Use of Stainless-Steel Tubes to Replace the Usual Copper Tubes in Flat Plate Solar Collectors in the Brazilian Solar Thermal Market: Overview and Impact on Energy Efficiency

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Abstract

Flat plate solar collectors (FPSC) should meet durability requirements which are related to the equipment ability to resist aging and damage occurring during lifetime. To face durability issues, especially concerning to freezing and corrosion resistance, Brazilian flat plate solar thermal collector manufactures are embracing product lines with stainless-steel (SS) tubes. Without wishing to proof if the use of SS tubes is beneficial to FPSC freezing and corrosion resistance, the objective of this work is restricted to analyze to what extent SS tubes are being used in Brazilian solar thermal market and its implications on solar collector thermal efficiency, considering that copper (Cu) tubes are the conventional material employed as FPSC tubes. For this purpose, a survey involving national manufacturers was carried out. Results revealed that 57% of the manufacturers belonging to the mandatory Brazilian Solar Thermal Labelling Program have at least one product line made of SS. Additionally, since SS has lower thermal conductivity than copper, an experimental study was conducted to identify the impact of Cu replacement by SS on FPSC thermal efficiency. Results showed that absolute and relative maximum reduction on efficiency is, respectively, around 2% and 7% at most, which is small when compared to the Cu to SS thermal conductivity difference, which is around 95% less for SS. This indicates that if freezing and corrosion resistance is confirmed, therefore, the use of SS tubes may be a good solution for solar thermal collectors installed in cold regions and/or subject to aggressive ambient/water conditions.

Keywords: Solar collector, thermal efficiency, stainless steel, copper, tubes

1. Introduction

Solar thermal energy is a renewable alternative that plays an important role in the energy transition. According to the REN21 Renewables Global Status Report 2024 Collection, only a small share of the total final energy consumed worldwide originates from renewable sources. At the global level, the shares of renewable energy used in the industrial and building sectors are 16.8% and 15.9%, respectively (REN21, 2024). The data therefore indicate that there is considerable potential to be filled using renewable energy sources, among which solar thermal energy stands out.

In this context, effective solar thermal energy exploitation must be based on high-quality flat plate solar thermal collectors (FPSC) that deliver the required efficiency and appropriate durability for users. Thermal efficiency is essential for expanding the use of solar heating systems, since more efficient collectors can produce more energy per unit of area, reducing costs. In addition, solar collector durability is also a mandatory requirement, as it is directly related to the technology reliability, assuring operation within appropriate standards and sustaining functionality throughout the entire equipment service life.

Among the various aspects to be considered when addressing durability, two of them earn particular attention: corrosion resistance and freezing resistance. In many locations, aggressive working fluid can damage the system, reducing the useful lifecycle of the equipment. In cold climates, low operating temperatures can cause the working fluid to freeze, which can result in irreversible damage such as component breakage and deformation.

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In Brazil, copper is the material that has been preferred for many years by the solar thermal industry to manufacture solar collector internal tubes. However, it can be noted that, in recent years, many Brazilians FPSC manufacturers are adopting a particular solution to overcome corrosion and freezing problems: setting up solar collectors' product lines based on stainless-steel (SS) tubes, instead of the usual copper (Cu) tubes. This work examines two questions: (1) to what extent is stainless steel being used in FPSCs manufactured in Brazil? (2) given that Cu thermal conductivity is about 20 times greater than that of SS, what is the resulting effect on FPSC thermal efficiency of using SS pipes instead of Cu pipes?

Finally, it is important to emphasize that this study does not aim to prove whether flat plate solar thermal collectors (FPSC) with SS tubes are more resistant to corrosion and freezing than FPSC with Cu tubes. The objective is restricted to analyze the effects on the efficiency of switching tube material from Cu to SS and how much the Brazilian solar thermal sector is embracing this alternative.

2. Corrosion in solar collectors

Corrosive processes in solar collectors must be considered as they threaten equipment and system durability. This topic is addressed in the Brazilian standard for solar water heating systems NBR 15569:2020 "Direct circuit solar water heating system - Design and installation requirements" as it states that "adequate protection and specification of the system components must be considered" (ABNT, 2020). Good practices to avoid corrosion are presented in the report "Corrosion and Scaling in Solar Heating Systems" from the United States Department of Energy. They include the use of deionized water, the management of the water pH in the range 7.5 to 9 and the elimination oxygen and carbon dioxide from the system (DOE, 1981).

