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SUNLIGHT IN COLORADO GREENHOUSES

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Measurements of diffuse and direct radiation in greenhouses, with six covers, showed an average transmittance of 60% of outside sunlight, with glass having the highest of 73%. If glass was shaded, however, it had the lowest transmittance. Double polyethylene in the winter had very low transmittance, whereas double polycarbonate had low transmittance regardless of season. Double acrylic had both highest and lowest direct radiation, depending upon season, but transmittance of 66 and 69%, the latter not significantly different from each other. FRP was intermediate to the above.

Introduction

The importance of energy transmission by greenhouse roofs is obvious. It is witnessed by the voluminous published information by European workers and investigations at Pennsylvania State University. It is rather surprising that similar work in a semi-arid, high light climate is nearly nonexistent, especially actual studies carried out in the common commercial ranges of Colorado. It is equally obvious that the proportions between direct and diffuse radiation inside a greenhouse can have significant effects on crop production. With the advent of relatively inexpensive data-logging equipment, and funds provided by the Kenneth Post Foundation, a study of actual sunlight transmission, and evaluation of direct and diffuse radiant energy, was undertaken in 1986-87.

Methods and materials

The manufacturer of the sensing units employed in this study emphasized difficulties that might occur if the spectral distribution of the energy being measured was different from natural, outdoor sunlight. To check this, we undertook testing of new units with a standard Eppley pyranometer (**Fig. 1**) as the calibration instrument, outdoors and under two different greenhouse covers with the instruments located approximately three feet above ground level. Under outdoor conditions, using the manufacturer's constants, the correlation between Eppley and the new pyranometers exceeded 0.99 (1.0 perfect) with a standard deviation for all three sensors used in this study of less than 30. However, when placed in the greenhouse, the correlations dropped to a minimum of 0.98 and the standard deviations increased at least ten times those obtained outdoors. That is, due to structural shading of "point" sensors in a greenhouse, the variability to be expected in any measurement series can be ten to 100 times higher than the same setup outdoors. Any differences in calibration due to spectral distribution under the different covers was masked, and, in fact, statistical analysis showed no significant differences between calibration slopes or origins of any of the sensors and the Eppley.

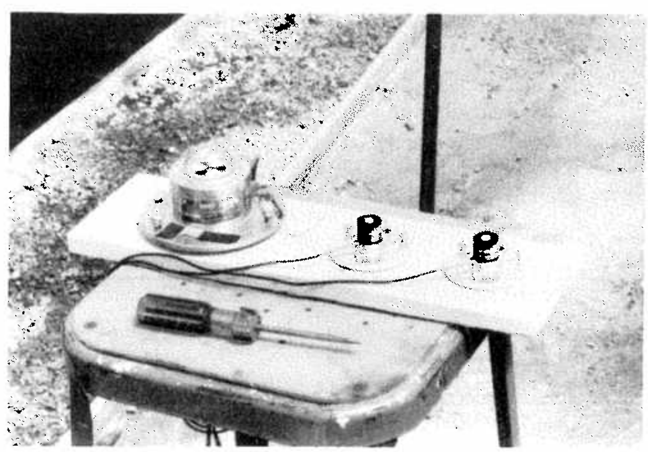

Fig. 1: Setup for calibration checks on silicon cell pyranometers used in radiation study, compared to an Eppley pyranometer on the left. Calibrations were conducted outside and under two different greenhouse covers.

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This variability of "point" sensors, when installed close to ground level in greenhouses, is one of the reasons why investigators will usually position a sensing unit directly under the cover — preferably on a south-facing roof. This does not provide a representative estimation of the environment to which the plants are subjected in the greenhouse, although the practice greatly decreases the amount of data necessary to arrive at reasonable results. Positioning a radiation sensor directly under the roof becomes rather difficult when one realizes that nearly 100% of the commercial establishments in Colorado are oriented north-south. This is despite all the published literature from more northern climates indicating that an east-west orientation will transmit more solar energy, and it is usually a more efficient structure, especially at high latitudes (40°+). The reasons for this commonality in Colorado are unknown.

