptance was shown to be stable up to 1000 cycles with no degradation in performance. Multilayer tubes made with four layers of fibers (4L) demonstrated slightly higher absorptance with an average of 0.97 compared to those with 6 layers (6L), α_{ave}=0.95.

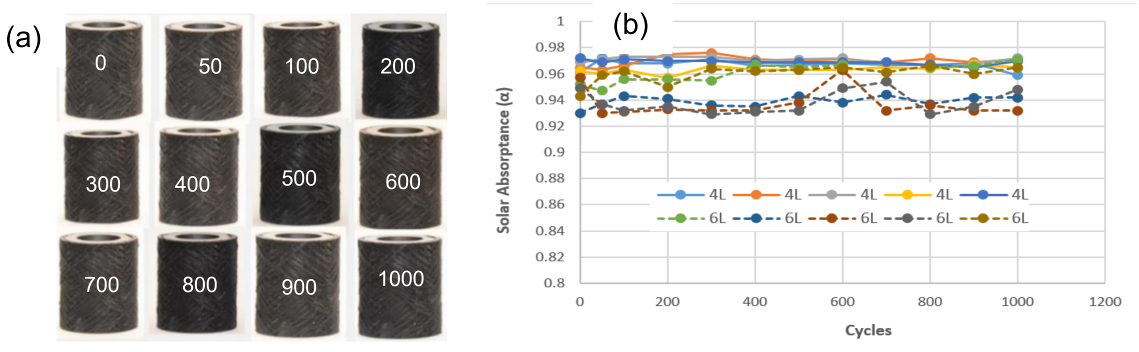

Figure 3. *Solar optical performance (samples (a) and absorptance results (b)).*

Thermal shock testing, also performed at the Sandia National Laboratories, used the solar furnace with a VeeJet 80100 spray nozzle to simulate rain on the receiver tubes. Temperatures were measured at 7 locations along the sample, on the front, back and inside of the tubes. Hoop strength was measured on representative samples prior to testing and on the actual shock tested samples with the goal of retaining 90% of the hoop strength after shock testing. Samples were heated to 900 °C, 1000 ˚C, and 1100 ˚C. A typical temperature profile is shown in Figure 4a for a 900 ˚C test. Results show that there is minimal degradation of multilayer tubes made with Hi-Nicalon (HN) fibers in hoop strength when shock tested up to 1100 ˚C. The hoop tensile strength of multilayer SiC tubes made with Nicalon-CG SiC fibers slightly increased with temperature (Figure 4b).

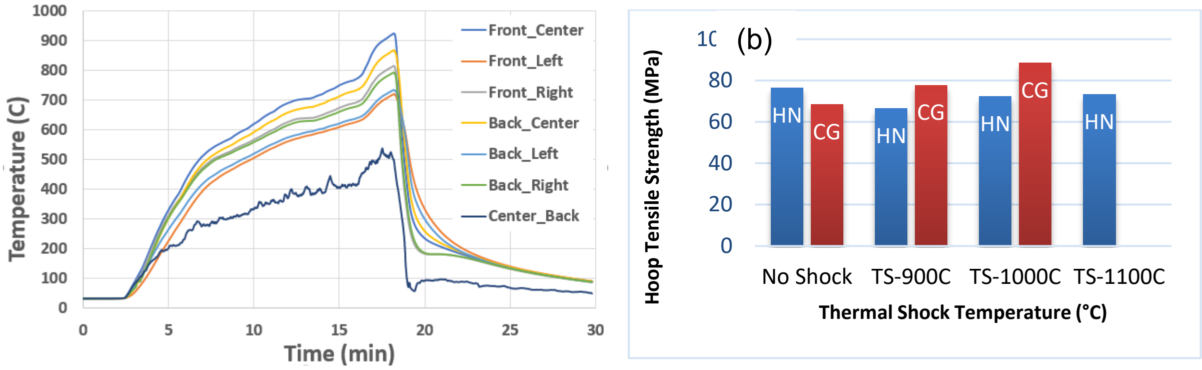

Figure 4. *Temperature profile of the 900 °C thermal shock test (a) and effect of thermal shock temperature on hoop tensile strength (b).*

Four-point bend impact tests were conducted in accordance with ASTM E2298 to evaluate the mechanical shock resistance of the multilayer SiC tubes. The goal was to have sufficient strength to resist fracture if a 1.5 pound wrench was dropped on the component from a height of 2 feet. SiC fiber type, CMC architecture, and fiber tension were compared. Results show acceptable mechanical shock resistance can be achieved for the defined requirement.