Another way to prevent corrosion in solar collectors is to use polymers instead of metallic materials, however this may cripple heat transfer processes and limit the maximum allowable operating temperature (Alghoul et al., 2005). Typically, corrosive processes in solar water heating systems are identified when a leak in the pipes is noticed. This was the case in the community of Civano, Arizona/US, reported by Menicucci et al. (2003). These authors identified that the corrosion was related to the aggressive water of the region combined with system high stagnation temperature and to small tube thickness (Menicucci et al., 2003).

At this point, regarding water quality, it is important to emphasize that the attribute designated "aggressiveness" has two main aspects. One is corrosion itself, resulting from the presence of substances such as iron and chlorides or a pH of the water far from neutral. Another aspect is the occurrence of scale and wear resulting from the crystallization of mineral salts such as magnesium and calcium on the inner surface of the pipe. This last characteristic is often classified as "hard water." This type of water can cause damage to the pipes, but it should be emphasized that it is not a corrosive phenomenon (Solarem, 2016).

Finally, corrosion prevention is particularly important in solar collectors used in desalination processes. Hermann et al. (2002) developed a solar collector resistant to seawater to be used in a pilot plant, using selectively coated glass tubes obtaining good efficiency results and ensuring corrosion resistance.

3. Freeze resistance in solar collectors

Preventing the working fluid from freezing in solar collectors is essential in locations where ambient temperatures can reach values near to zero degrees Celsius. The standard ISO 9806:2017 "Solar energy – Solar thermal collectors – Test methods" provides procedures for testing solar collectors in a cold chamber to assess the freeze resistance. The test prescribed by the standard involves carrying out repeated freezing and heating cycles in the range of -20°C to +10°C, maintaining each temperature (-20°C / +10°C) for 1 hour in each cycle (ISO, 2017).

When it comes to protecting solar collectors from freezing, two main approaches can be considered. The first involves the protection provided by the system through its operating mode, and the second involves providing resistance through the solar collector itself, using specific materials or construction features.

The use of anti-freeze fluids is an alternative for adapting the solar heating system. Alternatively, drain-down or drain-back systems could be used. When the temperature approaches zero degrees Celsius, the solar heater is drained (drain-down system), or the fluid is recirculated (drain-back system) (Botpaev et al., 2016).

Regarding providing resistance through the solar collector itself, some authors have been proposing solutions. Vera-Medina et al. (2018) proposed a solar collector with flexible silicone peroxide tubes and demonstrated its feasibility through tests and numerical simulations. Deng et al. (2019) studied a similar prototype using silicone material and compared its thermal performance with Solar Keymark-certified collectors, with good results. Zhou et al. (2017) studied the use of transparent insulation material (TIM) to mitigate freezing in solar collectors and proposed a mathematical model to analyze its thermal behavior. Finally, Wang et al. (2019) studied the possibility of applying phase change materials (PCM) as an anti-freezing solution in solar water heaters and found satisfactory results, also for preventing overheating.

4. Method

4.1. Market survey

For the first objective of this article, which is to evaluate the degree to which SS is used in FPSCs manufactured in Brazil, a survey was conducted evaluating local manufacturers. A list of certified solar heaters in the country was consulted to identify the manufacturers and existing product lines. Currently, in Brazil, certification of solar heaters is mandatory, and product data is available on the Brazilian Labeling Program's online platform. Each manufacturer was analyzed individually, recording if they have a product line made with SS tubes. In total, 32 manufacturers were consulted, 30 with certified products and 2 with products in the process of certification. The survey did not consider FPSCs manufactured abroad. It also did not include other types of solar heaters, such as those for swimming pools and collectors made with vacuum tubes.

4.2. Experimental analysis

For the second objective of this article, which is to assess the effect on FPSC thermal efficiency of using SS pipes instead of usual Cu pipes, an experimental test was performed. Two identical collectors, apart from tubing material (one made of copper and the other made of SS), were tested to determine their thermal performance.

Figure 1: Solar collectors selected for testing with stainless-steel tubes (left) and copper tubes (right).

