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Residual stress Measurement of Glass-to-Metal Seal in Solar Receiver Tube

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ABSTRACT

In parabolic trough solar power system solar receiver tube is a key component to convert the solar energy into thermal energy. The residual stresses that are generated during the cooling process of the seal can decrease the seal strength and induce the breakage of the glass-to-metal sealing. The reliability of receiver tube significantly influence due to the residual stresses which are generated during the cooling process of glass-to-metal sealing. The failure or degradation of solar absorber tubes is the single largest cost factor for current parabolic trough solar power plant. To lower the seal failure probability, the stress distributions in the glass side are analyzed by using photo-elastic technique in agreement with the analytic solution approach.

Keywords— Solar Absorber Tube, Glass-To-Metal Seal, Residual Stress, photo-elastic technique.

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I. INTRODUCTION

A parabolic trough solar receiver is one of the most important elements in the solar thermal power system for converting the solar energy into thermal energy. The receiver typically consists of a metal pipe with a solar selective coating and an evacuated glass tube. The receiver tube incorporates glass-metal transitional elements and metal bellows to achieve the necessary vacuum-tight enclosure and to accommodate for thermal expansion difference between the metal pipe and the glass envelope, where in the central metal pipe and the glass-metal transitional element are connected with each other by means of bellows so that they can move relative to each other in a longitudinal direction [1]. The vacuum enclosure serves primarily to significantly reduce heat losses at high operating temperatures and to protect the solar selective absorber surface from oxidation.

Glass-to-metal seals are widely used in the solar receiver tube that is a key component in the parabolic trough solar thermal power system [3]. The receiver tube consists of a central metal pipe with a cermet solar-selective absorber surface, surrounded by an evacuated glass envelope. Failure or degradation of the receiver, which causes vacuum loss, fracture of glass tube and solar selective coating degradation, is the single largest cost factor for present current and future solar power plant.

Breakage of glass-to-metal sealing is main cause for damages of receivers. The problems of sealing are adhesion and stress. The adhesion is only a firm layer of metal oxide that is soluble in both metal and glass, and is the means of obtaining adherence. The reliability of the glass-metal bond is determined by the thickness of the oxide film, the uniformity of the layer and the oxide species. Pre-oxidation is a common technique to improve the chemical bonding. Through exact temperature and process control, a good glass-to-metal seal can be obtained. So adhesion problem is ignored.

The residual stresses that are inevitable in the glass-to-metal seal as a result of the difference in thermal contraction of the two components from the sealing temperature down to the room temperature [2]. The stress can significantly decrease the seal strength and influence the reliability of the receiver tube. The temperature changes during operation can also induce thermal stress that is an overlapped stress in the glass-to-metal seal. Therefore, it is necessary to evaluate the magnitude and distribution of residual stresses and to explore whether the stresses are great enough to cause cracks. To ensure vacuum stability over the whole lifetime of the receiver tube, a glass-to-metal seal with high mechanical strength and temperature resistance is needed. This implies a stress-free bonding between the metal part and the glass part.

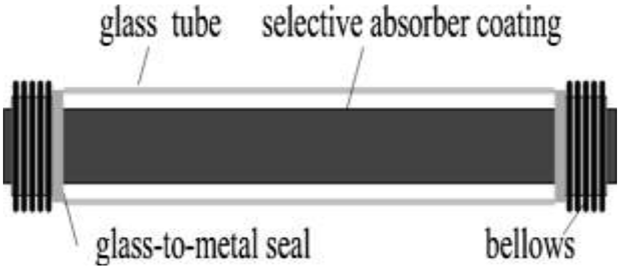


Fig. 1.Schematic of a typical solar receiver

II. PROBLEM STATEMENT

Glass-to-metal seals are widely used in the solar receiver tube that is a key component in the parabolic trough solar thermal power system. The receiver tube consists of a central metal pipe with a cermet solar-selective absorber surface, surrounded by an evacuated glass envelope. It incorporates glass–metal transitional elements and metal bellows to achieve the necessary vacuum-tight enclosure and to accommodate for thermal expansion difference between the metal pipe and the glass envelope [4].