Also, from the standpoint of easy access to the equipment, we deliberately installed the measuring equipment directly above the crop canopies (**Fig. 2**), as nearly in the center of the greenhouse as possible. The installation was usually within 50 feet of the south end of the particular structure so an outside pyranometer could be installed at least 15 feet from the south gable end. A "shadow" ring was constructed (**Fig. 3**) to protect one inside sensor from direct radiation. This shadowed sensor measured total diffuse radiation, and the difference between protected and unprotected sensors was automatically calculated as direct radiation. The positioning of the inside sensors with the shadow ring was critical, and we did not always have bright sunshine to adequately position the ring for recording from one week to the next.

Fig. 2: Typical placement of radiation measuring equipment in a commercial greenhouse range.

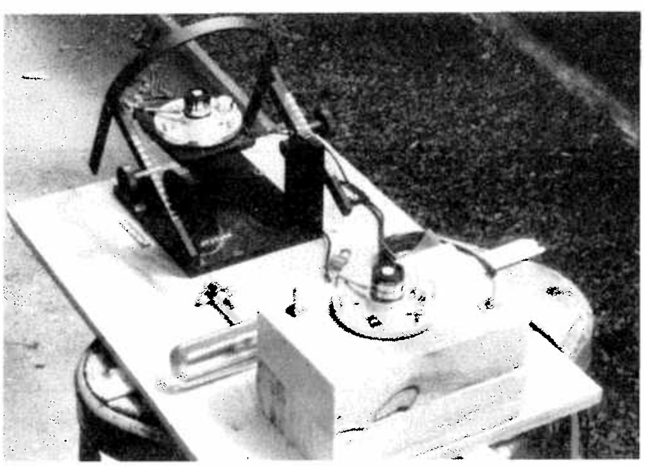

Fig. 3: The two inside pyranometers with the shadow ring mounted on one. The latter measured diffuse radiation, being protected from direct, while the other measured total inside radiation, direct radiation being found by subtraction.

The equipment was left in position for one week, recording the average energy at hourly intervals from 0800 to 1700. Because of variable daylengths, only the data from 1000 through 1600, and only three days in any one week, were retained for statistical analyses. At the end of each week, the data logger was brought to Fort Collins for data down-

Table 1: Description of installations utilized for measuring radiation in greenhouses.

Designation	Remarks
1. **Dbl PVF**	Air-inflated polyvinyl fluoride, N-S orientation, quonset shaped, about 1000 sq.ft. floor area, Oct. 7 through Oct. 9, 1986.
2. **FRP new**	Six ounce, fiber-reinforced plastic, corrugated, N-S orientation, quonset shaped, about 1000 sq.ft. floor area, Oct. 10 through Oct. 14, 1986.
3. **FRP E-W**	Same as No. 2 except orientation east-west, FRP several years old, commercial range, Jul. 22 through Jul. 24, 1986.
4. **FRP**	Same as No. 2, except commercial rose range, N-S orientation, Oct. 31 through Nov. 4, 1986.
5. **Dbl polycarb**	Two layer, structured polycarbonate, 16mm thick, commercial range, N-S oriented, poinsettia crop, Nov. 21 through Nov. 23, 1986.
6. **FRP**	Same as No. 2, commercial range in roses, several years old, Nov. 29 through Dec. 3, 1986.
7. **Dbl acrylic**	Structured, two layer acrylic, 16mm thick, new, N-S orientation, commercial range in carnations, Dec. 8 through Dec. 14, 1986.
8. **Dbl poly**	Double, air-inflated polyethylene, arch roof, commercial range in bedding plants, N-S orientation, Feb. 5 through Feb. 7, 1987.
9. **Glass**	Standard commercial range in carnations, N-S orientation, single layer, June 5 through June 8, 1987.
10. **Glass shaded**	Same as No. 9 except grower applied shading compound for summer, June 12 through June 14, 1987.
11. **Dbl poly**	Same as No. 8 except standard peak design, commercial range in roses, N-S oriented, June 20 through June 22, 1987.
12. **Dbl acrylic**	Same as No. 7, commercial range in carnations, Jul. 20 through Aug. 1, 1987.
13. **Dbl polycarb**	Same as No. 5 except commercial range fitted with thermal screens, miscellaneous flowering plants, Apr. 29 through May 1, 1987.

loading and storage on disc. The following week, the equipment was moved to a new location. Occasionally, it was necessary to return to a location to remove snow from the outside pyranometer.

A total of 13, three-day accumulations were obtained (**Table 1**). Of these, four of the 13 were duplicated at different times of the year — or at least the coverings were the same. In one location, the grower applied a shading compound to the roof, and the instrument left in place a second week. At two locations, workers in the greenhouse broke cable connections to the outside sensor, and these data were discarded.