Both collectors have gross area of 1.5 m^2, with 1.0 m width, 1.5 m length and 0.65 m thickness. Aperture area is 1.43 m^2. Collector cover is plain glass with thickness equal to 3.15 mm. External box is made of aluminum as well as the absorber plate which has thickness of 0.4 mm and 0.5 mm in lateral and central fins, respectively. Both have 0.2 m thick thermal insulation on the back. The items submitted to tests have both two header tubes and 8 parallel riser tubes and the absorber plate is attached to tube thought mechanical fitting.

Figure 2 shows a schematic drawing of the FPSC tested emphasizing the difference between samples related to tube material.

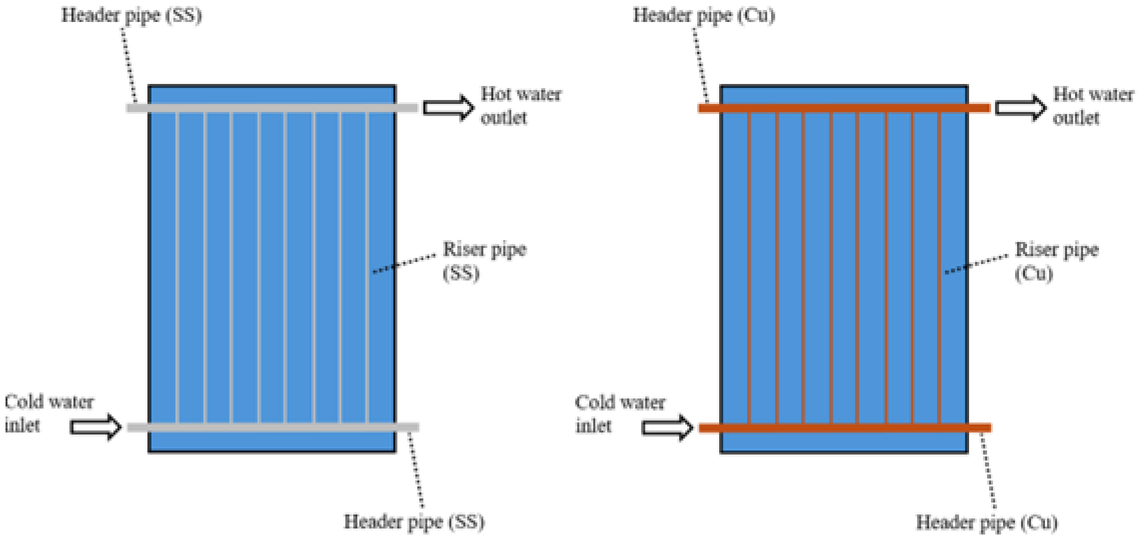

Figure 2: Solar collector schemes: stainless-steel tubes (left) and copper tubes (right).

Tests were performed using the artificial solar simulator shown in Figure 3. Solar simulator is installed in a climate-controlled chamber (96m2 and 8m high). The apparatus has two main parts. One of them (upper right side of Figure 3) contains eight lamps with a total power of 40kW that produce artificial solar radiation in a spectrum similar to that of natural solar radiation. The apparatus allows the lamps to be moved to ensure uniform irradiance incidence on the sample plane. Still in this part of the test facility there is an "artificial cold sky" composed of a steel frame with two layers of non-reflective glass where cold air circulates to prevent the incidence on the sample of infrared radiation generated by the lamps.

Figure 3: Solar simulator used to perform experimental tests.

The other part of the test facility is the test bench itself (bottom left of Figure 3). The test bench allows the solar collector to be installed in a position where the angle of incidence of the simulated solar radiation is zero, that is, the sun's rays are perpendicular to the collector plane. The water inlet and outlet pipes are connected so that water circulates at a uniform flow rate, and the collector operates under a steady-state condition.

The following variables were continually monitored during the tests: inlet and outlet water temperature, ambient air temperature, water flow rate and solar irradiance. Steady-state conditions were obtained for the following inlet temperatures: 20°C, 40°C, 60°C and 80°C.

