

A Comparative Analysis Between SiC and A740H Receiver Designs

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Abstract. The outlet temperature targets for Gen 3 Concentrating Solar Power (CSP) systems pose a significant challenge to the structural reliability of high-temperature metallic materials. Advanced ceramics are a promising option due to their high temperature strength and low thermal expansion. However, challenges such as limited ductility and fabrication issues need to be addressed. Before tackling manufacturing challenges, CSP developers must determine the viability of high temperature ceramic components in system design, considering factors like plant operating life. This paper presents a comparative design analysis of tubular external receivers constructed from a high temperature nickel-based superalloy, A740H and a monolithic ceramic material, commercial SiC, using *srlife*, an open-source receiver evaluation and life prediction tool. Results indicate that A740H receivers can achieve a 30-year service life if the flux is limited to 450 kW/m², which may not be economically viable. In contrast, the Weibull 3-parameter model estimates a service life exceeding 30 years for SiC receivers, even at a much higher flux limit of 1000 kW/m².

Keywords: Solar Receiver, High Temperature Design, Reliability

1. Introduction

To achieve the 2030 Levelized Cost of Energy (LCOE) target set by the SunShot initiative for CSP systems, highly efficient solar receivers capable of delivering heat transfer fluids (HTF) at outlet temperatures exceeding 720°C are required [1]. Previous studies [2, 3] have shown that designing such receivers for long service life – necessary to recover capital costs – using current-generation nickel-based alloys presents a significant challenge. Ceramic materials, with their exceptional high-temperature creep resistance, fatigue durability, and low thermal expansion, offer a promising alternative [4, 5]. However, challenges such as limited ductility, variability in material strength, manufacturing complexities, and difficulties in joining ceramic components to other ceramic or metallic parts must be overcome to enable the successful implementation of ceramics in CSP systems. Before tackling the manufacturing and joining challenges, designers and plant operators need to evaluate the viability of ceramics for high-temperature CSP components, carefully weighing their benefits against the costs compared to metals.

The engineering design of high-temperature ceramic components differs significantly from that of metallic materials, highlighting the need for the CSP community to have access to applicable design methods and software tools for ceramic receivers [6]. To address this, we have

recently extended the capability of *srlife* – an open-source receiver evaluation and life prediction tool originally developed for metallic receivers [7-9] – to predict the reliability of ceramic receivers operating at high temperatures over a given lifespan [10-14]. This new functionality enables comparative design analyses between ceramic and metallic receivers. Future updates to *srlife* will include cost analysis features, allowing for direct LCOE comparisons across different designs.

This study compares the performance of a nickel-based high-temperature superalloy, A740H, with a commercially available engineering ceramic, SiC, for high temperature receiver applications.

2. Receiver analysis method

Figure 1 shows the general process of evaluating a receiver using *srlife*. The user inputs tube dimensions, the number of tubes, panel arrangements, mass flow rates for each flowpath, and the net heat flux over time. To reduce analysis costs, a representative subset of tubes can be analyzed. *srlife* includes a thermohydraulic module that calculates the heat balance in each flowpath. The fluid mass flow rate can either be constant, leading to variable outlet temperatures, or time-dependent to maintain a consistent outlet temperature throughout the day. In the latter case, the mass flow rates at different times of the day can be determined iteratively using the thermohydraulic solver. The structural analysis module then calculates stress and strain fields based on internal pressure and temperature results from the thermohydraulic analysis.