Results

Plotting all data of total radiation in the structures as a percent of that outside showed no significant correlation between outside absolute sunlight and percent transmitted, although there was a slight trend toward lower transmittancy as sunlight increased. On the other hand, if data for all 13 conditions were plotted on an absolute basis (outside versus inside) a distinct relationship, as would be expected, was found (**Fig. 4**). Of particular interest was the slope of the computed regression line, 0.60 (r=0.89). That is, on the average, for every watt/sq.m. of outside radiation, only 0.6 watts/sq.m. was transmitted. There were significant differences between covers, but the general results did not indicate very high efficiency for energy transmission of Colorado greenhouses.

Glass, depending upon whether shaded by a compound, or clear, had the lowest and highest percent transmission of any of the covers (**Fig. 5**). Unfortunately, the glass cover was not duplicated, but the results showed a drastic loss in transmittancy when a shading compound was applied. The behavior of double, air-inflated polyethylene was also remarkable as it had both low and high transmittancy, depending upon the time of year (winter versus summer). Structured, double polycarbonate had average transmission below 60% regardless of the season. There was considerable condensate on the polycarbonate during the winter (No. 5), but none was noticed in the summer test (No. 13). The remaining, FRP and structured double acrylic, generally had percent transmission in the 60 to 70% range. No. 6 FRP was old fiberglass, and was changed the following year. Air inflated, polyvinyl fluoride (No. 1, PVF) had a surprisingly high transmissivity, but both No. 1 and No. 2 were small, quonset shaped structures of about 1000 sq. ft. floor areas.

The proportion of diffuse and direct radiation inside the houses was computed as the percent of outside, and percent of inside, radiation. Only the results as a percent of total inside are presented in **Fig. 6.** It was noted that the behavior of double, air-inflated polyethylene did not differ significantly with season in regard to diffuse and direct radiation — although transmissivity did, i.e. decreasing significantly in the winter (**Fig. 5**). On the other hand, double acrylic had both the highest and lowest percentages of direct and diffuse radiation (winter No. 7 versus summer No. 12), with relatively little change in transmissivity. Double polycarbonate, when covered with condensate, had the highest percentage of diffuse radiation (No. 5), but did not change significantly from summer to winter (No. 5 versus No. 13). However, the amount of direct radiation did decrease markedly but not significantly in the winter. There was less total energy transmitted in the winter by polycarbonate covers. FRP and glass covers were generally intermediate to the others with FRP usually having a higher proportion of diffuse radiation — unless the glass was shaded. The relatively high proportion of diffuse energy under clear glass was surprising. This might have been due to greater shading by the superstructure as contrasted to other covers which do not require sash bars for support. If compared on the basis of percent of *outside* radiation, clear glass had the highest percent diffuse. This would again suggest the

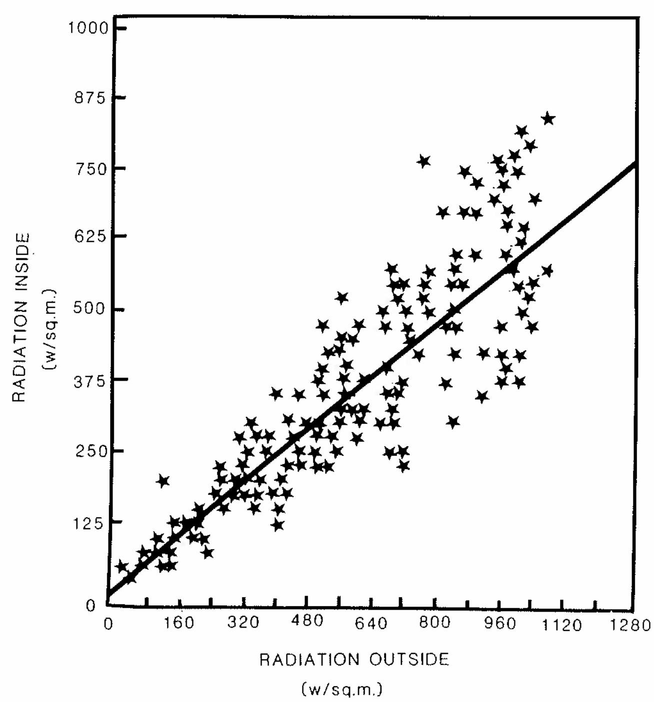

Fig. 4: Scatterplot of inside radiation in commercial greenhouses on outside total radiation. Regression line equation: Inside Rad. = 8.1 + 0.60(Outside rad.), correlation = 0.89, standard error of the estimate = 88.6.

