

PERFORMANCE OF COLOURED SOLAR COLLECTORS

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ABSTRACT:

The use of solar collectors with coloured absorbers for water heating is an area of particular interest when considering their integration with buildings. By matching the absorber colour with that of the roof or façade of the building, it is possible to achieve an architecturally and visually pleasing result. Despite the potential for the use of coloured absorbers very little work has been undertaken in the field.

In this study, the thermal performance of a series of coloured, ranging from white to black, water heating solar collectors is examined. Subsequently, the annual solar fraction for typical water heating systems with coloured absorbers is calculated. The results show that coloured solar collector absorbers can make noticeable contributions to heating loads. Furthermore, although their thermal efficiency is lower than highly developed selective coating absorbers, they offer the advantage of sensitive integration with buildings.

KEYWORDS: Solar collector, water heater, colour

1. INTRODUCTION

When examining solar collectors one could be excused for believing that they can have them “painted any colour ... so long as it is black”, as Henry Ford famously stated about the Model T Ford [1]. Until relatively recently, the idea of not using either a black, or other selective surface, coating appears to have avoided attention in the literature. The irony of significant amounts of research money and time being invested into developing high performance selective and black surfaces is that it misses the fact that, according to Weiss and Stadler [2], 85% of architects would prefer solar collectors in colours other than black, irrespective of the effect it may have on the system performance.

Tripanagnostopoulos et. al. [3] were perhaps the first researchers to seriously address the issue of coloured absorbers for solar collectors. In their study they examined the performance of unglazed and uninsulated, unglazed and insulated and glazed and insulated solar collectors that were black, blue and brown in colour. They showed that the efficiency of the collectors was actually quite similar despite their external appearance. Further they proposed the use of reflectors as a means of augmenting the performance of their collectors. In a follow-up study by Kalogirou et. al. [4], it was found that although coloured absorbers required higher levels of auxiliary heating, in a large domestic water heating application, the thermal output was only 18% lower than collectors with a selective surface.

In another recent study Medved et. al. [5] demonstrated the use of a brown unglazed solar collector for swimming pool heating. Although the influence of colour was not an objective of

their study, they note that their collector could achieve efficiencies of approximately 74% if it were optimised.

As an alternative to using a coloured absorber, Schuler et. al. [6-8] examined the use of coloured glazing as a means of changing the appearance of solar thermal collectors. In these studies thin film interference filters and multilayer optical stacks are presented as a means of achieving a coloured appearance from the glazing placed over the standard selective surface absorbers. The downside however, as the authors mention, is that there is still significant development needed to prove these glazings, both in terms of manufacturability and operational life.

Therefore, in light of the lack of data relating to the performance of coloured solar collectors the aim of this study was to examine how colour influenced the efficiency of solar thermal collectors.

2. COLLECTOR DESIGN

Unlike many commercially available collectors, and those of Tripanagnostopoulos et. al. [3], the collectors in this study were not constructed from finned copper tubes. Instead the collectors were fabricated from two colour coated mild steel sheets that were folded to form a rectangular cross section tube. Additionally mineral wool insulation was placed behind the absorber sheet and a low-iron glass cover above the collector as shown in Figure 1.

Although the fabrication of finned copper tube style collectors is well understood, the unconventional design of the collector, and the desire for it to be made from relatively low-cost pre-coated steel, presented a number of challenges. The main challenge is due to the fact that the material is galvanised and coated in paint. As such the material cannot be welded without removing both these coatings. In order to circumvent this issue, it was decided to bond the secondary folded sheet to the coloured absorber with a high temperature Silicone adhesive.

Due to the batch production nature of the prototype, the secondary sheet was folded using a brake press, holes were drilled to allow fluid into the underside of the rectangular tube, nipples were soldered to the rear surface around these holes to allow a manifold to be attached, the ends were sealed and the top absorber sheet was bonded into place. Finally, a removable low-iron-glass cover was placed over the collector to prevent convection losses.