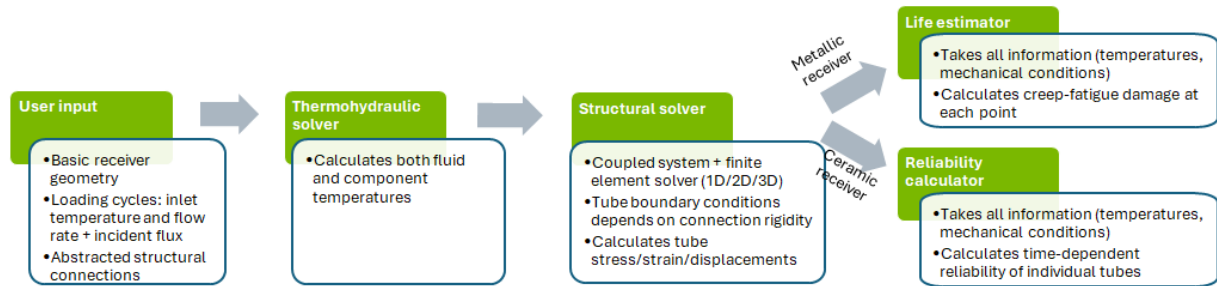


Figure 1. Flow chart illustrating analysis steps in receiver evaluation.

At this point, the software has generated stress and temperature profiles for each tube in the receiver. The next step is to convert these results into either creep-fatigue damage accumulation for metallic tubes or reliability predictions for ceramic tubes. For metallic receivers, the life is determined by the worst-case creep-fatigue damage accumulation. In contrast, the life estimation for ceramic receivers is probabilistic due to the stochastic nature of material failure, making deterministic predictions impossible. *srlife* predicts the reliability of ceramic tubes as a function of service life, allowing users to determine the life of the tubes for a given target reliability. The life of the ceramic receiver is then defined by the reliability of the tube with the lowest reliability.

Details of the *srlife* development and its various modules can be found in [7-13]. The creep-fatigue life estimation of A740H receiver is based on a bilinear creep-fatigue damage interaction diagram, as detailed in [8]. The reliability estimation for SiC receiver in this paper is based on the Principle of Independent Action (PIA) failure criterion, the Weibull crack density model, and a model accounting for sub-critical crack growth (SCG). Information on PIA and other ceramic failure models along with different reliability calculation options in *srlife* can be found in [12, 13].

This study also compares the Weibull 2-parameter (2P) and Weibull 3-parameter (3P) models for reliability estimation. While the Weibull 2P model is commonly used to represent the variability in ceramic strength, it can lead to overly conservative design predictions, particularly

for large components, as it calculates a nonzero probability of failure across the entire stress range. The Weibull 3P model, in contrast, introduces a threshold stress parameter, allowing for zero probability of failure when the applied stress is at or below this threshold.

3. Reference receiver and design variables

To ensure a fair comparison, this paper evaluates the performance of tubular external receivers constructed from A740H and SiC by optimizing their designs to maximize lifespan. The optimization process involves two steps: (i) determining the best receiver size and heliostat configuration for a given maximum allowable heat flux, and (ii) optimizing tube size and panel configuration based on the heat flux map. Three heat flux levels are considered: 1000 kW/m², 700 kW/m², and 450 kW/m². Adjusting the flux levels allows for balancing cost and performance trade-offs for both materials.

Table 1 lists the constraints and parameter ranges as well as the optimum receiver diameter determined using SolarPILOT [14] for each allowable flux limit, considering a constant receiver height of 12 m. For A740H tubes, the thickness is set to the minimum specified in the ASME B36.10M pipe schedule. For SiC tubes, the minimum thickness is 3 mm, reflecting the current ceramic tube manufacturing capabilities, as recommended by experts. The outer diameters for metallic tubes are also from the ASME B36.10M standard to avoid an excessively large design space, while ceramic tube diameters are unrestricted due to the flexibility of additive manufacturing. For a comparison of thermal and structural properties between A740H and SiC, interested readers are referred to the material library of *srlife* (available at <https://github.com/applied-material-modeling/srlife/tree/main/srlife/data>).

Table 1. Parameter constraint and ranges for system optimization.