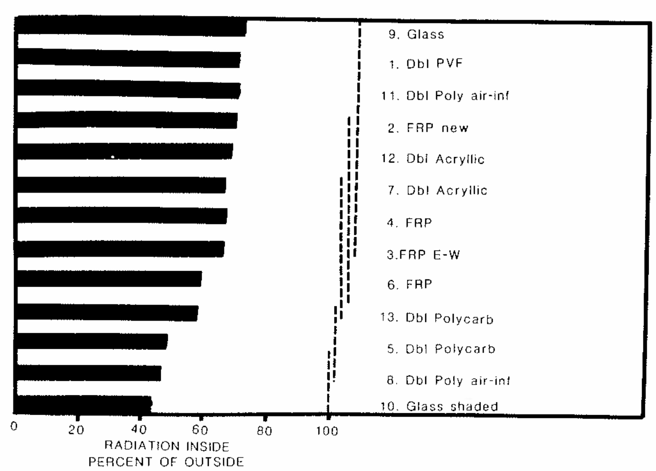

Fig. 5: Transmittance of six greenhouse covers under a variety of conditions, expressed as percent of total outside radiation. Vertical, dashed lines which bracket the same covers means the values were not significantly different from each other, i.e. No. **9 glass** was not different from No. **3 FRP** but was different from the remaining tests.

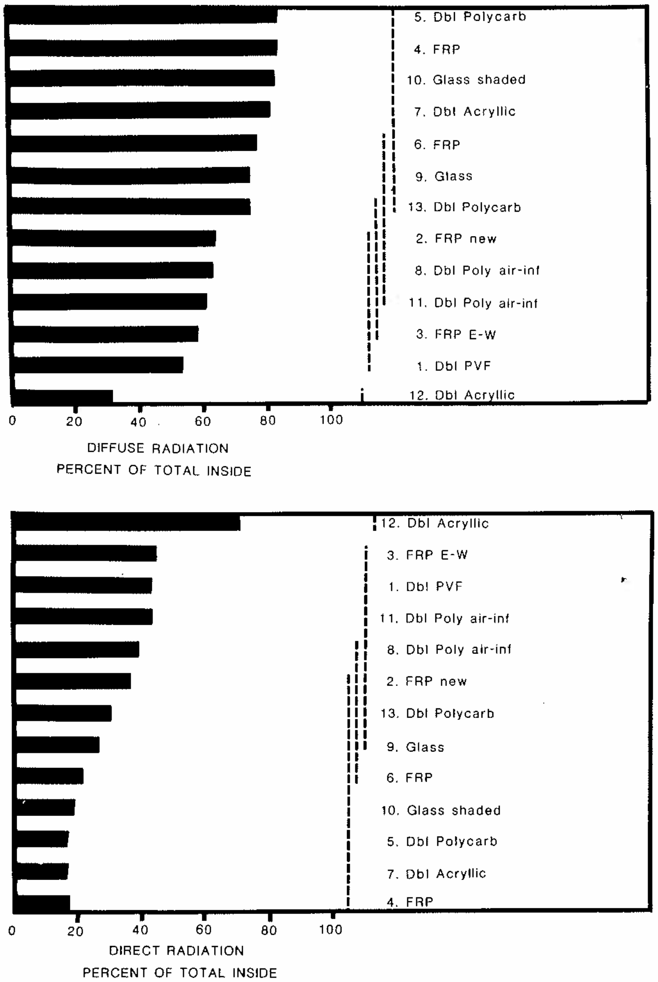

Fig. 6: Percentages of diffuse and direct radiation, expressed as percent of total *inside* radiation under six different greenhouse covers and variety of conditions. Vertical, dashed lines which bracket the different conditions mean that these results are not significantly different from each other.

influence of structural members in a glass covered greenhouse.