Breakage of glass-to-metal sealing is main cause for damages of receivers in existing power plants. The residual stresses that are generated during the cooling process of the seal can decrease the seal strength and induce the breakage of the glass-to-metal sealing. The failure or degradation of solar absorber tubes is the single largest cost factor for current parabolic trough solar power plant [2].

III. SCOPE

Parabolic trough technology the first choice for large-scale solar power generation, Concentrated Solar Power (CSP) technology uses energy from the sun to generate heat, which is used in steam cycles to produce electricity. The technology is particularly efficient in regions with high direct solar irradiation, encompassing the earth's sunbelt on both sides of the equator. CSP plants are used in a similar manner like conventional steam power plants. The key difference is that CSP plants use emission-free, clean solar radiation to produce heat instead of fossil or nuclear fuels.

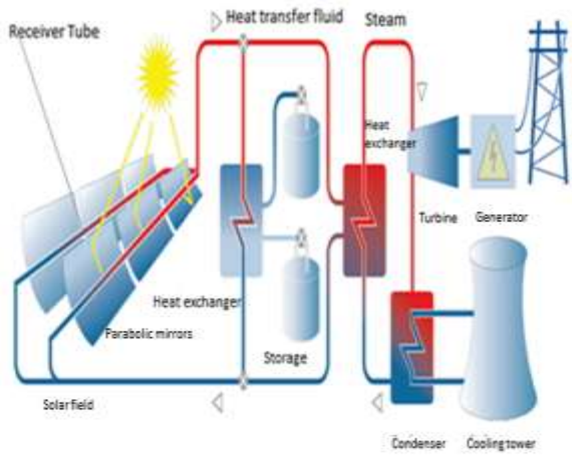


Fig. 2.Working principle of parabolic trough power plants

Amongst all CSP technologies, the parabolic trough technology has the longest commercial track record. Parabolic trough power plants are suitable for large-scale electrical output and can replace conventional thermal power plants without any qualitative changes in the electricity grid structure. Due to the option of thermal storage or hybridization, the turbines of CSP plants can also produce power in low solar radiation periods and at night, delivering power reliably.

IV. THE STRESS ANALYSIS OF SEAL

The key work is to reduce the residual sealing stress in the structural design of glass-to-metal seal. Apart from the sealing procedure, the strength of glass-to-metal sealing strongly depends on the four main parameters: the coefficient of thermal expansion, thermal conductivity, Young's modulus, and sealing structure parameter. The sealing structure is generally tubular seal that the edge of the metal ring is embedded into glass tube in the HCE. In order to obtain reliable sealing, we can either match the two coefficients of thermal expansion in order to avoid the stresses in the seals, or just limit the stresses to some values that are not dangerous for the integrity of the seal. According to the current technology, it can be divided between matched sealing and unmatched sealing.

In matched seals the thermal expansion coefficients of both components are similar at least in the temperature range between the strain point of the glass and room temperature. Above the strain point stresses can be relaxed by viscous flow. Below the strain point no stress relief takes place and stresses, owing to differential expansion of the two joined materials, become permanent. The stress σ, generated by the temperature change, ΔT, and the difference of the thermal expansion coefficients, $\Delta\alpha$, between the glass and the metal can be written as

$$\sigma = -A\,(\Delta\alpha\,\Delta T)$$

Where A is, in general, a position (x, y, z) dependent term involving the elastic modulus, E , and Poisson's ratio, μ, of both components. When the geometry of the glass to metal sealing is simple, e.g. a glass rod and a metal rod are fixed at one end and are restrained to move together at their other end. When they are heated up to a same temperature, it can be obtained

$$A = \frac{E_g \cdot E_m}{E_g + E_m}$$

Where E_g and E_m generally change very little as the materials change. To withstand greater changes in temperature, hard glass ($\alpha \leq 5\times 10\text{-}6$ /K, e.g. borosilicate glass) is needed for the receiver tube. The tensile strength of borosilicate glass is generally 40-120MPa. Therefore, in order to ensure that the stress level is in the safe range ($\sigma \leq$ 40MPa), the mismatch of the thermal expansion coefficients should not exceed the value given in equation as follows

$$|\alpha_m - \alpha_g|\, \Delta T \leq 7.5 \times 10^{-4}$$

The matched sealing then gives much lower residual stresses in the glass to metal seal than the tensile strength of the glass itself. However, this choice would lead to higher costs and pretty high difficulties for the suppliers in the world to match the highly dedicated glass requirements geometrical and water resistance.