Variables	Values/constraints
Climate	Dagget, CA, USA (flux data are in SolarPILOT)
Solar field power	180 MW _t
Allowable heat flux	1000 kW/m ² , 700 kW/m ² , 450 kW/m ²
Tower optical height	100 m
Max/min heliostat field capacity	2000 m / 50 m
Receiver thermal absorptance	98%
Receiver height or tube length	12 m
Receiver diameter	No constraint (optimum values are 10, 16, and 24 m for 1000, 700, and 450 kW/m ² allowable fluxes, respectively, determined using SolarPILOT)
Tube outer diameter	42.2 mm, 33.4 mm, 21.2 mm (metal); No constraint (ceramic)
Tube thickness	≥1.24 mm (metal), ≥3 mm (ceramic)
Total flowpaths; total panels (equal number of panels per flowpath)	2; 12, 18, 24, and 30
Tube material	Metal: A740H; Ceramic: SiC
HTF; inlet/outlet temperature	NaCl-KCl-MgCl ₂ ; 500°C/720°C
HTF outlet pressure; pressure loss	0.5 MPa; ≤ 3 MPa

4. Receiver life comparison

We utilize *srlife* to estimate the life of receiver. First, the thermohydraulic module of *srlife* is used to determine the temperature history in the tube. This analysis is set to run iteratively to determine the optimal flow rate for the HTF for a target outlet temperature of 720°C. Figure 2 shows example results from thermohydraulic analysis. The figure plots the mass flow rate and the HTF and tube crown temperatures (shown for the hottest and coldest tubes in the panels) along the flow path as functions of time. The results from the thermohydraulic analysis are then

utilized to determine the pressure loss between the inlet and outlet, and this information is used to impose the pressure load in the structural analysis. Using the stress and strain history from structural analysis, *srlife* performs the damage or reliability analysis, depending on the type of material, to estimate the life of the receiver.

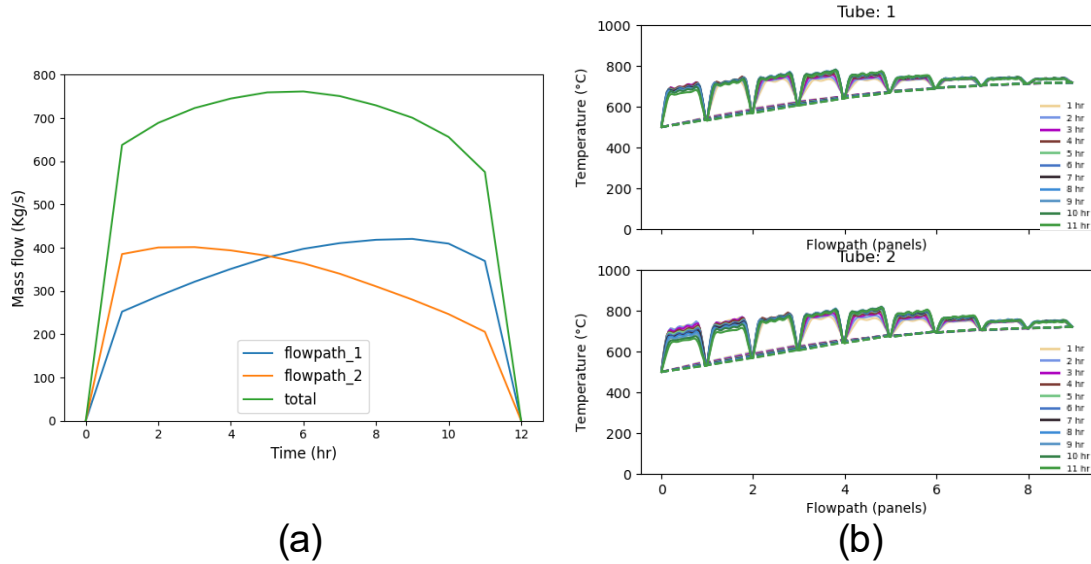


Figure 2. Example results showing (a) variation in HTF mass flow rate during the day for a constant outlet temperature of 720°C; and (b) changes in HTF (dashed lines) and tube crown (solid lines) temperatures (shown for the coldest and hottest tubes in the panels) along flowpath-1 at different times of the day. Results are shown for A740H receiver with a height of 12 m and diameter of 10 m (allowable flux: 1000 kW/m²).