2.1.2 Component joining

Three types of joint materials (JM) were investigated for joining SiC components. The test samples were designed to be suitable for both helium leak (hermiticity) and joint shear strength tests. The microstructures of joint materials are shown in Figure 5. The joint material, JM1, had no microcracks at the joint/SiC interface, which also demonstrated helium hermicity. Microcracks developed at the JM2/SiC interface during cooling, which can cause leakage and joint failure over time. This joint material also did not show hermeticity. The JM3 interface showed some phase separation, however, no microcracks were observed.

Samples were tested for hermeticity using a Varian 979 Helium Leak Detector. JM1 had a hermetic seal after fabrication and did not show signs of deterioration after 2500 hours of salt corrosion testing. All joining materials showed acceptable shear strength, about 4000 psi, before and after salt corrosion testing. Joint material microstructure and interface with the SiC substrate was evaluated. JM1 and JM3 showed acceptable microstructure and interface, while JM2 had microcracks after sample fabrication.

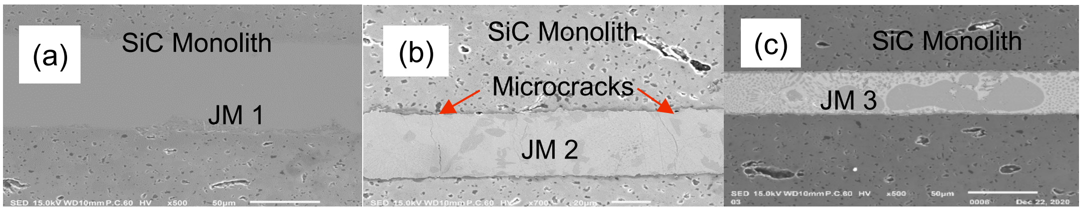

Figure 5. *Joint material microstructure.*

2.1.3 Corrosion in molten chloride salt

The objective of corrosion testing was to evaluate the salt corrosion resistance of monolithic SiC and SiC joined with three different joint materials after salt exposure at 800 °C for 2500 hours. The chloride salt composition was a mixture of $KMgCl_3$/NaCl/Mg which was prepared and purified according to the NREL salt collective guidelines [4].

Monolithic SiC tubes and Haynes 230 baseline samples were tested in the chloride salt and evaluated after 1000 and 2500 hours. The initial evaluation, after 1000 hours, showed that the SiC samples did not show any signs of corrosion and, in fact, gained weight due to dried salt that could not easily be removed. The Haynes 230 sample had an average weight loss of 29 mg/in^2. The final evaluation, after about 2500 hours, again showed slight weight gain of the SiC sample due to residual salt while the Haynes 230 sample had an average weight loss of 191 mg/in^2, which was about 6.5 times the corrosion observed after 1000 hours.Three joint materials were corrosion tested at 800 ˚C for 1000 and 2500 hours along with Haynes 230 baseline samples for comparison. Joint materials 1 and 2 showed slight weight gain after 1000 hours with additional weight gain observed after 2500 hours, indicating residual salt adhesion and incomplete cleaning, but no evidence of corrosion. Joint material 3 showed 0.05 weight percent weight loss after 2500 hours. The Haynes 230 samples showed 1.4 weight percent weight loss after 1000 hours and 8.5 weight percent weight loss after 2500 hours.

2.2 Receiver design, analyses, and cost

To mitigate scale up risk, CTP started the design and analyses of the CSP receiver “with the end in mind“, as shown in Table 1. The initial conceptual design started with a 2 MWt design point, from which the 200 kWt prototype was designed, taking into account design features required for larger demonstration plants. Once the conceptual design was complete, and initial manufacturing development was performed, the design was updated to a preliminary design taking into account lessons learned. This preliminary design was used to fabricate the prototype receiver.