The unmatched seal are based either on the fact that the stresses developed in the glass are relieved by plastic or elastic deformation in the metal or on the fact that the developed stresses are only compression. The unmatched seal used in current designs is known as a Housekeeper seal which consists of a thin metal with blade like edges inserted into the glass to form the junction. The unmatched stainless steel-Pyrex glass seals were used in the original Luz receiver tubes which experienced high failure rates approximately 4–5% per year. Stress analysis has indicated that the high stresses resulted from differential expansion between the metal and the glass when solar flux is incident on the seal areas is the primary cause of this failure.

A Design

The manufacture of receiver tube is constrained by the reliability of glass-to-metal seals. The specimen comprises of a metal ring and a glass tube. The seal configuration used in solar receiver tube is a tubular seal, of which the edge of the metal ring is embedded into the glass wall. In order to obtain reliable seals, a kind of borosilicate glass with high optical transmittance is chosen in the experiments.

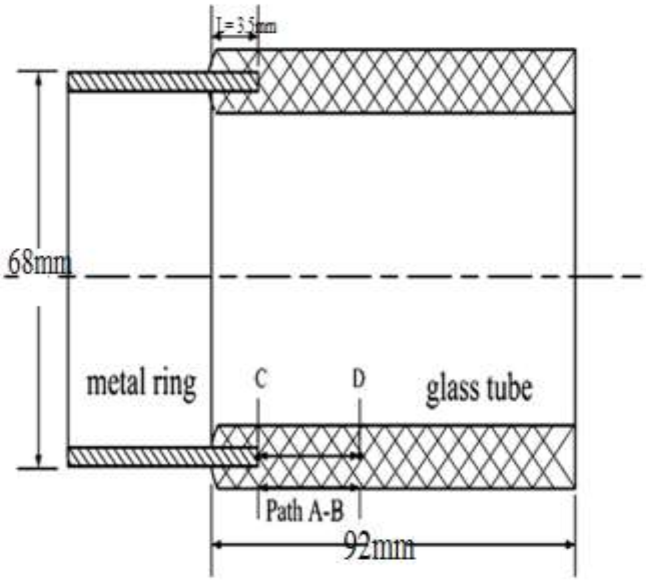


Fig. 3.Diagram of tubular seal

The glass tube has an outer diameter of 70 mm, a wall thickness of 3 mm, and a length of 113mm. The metal ring is made of the stainless steel 304 that has similar thermal expansion coefficient with the borosilicate glass. The metal ring has an outer diameter of 68 mm, a wall thickness of 1 mm and a length of 24mm. L designates the depth of metal ring embedded into glass. The diagram of tubular seal is shown in fig.3.

B Stress Analysis of Sealing Structure

In order to analyse the main problems and obtain the basic rules, a satisfactory approximate theory can be developed by making the following assumptions

i. The theory of thin shell can be applied to the analysis of sealing stress. The thickness of glass tube is far less than its radius, so this assumption is rational.
ii. The transient stress which caused by the uneven distribution of temperature in the sealed element is not considered in the calculation.
iii. The CTE of metal is assumed to be bigger than that of the glass, $\alpha_m > \alpha_g$ It is impossible that the coefficients of expansion of metal and glass are the same over the whole temperature range from room temperature up to the transition point.

Through the assumptions, the structure of glass-to-metal seal is simplified as the diagram shown in Fig.3. According to the theory of thin shell and thermal stress theory, the contraction distortion of metal ring is larger than that of glass in the radial direction when the element is cooled from sealing temperature to ambient temperature. Both the glass tube and the metal ring are subject to the action of bending moments M (Nm/m) and shearing forces P (N/m) by contrary directions. The glass tube and the metal ring should meet the displacement and turn-angle displacement compatibility equation

$$\Delta_m^P - \Delta_m^M + \Delta_g^P + \Delta_m^M = \Delta$$
$$\theta_m^P - \theta_m^M = \theta_g^P + \theta_g^M \qquad (1.1)$$

Where, $\Delta_m^P = PK_m$,which denotes the radial displacement of metal ring caused by the forces P; $\Delta_g^P = PK_g$,which denotes the radial displacement of glass tube caused by the forces P; $\Delta_m^M = MK_m$,which denotes the radial displacement of metal ring caused by the moment M; $\Delta_g^M = MK_g$,which denotes the radial displacement of glass tube caused by the moment M; $\theta_m^P = PK'_m$,which denotes the turn-angle displacement of metal ring caused by the forces P; $\theta_g^P = PK'_g$, which denotes the turn-angle displacement of glass tube caused by the forces P; $\theta_m^M = MK''_m$, which denotes the turn-angle displacement of metal ring caused by the moment M; $\theta_g^M = MK''_g$, which denotes the turn-angle displacement of glass tube caused by the moment M.