The instantaneous thermal power produced (Q) at each water inlet temperature is given by:

$$Q = \dot{m}.c.\Delta T \qquad \text{(eq. 1)}$$

- $\dot{m}$: mass flow rate of the fluid (kg/s)
- c: specific heat capacity of the fluid ($J/kg.°C$)
- ΔT: temperature difference between inlet and outlet water (°C)

The collector's instantaneous thermal efficiency (η) is then calculated:

$$\eta = Q/(A.G) \qquad \text{(eq. 2)}$$

- Q: instantaneous thermal power (W)
- A: collector aperture area (m^2)
- G: solar irradiance (W/m^2)

Instantaneous thermal efficiency is usually plotted in a curve as function of a quantity that represents the operating condition. In the case of this work, the modified temperature difference (T_m^*) is the variable chosen to describe the operating condition, defined as follows:

$$T_m^* = (T_m - T_a)/G \qquad \text{(eq. 3)}$$

- T_m: mean water temperature (°C), the mean value between inlet and outlet water temperatures
- T_a: ambient temperature (°C)
- G: solar irradiance (W/m^2)

Finally, the efficiency used to compare the performance of SS-tube FPSC and Cu-tube FPSC showed in Figure 1, is calculated by statistical curve fitting of points $(x, y) = (T_m^*, \eta)$ obtained under steady-state condition:

$$\eta = \eta_0 - a_1.T_m^* - a_2.G.(T_m^*)^2 \qquad \text{(eq. 4)}$$

- η: instantaneous efficiency (Equation 2)
- T_m^*: modified temperature difference (Equation 3)

- η_0, a_1, a_2: constants from regression analysis
- G: solar irradiance (W/m^2)

To compare SS and Cu FPSC alternatives, two additional variables, namely absolute loss of efficiency L_a and relative loss of efficiency L_r, were introduced as shown in Equations 5 and 6, respectively:

$$L_a = \eta^* - \eta_{low} \quad \text{(eq. 5)}$$

- η^*: instantaneous efficiency of the sample with higher results (whether SS or Cu FPSC)
- η_{low}: instantaneous efficiency of the sample with lower results (whether SS or Cu FPSC)

$$L_r = (\eta^* - \eta_{low})/\eta^* \quad \text{(eq. 6)}$$

By definition η^* is always greater or equal to η_{low} and absolute loss of efficiency L_a and relative loss of efficiency L_r are functions of T_m^*.

Also, for comparison purposes, the maximum thermal power output Q_{max} or the peak power of a solar collector can be calculated using Equation 7:

$$Q_{max} = \eta_0 . A . G \quad \text{(eq. 7)}$$

- η_0: peak efficiency based on Equation 4
- A: collector aperture area (m^2)
- G: solar irradiance (W/m^2)

5. Results

5.1. Market survey

The following results were obtained from the market survey proposed in section 4.1:

- 56.7% of the companies have at least one product line with stainless steel (SS) tubes
- 43.3% of the companies do not have any product line with SS tubes
- All products that use SS, apply this material for collector risers and headers and not for the absorber plate, as proposed by He et al. (2024)
- SS solar collector lines are not the manufacturers main ones but serve a segment of the market
- Most of the manufacturers that use SS tubes claim this product line is designed to be freeze and corrosion resistant

4.2. Experimental analysis

Experimental tests were performed on the samples shown in Figure 1 according to the method defined in section 4.2. The instantaneous efficiencies obtained are presented in Figure 4.

Results show very similar thermal efficiencies for both samples. However, it was observed that the stainless-steel solar collector resulted in slightly lower efficiency values than the copper sample. This loss in efficiency is consistent with the physical properties of the materials, as the thermal conductivity of stainless-steel is lower than that of copper. The ratio of copper to stainless steel thermal conductivity is approximately 20.