Table 1. *CTP design scale up approach.*

Program Progression

Phase / Timing	Description
Commercial Readiness (200 MWt) … ~ 2030 • Project Development	• Multi-panel (~cylindrical); ~ 200 MWt; 40 panels, 1.5 m panel width, 34 tubes per panel; cylinder height ~ 7.8 m; cylinder diameter ~ 9.3m • 1000 suns
Pilot Plant Demo (~40 MWt) … ~ 2029 / 2030 • Achieve “plant-level” commercial project “bankability” (i.e., ability to obtain project financing with favorable terms by demonstrating performance, lifetime, and cost with acceptable risk)	• Multi-panel; ~ 8 panels, 5 MWt each; ~ 34 tubes per panel; each panel 1.5 m x 3.9 m ~ 1.4 m (half cylinder ~ 7.5 m diameter) • 1000 suns
Integrated System Demo (~2 MWt) … ~ 2025 / 2026 • Demo integrated system “commercial feasibility” (i.e., likelihood of being able to achieve commercial-scale plant-level objectives)	• Single panel; ~ 2 MWt; ~ 27 tubes per panel; ~ 1.2 m wide x 3.0 m high • 600 suns
Prototype Receiver Demo (200 kWt) … ~ 2024 • Demo receiver “commercial feasibility” (i.e., likelihood of being able to achieve commercial-scale receiver objectives)	• Single panel scaled down from 2 MWt panel size; 0.67 m wide, 0.89 m high, 15 tubes • 400 suns

2.2.1 Receiver design and analysis

The prototype design included the use of the CTP multilayer SiC tubing to construct the receiver. The overall design is an inverted U-tube concept with the inlet and outlet headers at the bottom of the assembly (Figure 6). The design was analyzed for flow distribution and pressure drop under assumed test site conditions. Detailed stress analyses were performed to ensure the pressure boundary would withstand operating conditions. Stresses considered were static cantilever loads of the U-tube assembly, temperature induced stresses, wind loads, and support structure stresses. The design was shown to be satisfactory for testing, although the predicted efficiency was lower than what would be projected in larger assemblies due to the low salt flow.

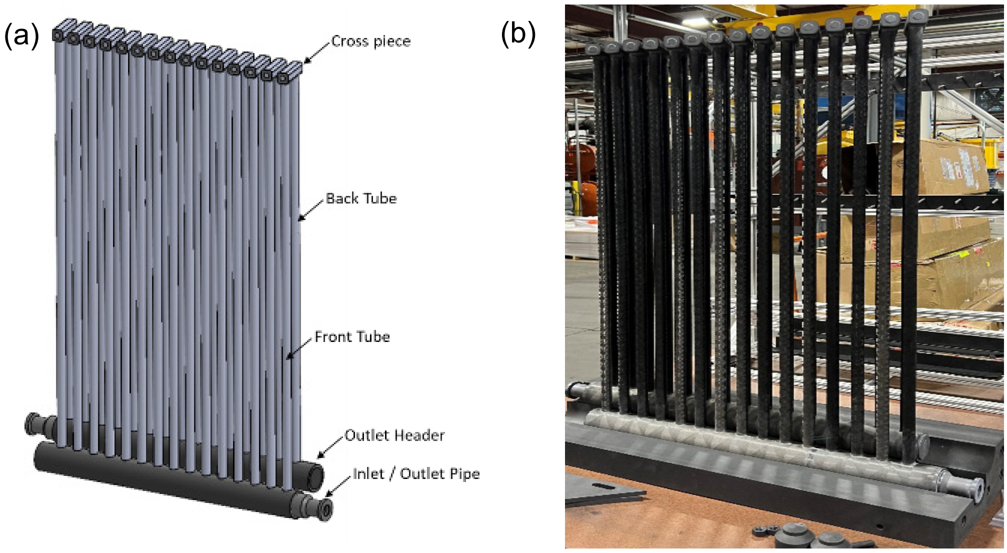

Figure 6. *200 kWt prototype receiver (a) preliminary design, (b) as-fabricated.*