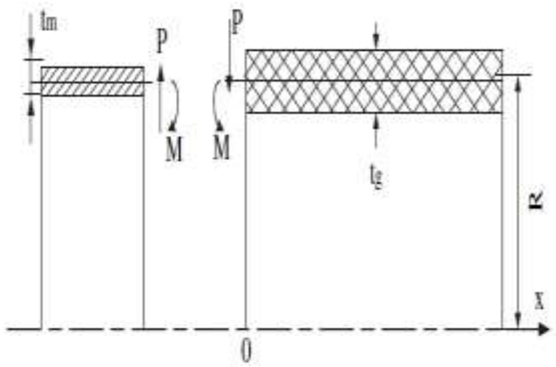


Fig. 4.Structure of the glass-to-metal seal

$$K_m = \frac{1}{(2\beta_m^3 . D_m)}; \quad K'_m = \frac{1}{(2\beta_m^2 . D_m)};$$

$$K''_m = \frac{1}{(\beta_m . D_m)}; \quad K_g = \frac{1}{(2\beta_g^3 . D_g)}; \quad K'_g = \frac{1}{(2\beta_g^2 . D_g)};$$
$$K''_g = \frac{1}{(\beta_g . D_g)}; \ \beta = \left[\frac{3(1-\mu^2)}{t^2 . R^2}\right]^{0.25}; D = \frac{E\,t^3}{12(1-\mu^2)}$$

Where,K_m, K'_m and K''_m denote the flexibility factors of metal ring, K_g, K''_g and K'_g , the flexibility factor of glass tube, D the flexural rigidity of material, R the radius of the middle plane in glass tube. t, α, μ and E respectively denotes the thickness, CTE, Poison' ratio and Young's modulus.

When the sealed elements are annealed, the glass can relieve internal stresses generated not only by the difference of CTEs of glass and metal but also by the sealing geometry. When the temperature is below the transition point (T_g), it retain the thermal stresses which will be permanent.

Where, $\Delta = (\alpha_m - \alpha_g)\,\Delta T\,R$. Δ is the radial displacement difference between glass tube and metal ring caused by the different CTEs from transition point to room temperature. Substituting these values in Equation (1.1), we obtain

$$P = \frac{(\alpha_m - \alpha_g)\Delta T . R}{\left[(K_m + K_g) - \frac{(K'_m - K'_g)^2}{(K''_m + K''_g)}\right]} \qquad (1.2)$$

$$M = \frac{K'_m - K'_g}{K''_m + K''_g} . P \qquad (1.3)$$

According to the expression P and M, we can obtain the analytic solutions are shown as following equations

$$\sigma_{xg} = \pm \frac{6}{t_{g.\beta}^2} . e^{-\beta x}\ [(\beta M + P)\sin\beta x + \beta M\ \cos\beta x] + \frac{t_m^2 E_m E_g \Delta t(\alpha_m - \alpha_g)}{t_g(t_m E_m + t_g E_g)}$$

$$\sigma_{\theta g} = -\frac{2R\beta}{t_g} e^{-\beta x}\ [(\beta M + P)\cos\beta x - \beta M \sin\beta x]$$

$$\tau_{xrg} = -\frac{1}{t_g} e^{-\beta x}[P\cos\beta x - (P + 2\beta M)\sin\beta x]$$

Where, σ_{xg}, $\sigma_{\theta g}$, τ_{xrg} and denotes respectively the axial stress, circumferential stress and tangential stress on the glass tube. R , t , α , μ ,E , D , x and β respectively denotes the radius of the middle plane, the thickness of tube, CTE, Poison' ratio, Young's modulus, the flexural rigidity of material, distance from the interface and the flexibility factors.