For A740H, *srlife* estimates the creep-fatigue life based on calculated creep and fatigue damages. Table 2 lists results from design optimization of A740H receiver for an allowable heat flux of 750 kW/m². Config.#4 in Table 2 is found to be the best among all the configurations considered since it achieves the maximum creep-fatigue life while meeting the maximum pressure loss criteria, i.e. 3 MPa (see Table 1).

Table 2. Optimization of A740H receiver design for an allowable flux of 700 kW/m². '#' indicates the best among all the design configurations considered.

Config.	Tube t (mm)	Tube OD (mm)	Total panels	Total tubes	Max. tube T (°C)	P loss (MPa)	Avg. cf life (days)
1	1.24	42.2	24	1152	784	1.20	617
2	1.24	42.2	30	1140	763	2.22	704
3	1.24	33.4	18	1458	791	1.17	617
4 [#]	1.24	33.4	24	1440	764	2.59	732
5	1.24	33.4	30	1440	748	4.87	1282
6	1.24	21.3	12	2244	790	1.81	703
7	1.24	21.3	18	2250	756	5.87	1265

For SiC receiver, design optimization is done based on the time-independent reliability analysis. Table 3 present the optimization results for the SiC receiver design for an allowable flux of 700 kW/m². Configuration-1 in the table corresponds to the optimum design for A740H, included to illustrate the performance of SiC tubes if a 1.24 mm tube thickness could be achieved. However, the minimum tube thickness considered in this study is 3 mm for SiC, as listed in Table 1. Increasing the tube thickness from 1.24 mm to 3 mm while maintaining the inner diameter the same increases the maximum equivalent stress and therefore reduces the reliability according to the Weibull-2P model (see configuration-2 vs configuration-1 in Table 3). Although a thicker tube reduces the stress from HTF pressure, it significantly increases

thermal stress due to a higher through thickness thermal gradient. The pressure drop for the configuration-2 is 3.24 MPa, exceeding the design constraint of 3 MPa.

Table 3. Optimization of SiC receiver design for an allowable flux of 700 kW/m². '#' indicates the optimum design configuration. '\$' indicates the configuration found for optimum design of A740H receiver.

Con-fig.	Tube t (mm)	Tube OD (mm)	Total panels	Total tubes	Max. tube T (°C)	P loss (MPa)	Max. eq. stress (MPa)	Min. tube reliability (time-independent)	
								Weibull-2P	Weibull-3P
1\$	1.24	33.40	24	1440	747	2.59	91	59%	100%
2	3	36.92	24	1320	766	3.24	99	35%	100%
3#	3	38	24	1272	768	2.88	102	25%	100%
4	3	39	24	1248	770	2.60	104	17%	100%
5	3	40	24	1224	773	2.36	109	10%	100%

To reduce the pressure drop, the outer tube diameter is increased from 36.92 mm in configuration-2 to 38 mm in configuration-3. However, this increase leads to a higher maximum equivalent stress and further reduced reliability, again according to the Weibull-2P model. The pressure drop for Configuration-3, at 2.88 MPa, is within the design constraints, making configuration-3 the optimal design. Increasing the outer diameter above 38 mm decreases the pressure drop but does not improve structural performance.

It is important to note for all the configurations in Table-3, the reliability is estimated to be 100% when using the Weibull-3P model. This is because the stresses in all the receiver tubes are below the threshold stress of the Weibull-3P model. The probability of failure equations for Weibull-2P and Weibull-3P models are provided in Equation-1 and Equation-2, respectively.

$$P_{f,2P}(\sigma) = 1 - \exp\left(-\left(\frac{\sigma}{\sigma_{o,2p}}\right)^{m_{2p}}\right) \quad (1)$$

$$P_{f,3P}(\sigma) = \begin{cases} 0 & ; \text{if } \sigma \leq \sigma_u \\ 1 - \exp\left(-\left(\frac{\sigma - \sigma_u}{\sigma_{o,3p}}\right)^{m_{3p}}\right) & ; \text{if } \sigma > \sigma_u \end{cases} \quad (2)$$

where P_f is the probability of failure, σ the stress, m the Weibull modulus, σ_o the scale parameter, and σ_u the threshold stress. As Equation-2 indicates, the probability of failure is always zero for the Weibull-3P model when the stress is below the threshold stress.