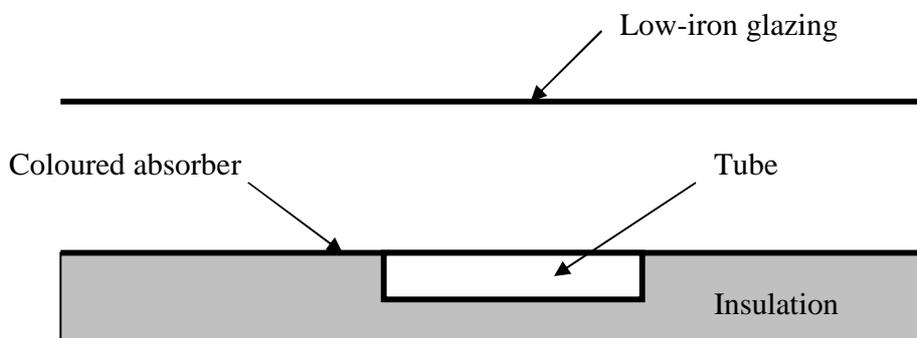


Figure1: Partial cross-section of coloured collector

3. MEASUREMENT OF COLOURED ABSORBER PERFORMANCE

When examining the performance of either glazed or unglazed coloured flat plate solar collectors, it is important that we are able to characterise their spectral absorption characteristics. From a theoretical perspective the thermal efficiency of a flat plate solar collector can be represented by a relationship between the collectors heat removal factor (F_r), the collector heat loss coefficient (U_L), the inlet (T_i) and ambient temperatures (T_a), solar radiation (G'') and the collector transmittance-absorptance product ($\tau\alpha$) as shown in Equation. 1.

$$\eta = F_r(\tau\alpha) - F_r U_L \left(\frac{T_{in} - T_a}{G''} \right) \quad (1)$$

Of these parameters, the transmittance-absorptance product is the only one that is based solely on a physical property of the collector materials. The absorptance provides a measurement of the optical properties of the radiation absorbing surface, in this case the coloured absorber, while the transmission component measures the portion of the radiation transmitted by any glazing layer. Therefore, in order to understand the optical characteristics of the coloured collectors it was decided to determine their absorptance properties over the solar radiation spectrum.

To determine the absorption of the colour coated mild steel the diffuse reflectance (ρ) of a white, red, green, grey and black sample were measured at 20 nm wavelength intervals between 300 nm to 2500 nm using a spectrophotometer and a 6° integrating sphere at Industrial Research Limited (Wellington, NZ). Based on the reflectance measurements it is possible to determine the absorptance (α) component using Equation 2, as it can be assumed that there is no “transmittance” component in air [9].

$$\alpha = 1 - \rho \quad (2)$$

By integrating the absorptance derived from the measurements of the reflectance it was found that the black painted steel had relatively constant reflectance characteristics across the measured wavelengths of the Air Mass 1.5 (AM1.5) solar spectrum. However the other coloured samples, as would be expected, were more sensitive to wavelength. In particular the white sample absorbs less than 35% of the AM1.5 radiation. Interestingly, the red sample absorbed a large portion of the shorter wavelengths (<1100nm) than the longer wavelength radiation, where it reflected a similar portion of the radiation to the white sample. This is somewhat self-evident however, as the sample appears red because it will absorb all wavelengths other than those that correspond to the red portion of the visible spectrum.

Having determined the absorption characteristics of the absorber, to determine the transmittance-absorptance product of a glazed coloured collector it is necessary to substitute the measured spectral absorption characteristics and the low iron glass transmittance characteristics of Dietz [10] into Equation. 3.

$$\tau\alpha = \frac{\int_{\lambda_1}^{\lambda_2} \tau_{\lambda} \alpha_{\lambda} I_{\lambda,i} d\lambda}{\int_{\lambda_1}^{\lambda_2} I_{\lambda,i} d\lambda} \quad (3)$$

By integrating these values over the AM1.5 spectrum it is found that the transmittance-absorptance product for glazed solar collectors of the various colours. Based on this method, the transmittance-absorptance values determined for each colour are given in Table 1.

Table 1: Transmittance-absorptance product of glazed coloured collectors

Colour	Transmittance-absorptance product
Black	0.87
Grey	0.81
Green	0.72
Red	0.60
White	0.32

4. THEORETICAL COLOURED COLLECTOR PERFORMANCE

Having determined the transmittance-absorptance product for the various coloured glazed collectors it is possible to determine their theoretical performance using a one-dimensional steady state thermal model based on the Hottel-Whillier-Bliss equations presented by Duffie and Beckman [9].