V. EXPERIMENTAL ANALYSIS

For Photo-Stress analysis, a reflection polariscope is used to observe and measure the surface strains on the photoelastically coated test part. The Photo-Stress plus LF/Z-2 Reflection Polariscope covers a wide range of strain measurement capabilities.

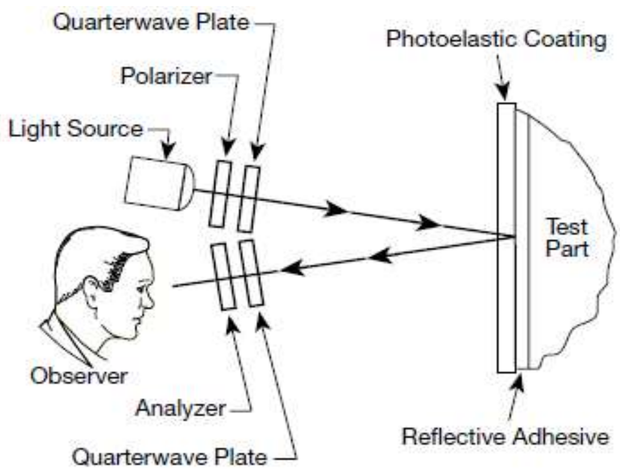


Fig. 5.Schematic representation of reflection polariscope

For instance, measurements made on small parts or in regions of high stress concentration are both easier and more accurate when zooming in with the digital video camera supplied with the polariscope.

The reflection polariscope is used for experimental method to find stress distribution in a material. The method is mostly used in cases where mathematical methods become quite cumbersome. Unlike the analytical methods of stress determination, photo elasticity gives a fairly accurate picture of stress distribution, even around abrupt discontinuities in a material. The method is an important tool for determining critical stress points in a material, and is used for determining stress concentration in irregular geometries. The various parts of the reflection polariscope are-

I. Polariscope head
II. Polariscope light source
III. Light source Power supply
IV. Laser light source.
V. Polariscope and video camera mounting plate.
VI. Electronic compensator.
VII. Video camera

Fig.6. LF/Z-2 Reflection Polariscope

Reflection polariscope works on the photoelasticity principle i.e. when the light is passing through polarizer & reflects from coated surface of specimen and observed through analyzer. The generation of various fringes observed in analyzer. To translate measured fringe orders in strains or stress in reflection photoelasticity. The basic relationship between strain and fringe order is

$$\varepsilon_1 - \varepsilon_2 = \frac{N\lambda}{2tK} = Nf$$

Where, ε_1, ε_2 = principal strains (m/m)

N = fringe order, or number of wavelengths of relative retardation.

λ = wavelength of tint of passage in white light, taken as 575 nm.

t = coating thickness, in (0.075mm)

K = strain-optic coefficient of the photoelastic plastic(4×10^{-6}) .

f = fringe value of the plastic coating, (m/m) per fringe

Engineers and designers often work with stress rather than strain and for this purpose it is transformed by introducing Hooke's law for the biaxial stress state in mechanically isotropic materials:

$$\sigma_1 - \sigma_2 = \frac{E}{1+v} Nf$$

Where,

$\sigma_1 - \sigma_2$ = principal stresses in test part surface

E = elastic modulus of test part

v = Poisson's ratio of test part

VI. RESULT AND DISCUSSION

A. Testing results for glass-to-metal seal

Fig.7.PhotoStress fringe pattern at Zero compensator reading

In figure7 fringe pattern is visible in analyzer so it is cleared that residual stresses are generated during the manufacturing process of glass-to-metal seal.

The residual stresses generated at time of manufacturing are maximum at the interface end of glass-to-metal seal and these stresses decreases along this direction on tube (see fig. 7, 8 & 9).