Figure 3 compares the Weibull-2P and Weibull-3P model fit to the experimental data, along with the range of maximum equivalent stress values listed in Table 3 and the threshold stress of the Weibull-3P model. As the figure indicates, the maximum equivalent stress in all configurations is below the threshold stress, both for volume and surface flaws, resulting in a 100% reliability prediction for the Weibull-3P model. In contrast, the Weibull-2P model predicts a nonzero probability of failure even when the equivalent stress is near zero. For large components, like the 12 m long receiver tubes considered in this study, the estimated probability of failure for each element in the finite element model of the tube can quickly add up to a large value to probability of failure, resulting in a low reliability estimation of the tube.

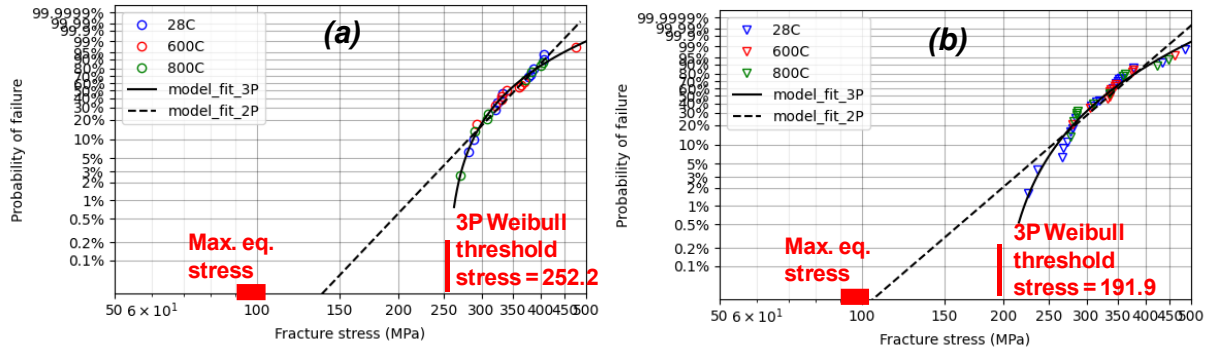


Figure 3. Maximum equivalent stress in the SiC receiver with optimum configuration for 700 kW/m² allowable flux is compared to the Weibull-2P and Weibull-3P model fit to experimental strength data of SiC for failure due to (a) volume flaws and (b) surface flaws.

As Figure 3 shows, the maximum equivalent stress is well below the minimum experimental strength of the material, indicating that tube tubes never fail in these stress levels. However, the Weibull=2P model still predicts low reliability. This comparison between Weibull-2P and Weibull-3P model estimations highlights two key points for designing ceramic receiver tubes: (1) do not reject a ceramic material solely based on Weibull-2P model results, and (2) test larger specimens and tubes to have higher confidence on the threshold stress estimation. The second point is important because, in large components like receiver tubes, reliability estimates using the Weibull-3P model are mostly controlled by the threshold stress parameter.

Table 4 presents the time-dependent reliability as a function of service life for the optimal SiC receiver design (configuration-3 from Table 3) for an allowable flux limit of 700 kW/m². The time-dependent reliability analysis accounts for SCG caused by high operating temperature and the diurnal cyclic loads. Details on the estimation of SCG parameters from experiments can be found in [13]. As shown in Table 4, the transformed equivalent stress – a modification of the equivalent stress to include the effects of SCG – increases with service life. Consequently, reliability predictions based on the Weibull-2P model decrease as the service life increases. However, the Weibull-3P model consistently predicts 100% reliability, even for a service life of 30 years, because the maximum transformed stress remains below the threshold stress.