Under these conditions the useful heat gain can be calculated using Equation 4.

$$Q = AF_R [(\tau\alpha).G'' - U_L(T_{in} - T_a)] \quad (4)$$

Where the useful heat gain (Q) is given by a relationship between the collector area (A), the heat removal efficiency factor (F_R), the transmittance-absorptance product of the coloured collector ($\tau\alpha$), the solar radiation (G''), the collector heat loss coefficient (U_L) and the temperature difference between the collector inlet temperature (T_{in}) and the ambient temperature (T_a).

The heat removal efficiency factor (F_R) can be derived from Equation 5, which accounts for the mass flow rate in the collector (m) and the specific heat of the collector fluid (C_p).

$$F_R = \frac{mC_p}{AU_{loss}} \left[1 - e^{-\frac{AU_{loss}F'}{mC_p}} \right] \quad (5)$$

To determine the heat removal efficiency factor it is necessary to calculate a value for the corrected fin efficiency (F'). This is done by first calculating the fin efficiency (F) using Equation 6. This determines the efficiency of the finned area between adjacent tubes and takes into account the influence of the tube pitch (W) and the tube width (d). Furthermore, the coefficient (M) accounts for the thermal conductivity of the absorber and is derived from Equation 7.

$$F = \frac{\tanh\left(M \frac{W-d}{2}\right)}{\left(M \frac{W-d}{2}\right)} \quad (6)$$

$$M = \sqrt{\frac{U_{loss}}{K_{abs} L_{abs}}} \quad (7)$$

Therefore, the corrected fin efficiency (F') can be calculated using Equation 8, noting that there is not bond resistance term as would be found in the analysis of a finned tube analysis and where the overall heat loss coefficient (U_L) of the collector is the summation of the collector's edge, bottom and top losses. It is taken that the bottom loss coefficient is given by the inverse of the insulations R-value (i.e. K_b/L_b) and Equation 9 gives the edge losses, where p is the collector perimeter and t is the absorber thickness.

$$F' = \frac{\frac{1}{U_L}}{W \left[\frac{1}{U_{loss} (d + (W - d)F)} \right] + \frac{1}{\pi d h_{fluid}}} \quad (8)$$

$$U_{edge} = \frac{K_{edge} p t}{L_{edge} A_{collector}} \quad (9)$$

The top loss coefficient is a function of both radiation and wind and can be calculated using Klein's empirical equation (Equation 10) [9].

$$U_{top} = \left\{ \frac{N}{\frac{c}{T_{pm}} \left(\frac{T_{pm} - T_a}{N - f} \right)^e} + \frac{1}{h_w} \right\}^{-1} + \frac{\sigma (T_{pm} + T_a) (T_{pm}^2 + T_a^2)}{(\varepsilon_p + 0.00591 N h_w)^{-1} + \frac{2N + f - 1 + 0.133 \varepsilon_p - N}{\varepsilon_g}} \quad (10)$$

Where:

$$c = (520 - 0.000051 \beta^2) \quad f = (1 + 0.089 h_w - 0.1166 h_w \varepsilon_p) (1 + 0.07866 N)$$

$$e = 0.430 \left(1 - \frac{100}{T_{pm}} \right) \quad T_{pm} = T_{in} + \frac{Q / A_{collector}}{F_R U_{loss}} (1 - F_R)$$

and β is the collector mounting, σ is the Stefan-Boltzmann constant, N is the number of covers or glazing layers, ε_g is the emittance of the glazing, ε_p is the emittance of the plate and h_w is the convection heat transfer due to the wind.

From these equations it is then possible to calculate the useful heat gain from the solar collector. By taking the ratio of the useful heat gain to the total radiation falling on the collector area (Q/AG'') we can subsequently determine the theoretical efficiency as given in Equation 1.

Therefore, by substituting the design parameters listed in Table 2 into the equations listed above, in combination with the measured transmittance-absorptance products for glazed collectors, it is possible to determine the theoretical thermal efficiency for the coloured collectors.