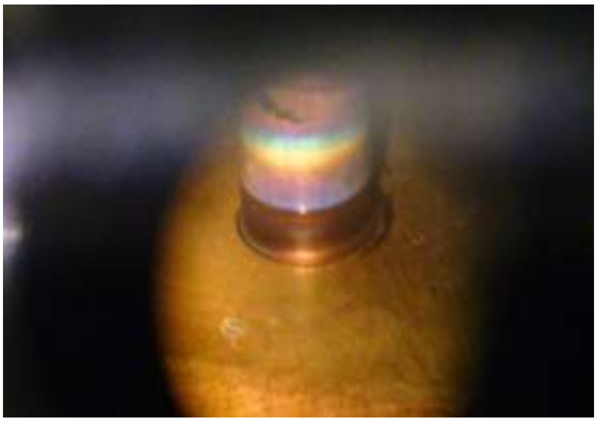


Fig.8.PhotoStress fringe pattern at 7mm from interface of glass-to-metal seal

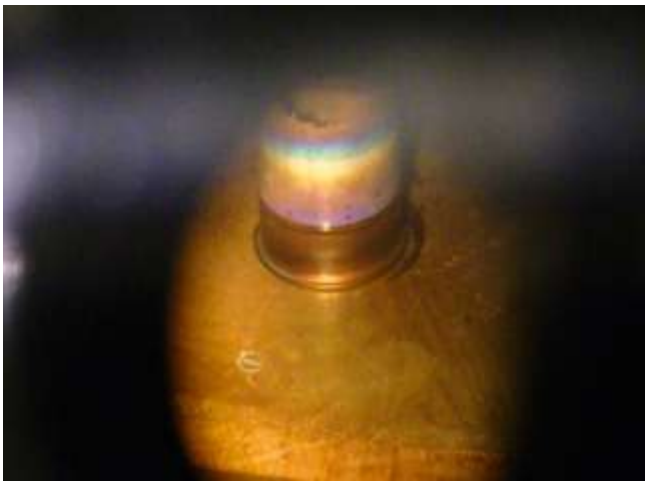
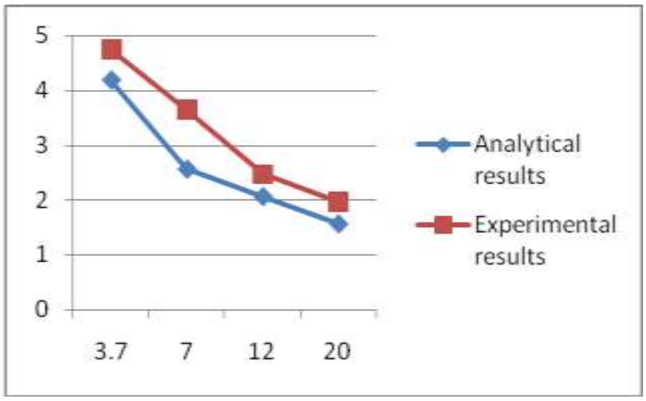


Fig.9.PhotoStress fringe pattern at 3.5mm from interface of glass-to-metal seal

Table 1: Comparison between analytical and experimental results

Distance from interface (x) mm	Analytically Stress Calculated $\sigma_1 - \sigma_2$ Mpa	Experimental Stress Analysis $\sigma_1 - \sigma_2$ Mpa
3.7	4.1831	4.753
7	2.564	3.64924
12	2.065	2.4685
20	1.569	1.9624

Above table shows the stress distribution of glass-to-metal seal of Stainless steel 304 and Borosilicate glass at various point. The axial stresses (σ_1) are tensile on the outer surface of the glass tube and compressive on the inner surface. Since the glass is fragile material and its tensile strength is far less than the compressive strength, the residual tensile stress is the most dangerous on the glass tube. The circumference stresses (σ_2) are compressive near the glass-to-metal interface on the glass tube, while axial stresses are tensile on the outer surface of the glass tube and compressive on the inner surface.



Graph shows the difference between experimental and analytical stress distribution of glass-to-metal seal.

VII. CONCLUSION

This paper reports an evaluation of the residual stresses distribution in glass-to-metal seals in solar receiver tube by using reflection polariscope. And by using the thin shell theory and thermal stress theory, this paper also analyzes the glass-to-metal sealing residual stress theoretically in the solar absorber tube. The experimental results agree with the theoretical results. The following conclusions can be reached:

I. The dangerous stress concentration generally occurs in the vicinity of the glass–metal interface.

II. The results show that the difference of CTE for the glass and the metal is the principal factor affecting the magnitude of residual stress.

In this paper we obtain the result for Stainless steel 304 and Borosilicate glass which gives residual tensile stress c= 4.753Mpa , which is dangerous to solar tube.

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