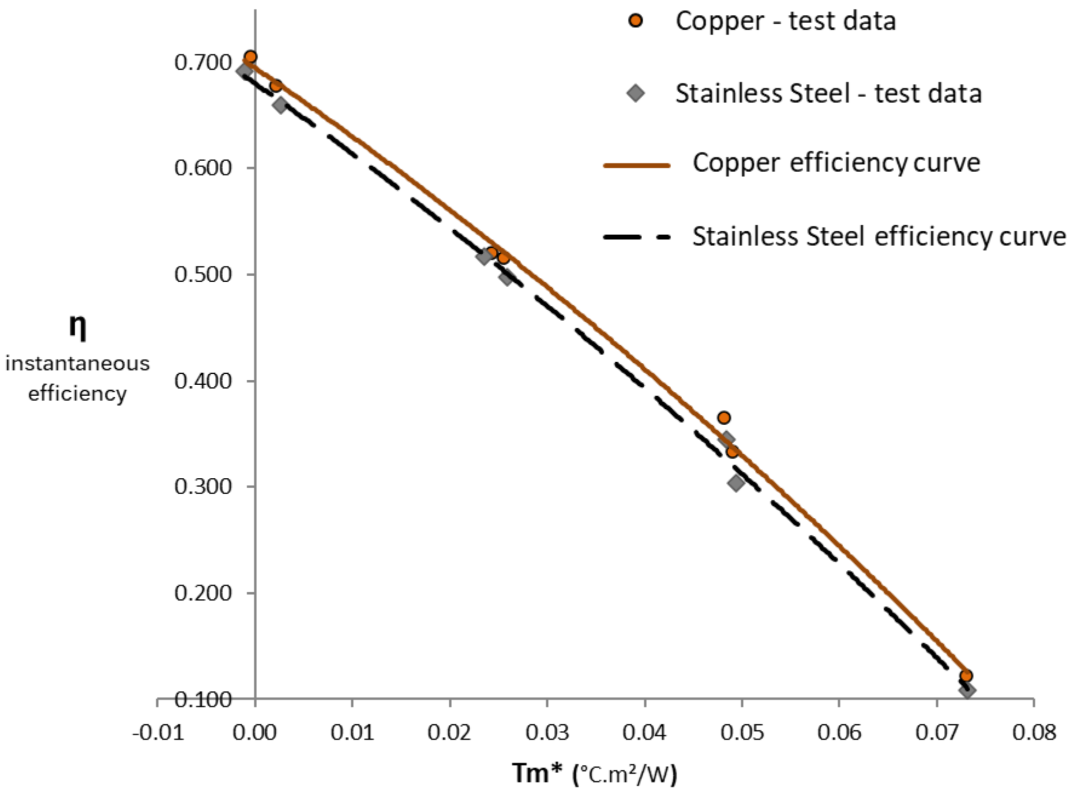

Figure 4: Instantaneous efficiencies determined in the experimental tests.

If, under hypothetical conditions, heat transfer was exclusively the result of thermal conduction, the useful energy available to the working fluid would be, in theory, 20 times greater in the copper solar collector. What is observed, however, is that the influence of the tube material on overall efficiency, which involves all heat transfer processes within the collector, is very small.

Analyzing Figure 4 it is possible to note that inclination and curvature of both efficiency curves are similar. However, at the point of maximum efficiency (η_0) and at maximum operating conditions (for which the efficiency equals zero) the difference between the curves can be better verified. Table 1 summarizes this information. Table 1 also presents the peak power (Equation 7) for both samples.

Table 1: Efficiency curves parameters.

Parameter	Cu FPSC	SS FPSC
Maximum efficiency (%)	69.5	68.0
Maximum modified temperature difference ($°C.m^2/W$)	0.0862	0.0849
Peak power (W), considering $G = 1000\ W/m^2$	998.8	972.8

These differences can also be analyzed from the perspective of a so-called efficiency loss, which occurs when SS is hypothetically used instead of Cu as the tube material. To this end, Equations 5 and 6, defined above, are used. Since the efficiency of the copper collector is greater than that of the SS collector, the value of η^* corresponds to the copper sample and η_{low} corresponds to the SS sample.

Figure 5 shows the absolute efficiency loss L_a as a function of T_m^*, and Figure 6 plots the relative efficiency loss L_r as a function of T_m^*. Considering the operating range of T_m^* from 0 to 0.06, as shown in Figures 5 and 6, the maximum efficiency loss was around 1.8 % in absolute terms and around 7% in relative terms.