Table 2: Design parameters for coloured solar collectors

Parameter	Symbol	Value	Unit
Number of covers	N	1	
Emittance of plate	ε_p	0.95	
Emittance of cover	ε_c	0.88	
Number of tubes	n	2	
Collector Length	L	1.96	m
Collector Breadth	b	0.5	m
Collector Area	A	0.98	m ²
Absorber thickness	t	0.5	mm
Tube Hydraulic Diameter	d_h	9	mm
Tube Spacing	W	0.2	m
Tube Width	d	50	mm
Insulation Conductivity	k	0.045	W/mK
Back Insulation Thickness	L_b	0.1	m
Edge Insulation Thickness	L_{edge}	0.025	m
Absorber Conductivity	k_{abs}	50	W/mK
Mounting Angle	β	37	degrees

Subsequently it can be seen that the predicted thermal efficiency for each of the coloured collectors in Figure 2. As would be expected, the black collector has the highest predicted efficiency while the white collector has the lowest.

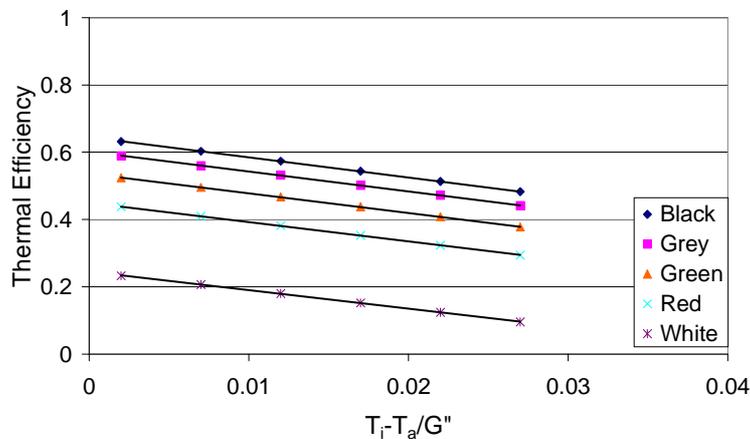


Figure 2: Theoretical efficiency of glazed coloured solar collectors

5. EXPERIMENTAL METHOD AND ANALYSIS

Although Figure 2 illustrates the potential performance of glazed colour collectors, good practice necessitates validating the model experimentally. As such two glazed prototype collectors were constructed for testing: one green and one grey. Although there are a number of potential methods for determining the thermal efficiency of solar water heaters; for this study a steady state outdoor thermal test setup similar to that recommended in AS/NZS 2535.1 [11] was used, as shown in Figure 3.

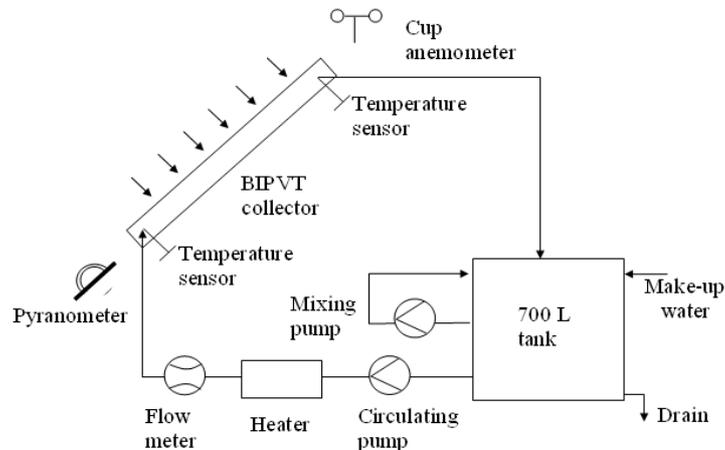


Figure 3: BIPVT collector test system

In order to test the prototype collectors, an unimpeded north facing test location was found on the University of Waikato library roof. The global solar radiation incident on the collectors' surface was measured using a calibrated WMO First Class pyranometer mounted inline with the collector at an angle equal to the local latitude (37 degrees).

Calibrated T-type thermocouples ($\pm 0.3\text{K}$) were used to measure the inlet and outlet temperatures to the collector, and the ambient air temperature. A cup anemometer mounted adjacent to the test stand was used to monitor the wind speed. The flow rate through the collector was set at a constant rate and monitored throughout the testing periods by measuring the time taken for a known mass of water to pass through the collector.

Additionally, an instantaneous electric water heater with temperature control was mounted on the inlet side of the collector to provide a controllable inlet water temperature. The outlet from the collector was returned to a 700-litre water tank where it was well mixed to ensure that the heater did not encounter large instantaneous temperature variations.