2.2.2 Cost assessment

Estimating the manufacturing cost of a commercial CSP receiver is based on the preliminary design Bill of Materials with each component broken down to its commodities, e.g. receiver tubes consist of monolithic SiC tubes, SiC fiber, preceramic resin, fiber interface coating, etc. Each commodity is added for each component in the CSP receiver to determine the total commodity quantity required. This production cost estimate was calculated to determine the feasibility of achieving published CSP cost targets once CTP is in full-scale production. For this analysis, it is assumed that the facility will be manufacturing CSP receivers to produce approximately 1,000 MW_t per year. The component quantity and composition are based on the CTP SiC CSP receiver preliminary design, completed for project DE-EE0008995. From this preliminary design, the quantity of headers, receiver tubes, inlet and outlet pipes, etc. were calculated. To these quantities, a 15% scrap factor was added to obtain the commodity order quantity. Vendors were contacted to provide quotes for the requested production quantities.

In addition to these commodity prices, engineering estimates were used to estimate costs of special tooling, joining materials, subcontract costs and travel. In addition, since the support structure and back plate of the receiver will be site-specific, a budget allowance of $3,000,000 is included in the estimated price. The cost breakdown for 1,000 MW_t SiC receivers is depicted in Figure 7. Based on this analysis, production cost for 1,000 MW_t will be on the order of \$64/kW_t installed. Because there will be a learning curve associated with the scale up activities and, as production proceeds and output in increased, the cost per kW_t will decrease over the next decade.

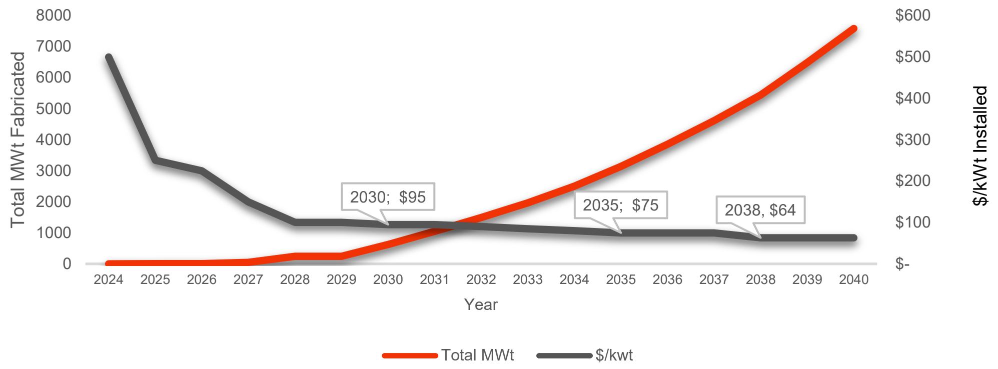

Figure 7. *CSP production cost projection.*

2.3 Conclusions and next steps

2.3.1 Conclusions

The following conclusions are made from the development program DE-EE0008995:

- Manufacturing a SiC CSP receiver is feasible with CTP's multilayer tube technology
- An efficiency of 88% was calculated for the 200 kWt prototype receiver
- Absorptance of 0.97 was demonstrated with no degradation up to 1000 thermal cycles
- Thermal shock resistance was demonstrated up to 1000 ºC with no reduction in hoop strength after thermal shock
- Corrosion resistance of SiC monolith and joint material was demonstrated at 800 ˚C for 2500 hours
- Current analysis demonstrates enhanced performance and lifetime at lower cost for CTP's SiC receiver relative to high nickel alloys.

2.3.2 Next steps

The following work is recommended to mitigate additional risk associated with the scale up and deployment of CSP receivers using CTP's multilayer SiC components.

- Improve CMC thermal conductivity to further improve receiver efficiency
- Continue development of joint configuration and joining materials
- Advance receiver assembly process to mitigate manufacturing risks associated with large, complex assemblies
- Perform additional high temperature component testing
- Perform on-sun receiver testing
- Initiate ASME code development

Data availability statement

Data supporting this article may be obtained by contacting Ceramic Tubular Products.

Underlying and related material

Not applicable to this publication

Author contributions

Jeff Halfinger: Funding Acquisition, Conceptualization, Project Administration, Supervision, Writing – Review & Edit.

Farhad Mohammadi: Data curation, Investigation, Methodology, Validation, Writing – Review & Edit.

Dale Rogers: Visualization, Conceptualization, Writing – Original Draft.

Competing interests

The authors declare that they have no competing interests.

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