Figure 4 summarizes the analysis results, comparing the estimated lives of A740H and SiC receivers as a function of allowable flux limits. For life estimations using the Weibull-2P model analysis, a target reliability of 50% is considered. As the figure indicates, the Weibull-2P model predicts nearly zero year life for all three flux levels. This is due to the inherent limitation of the model when calculating reliability of large components. Based on the Weibull-3P model SiC receiver will last longer than 30 years at all flux level with 100% reliability. In contrast, A740H receiver is estimated to have a very short life at high flux level, but it could service up to 30 years if the allowable flux is limited to 450 kW/m². However, operating the receiver at lower flux increases the number of required tubes, as shown in Figure 4.

Table 4. Time-dependent reliability of the optimum SiC receiver design for 700 kW/m² flux limit as a function of service life.

Life time (days)	Max. transformed eq. stress (MPa)	Min. tube reliability (time-dependent)	
		Weibull-2P model	Weibull-3P model
0	102	25%	100%
1	116	3.0%	100%
10	120	1.5%	100%
100	125	0.2%	100%
1000	129	0%	100%
10000 (30 years)	134	0%	100%

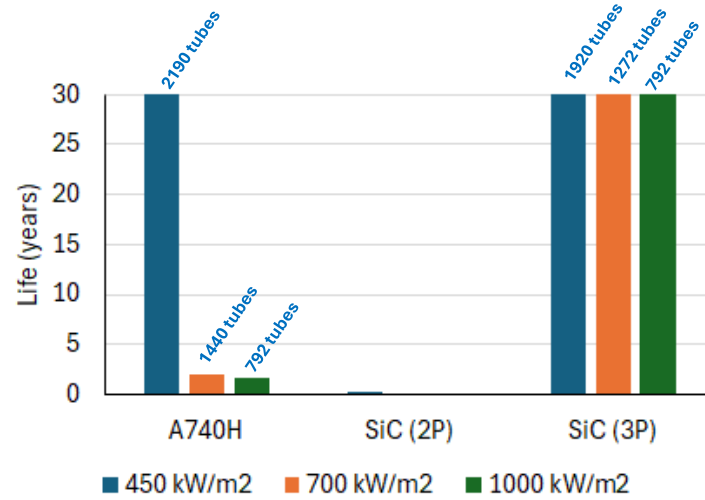


Figure 4. Receiver life comparison between A740H and SiC and the number of required tubes for each optimal design as a function of allowable flux limit.

5. Conclusion

This comparative analysis between a metallic material, A740H and a ceramic material, SiC for receiver designs highlights the critical role of material selection in achieving long-term reliability and performance in Gen 3 CSP systems. While high-temperature nickel-based alloys like A740H offer the potential for a 30-year service life, this is only achievable under a limited flux of 450 kW/m², which may present economic and operational challenges due to the need for larger receiver sizes and more tubes. In contrast, ceramic materials, specifically SiC, demonstrate superior performance in terms of high-temperature reliability. The Weibull-3P model predicts that SiC receivers can consistently deliver over 30 years of service life, even under flux levels as high as 1000 kW/m², with 100% reliability. The study also underscores the limitations of the commonly used Weibull-2P model, which tends to underestimate the reliability of large ceramic components. The Weibull-3P model, by incorporating a threshold stress parameter, provides a more realistic prediction, especially for large-scale applications. Finally, while ceramics like SiC present fabrication and ductility challenges, their high-temperature strength and low thermal expansion make them a promising alternative for CSP receiver designs.

Data availability statement

The material data used in receiver analysis is contained in the distribution of the *srlife* software, available at <https://github.com/Argonne-National-Laboratory/srlife>.

Underlying and related material

The underlying experimental data are available in ANL reports cited in the text.

Author contributions

Bipul Barua: Conceptualization, Formal analysis, Investigation, Methodology, Visualization, Writing – original draft. **Pawan Chaugule:** Methodology, Formal analysis, Writing – review & editing. **Mark C. Messner:** Conceptualization, Methodology, Funding acquisition, Writing – review & editing, Project administration, Resources. **Dileep Singh:** Project administration, Resources, Writing – review & editing.

Competing interests

The authors declare no competing interests.

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