A prerequisite to accurately determining the performance of the collector is to conduct a number of outdoor tests under a range of ambient conditions and allow it to reach steady state for each condition. Subsequently, when analysing the collectors, the instantaneous collector efficiency can be reached directly from the experimental results by taking the ratio of heat transfer in the collector to the product of the collector area and the global solar irradiance.

6. EXPERIMENTAL PERFORMANCE OF COLOURED COLLECTORS

From the experimental data collected during the testing it was possible to derive the efficiency equation of the both coloured collectors using a linear least squares regression analysis. The experimental data yields two equations that describe the grey and green collector efficiencies respectively, as shown in Equations 11 and 12.

$$\eta = 0.65 - 10.4 \frac{T_i - T_a}{G''} \quad (11)$$

$$\eta = 0.63 - 14.6 \frac{T_i - T_a}{G''} \quad (12)$$

Although this is the most common way of presenting the efficiency of the collector it can be better understood from an inspection of Figures 4 and 5, where the theoretically predicted efficiencies of the glazed coloured collectors are also shown.

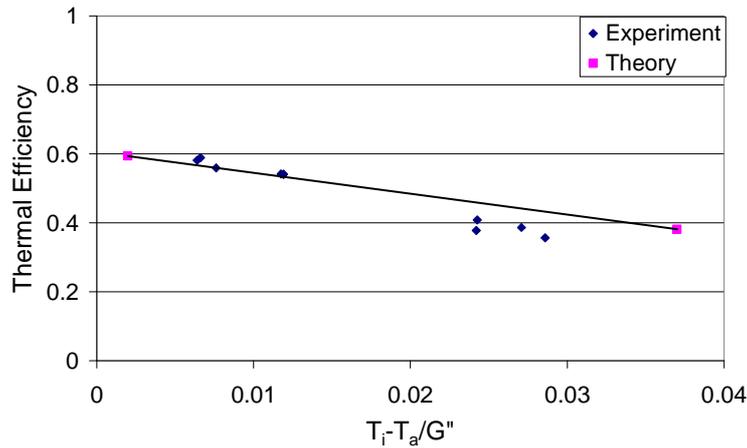


Figure 4: Experimental and theoretical efficiency of glazed grey solar collector

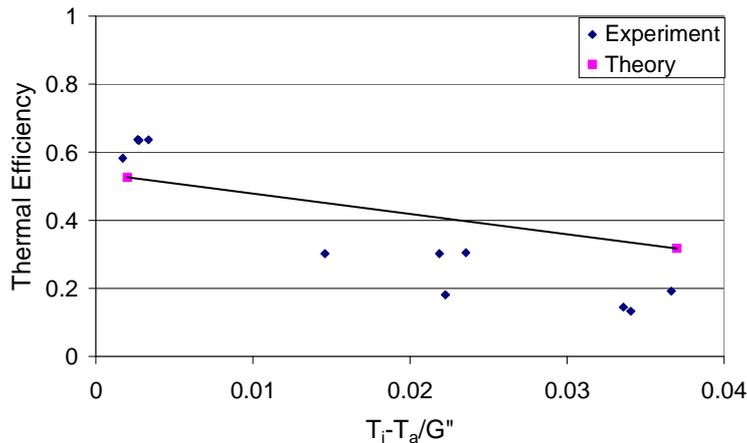


Figure 5: Experimental and theoretical efficiency of glazed green solar collector

From Figure 5, it can be seen that there is a discrepancy between the experimental and theoretical result for the green collector. This was due to unusually high wind speeds during the test leading to higher convective heat losses in the experiment than predicted by the model. However for the most part, the theoretical prediction corresponds fairly well with the experimental data. As such it is possible to optimise the collector using the measured values of the transmittance-absorptance product and the one-dimensional thermal model presented.

7. ANNUAL PERFORMANCE OF COLOURED COLLECTORS

Having demonstrated and validated the design of the coloured solar collectors, it was decided to examine the fraction of a typical domestic water-heating load that could be provided

by the various theoretical coloured collectors. Therefore, an F-chart [9] was constructed for the operation of the collectors in Auckland based on weather data was taken from NIWA [12]. Although not as “in-depth” as a full annual transient analysis, such as could be performed by a program such as TRNSYS, the F-chart has been shown to provide good prediction of annual solar fractions [9].