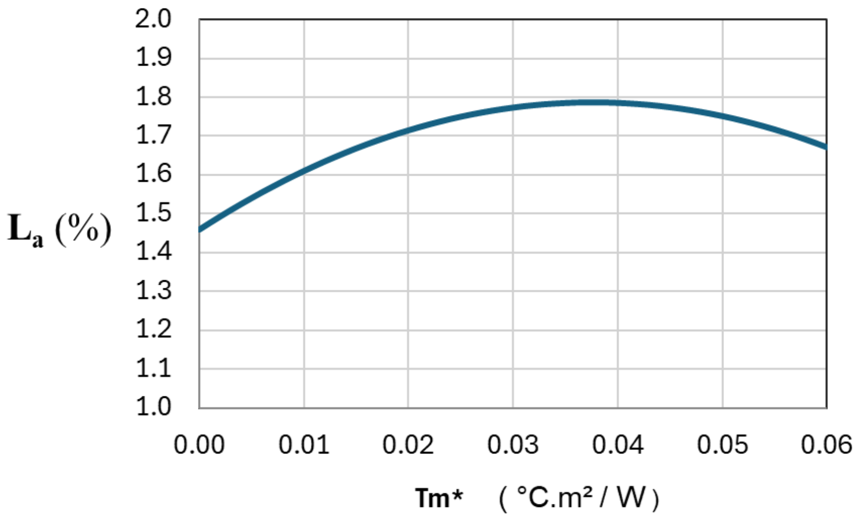

Figure 5: Absolute loss of efficiency in the operating range.

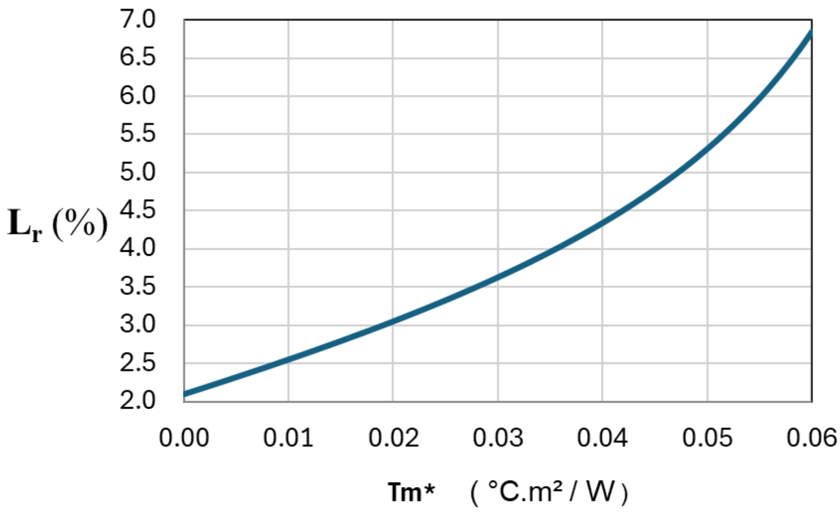

Figure 6: Relative loss of efficiency in the operating range.

The increase in relative efficiency loss (L_r) as the T_m^* value increases is explained by the fact that the absolute loss (L_a) is practically constant throughout the operating range. For high T_m^* values (close to 0.06), the absolute efficiency loss (between 1.4 and 1.8%) corresponds to a higher percentage of the total efficiency, since the efficiency is lower in this situation.

Finally, it can be noted that, in practice, using SS instead of Cu results in a displacement in the efficiency curve without a change in slope and curvature (see Figure 4). This is consistent with what would be expected from the use of a material with lower thermal conductivity (stainless-steel) for the tubes. The plate temperature, which determines heat losses, remains unchanged despite the material modification, so the slope and curvature of the efficiency equation remain the same. Heat transfer from the plate to the water, on the other hand, is affected, resulting in a lower η_0 value, reflecting the downward displacement in the curve.

6. Conclusions

This work deals with the use of stainless-steel (SS) pipes in FPSCs in the Brazilian market to prevent corrosion and freezing. The study investigated the product lines of 32 national manufacturers and identified that more than half of them have at least one product line with SS tubes. Experimental tests showed, when SS is used, an absolute reduction in thermal efficiency of 1.5% to 1.8% and a relative reduction of 2% to 7%, depending on the operating temperature. Although a loss of efficiency was observed, it was much smaller than the reduction in thermal conductivity (k) observed from copper to SS, of approximately 20 times, indicating that if freezing and corrosion resistance is confirmed in solar collector with tubes made with stainless-steel, then they may be a good solution for solar heaters installed in cold regions and/or subject to aggressive ambient/water conditions.

7. Acknowledgments

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8. References

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