For the calculation of the radiation it was assumed that the collector was oriented facing north and that the collector was inclined at angle equal to latitude. Furthermore, the system was assumed to consist of 4m² of coloured collectors, coupled to a 170-litre storage tank providing the monthly heating loads shown in Figure 6.

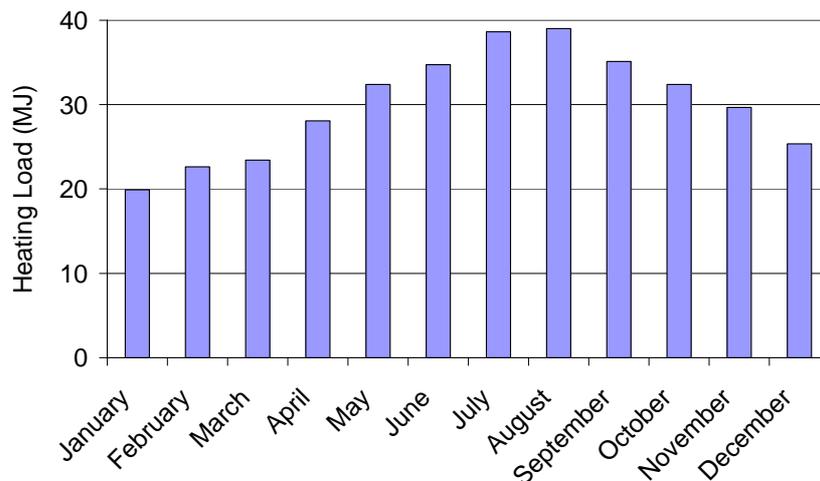


Figure 6: Monthly heating load for F-chart analysis

From the F-chart analysis it was found that, as expected, the black coloured collector had the highest annual solar fraction. However, it was also found that although the efficiency of the coloured collectors was lower, they were still able to provide a reasonable fraction of the heating load, as shown in Figure 7.

It is interesting to note that even the white collector is able to provide approximately 25% of the heating load. As such there appears to be significant scope to vary solar collector colour and maintain a degree of solar heating.

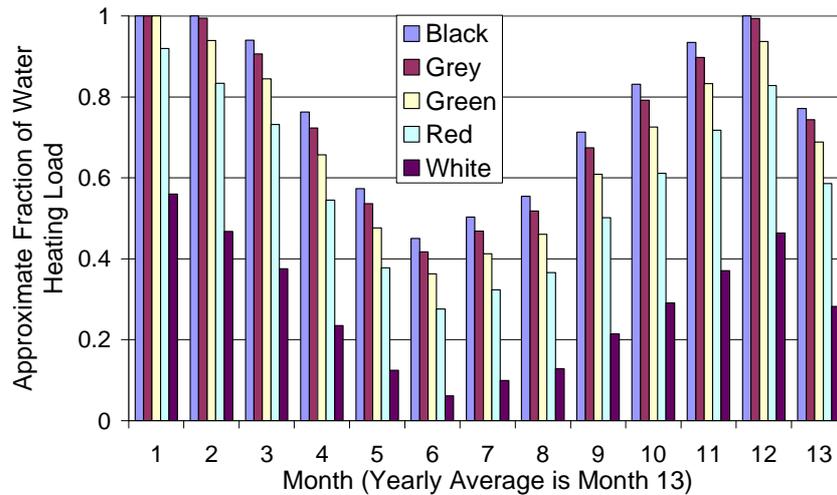


Figure 7: Approximate solar fraction provided by glazed coloured solar collectors

8. CONCLUSIONS AND DISCUSSION

Until recently the use of coloured solar collectors appeared to have been passed over in favour of improving black and selective surfaces. Over the course of this study it has been shown that the performance of coloured solar collectors can be accurately modelled using a combination of experimental and numerical techniques. Furthermore, it has been shown that despite their lower efficiencies low-cost coloured mild steel collectors could potentially provide noticeable contributions to domestic water heating loads.

Finally, given the recent drive towards building integration of solar collectors [2] it would appear that the use of coloured solar collectors will start to be an area that receives more attention than it has to date.

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