To get a better idea of the relationship between sunlight and season, we restricted data analysis to those covers which were duplicated at different times of the year. This allowed us to compare FRP, acrylic, polycarbonate and polyethylene covers as a function of cover, season and time (**Tables 2 and 3**). There were no significant differences between time-of-day as far as the relative values of percent transmission, diffuse and direct were concerned. With the exception of FRP tests, which were conducted in two successive months during the fall, tests denoted "Period 1" were those conducted in the winter, whereas "Period 2" were those obtained in the summer (**Table 2**). Except for diffuse radiation as a percentage of total outside, all comparisons were statistically significantly different. Higher outside radiation meant higher transmissivity of all covers with an obvious greater proportion of direct radiation and decreased diffusive radiation.

Table 4 presents the average absolute radiation, diffuse and direct, under all conditions. In this comparison, FRP had the least total inside, diffuse and direct of any of the four covers in this comparison. However, these measurements were in October and November, whereas the other three had data obtained in the summer as well as in the winter. Double polyethylene had the greatest diffuse radiation and acrylic had the highest direct radiation as well as the greatest total inside radiation.

Table 4: Average absolute radiation (w/sq.m.) for FRP, acrylic, polycarbonate and polyethylene greenhouse covers.

Cover	Total inside	Cover	Diffuse	Cover	Direct
FRP	194	FRP	152	FRP	42
Polycarb.	228	Acrylic	165	Polycarb.	61
Polyethy.	380	Polycarb	168	Polyethy.	171
Acrylic	383	Polyethy	216	Acrylic	225

Table 2: Average percent transmitted, diffuse and direct radiation in commercial greenhouses under acrylic, polycarbonate, FRP and polyethylene covers at two periods of the year. Period 1 generally winter, Period 2 mostly high light summer conditions.

Period	Percent transmitted	% diffuse of outside	% direct of outside	% diffuse of inside	% direct of inside
1	57	44	12	78	23
2	64	39	26	61	40
Significance	*	NS	*	*	*

Table 3: Average percent radiation transmitted, diffuse and direct radiation of FRP, acrylic, polycarbonate and polyethyelene greenhouse covers.

Cover	Percent transmit	Cover	% diff of out	Cover	% dir of out	Cover	% diff of in	Cover	% dir. of in
Poly-carb.	53	Poly-ethy.	35	FRP	12	Acrylic	57	FRP	19
Poly-ethy.	59	Acrylic	38	Poly-carb.	12	Poly-ethy.	62	Poly-carb.	24
FRP	62	Poly-carb.	42	Poly-ethy.	25	Poly-carb.	80	Poly-ethy.	41
Acrylic	68	FRP	51	Acrylic	31	FRP	80	Acrylic	44

When scatter plots of the four covers were made (**Fig. 7**), the results showed absolute diffuse radiation to increase linearly until about 300 to 400 w/sq.m. This would correspond to cloudy conditions with little direct sunlight. Plotting direct radiation (**Fig. 7**) showed fairly low levels up to about the same range as for diffuse. Above 400 w/sq.m., diffuse radiation tended to remain constant with the particular cover characteristics apparently having greater influence. The very low values at high total radiation levels (500 to 800 w/sq.m.), were obtained under polycarbonate covers. There was insufficient data to obtain meaningful relationships for individual covers, other than those already mentioned.

Summary

In general, the transmissivity percentages often found in the literature are obtained under ideal conditions with the sensor in close proximity to the covering material. The actual energy impinging on a crop canopy can be considerably less. The behavior of double polycarbonate and double polyethylene covers suggests these are not the best covers for winter conditions in Colorado, especially if condensate on the cover becomes a problem. The benefits of FRP covers for Colorado, reported by Holley and his students in earlier CFGA Bulletins, might also be attributed to the fact that FRP does not have to be shaded in the summer when growing carnations or roses. Certainly the results of this study on glass showed a drastic reduction in total inside radiation when a shade compound was applied. The results with lighter, inside shading materials at Colorado State University suggest that considerable care must be used to avoid significant yield reduction. Given a good cooling system, one is almost better off to keep a clear cover than to attempt shading even in the summer. A double acrylic cover was peculiar inasmuch as transmissivity did not change remarkably with season, but the proportions of direct and diffuse radiation did, with the percentage of direct radiation increasing as outside sunlight increased. This reversal from summer to winter was not as obvious with FRP.

These results suggest that further studies of this type under Colorado conditions could result in more efficient greenhouse structures for our climate and a significant saving to commercial growers.

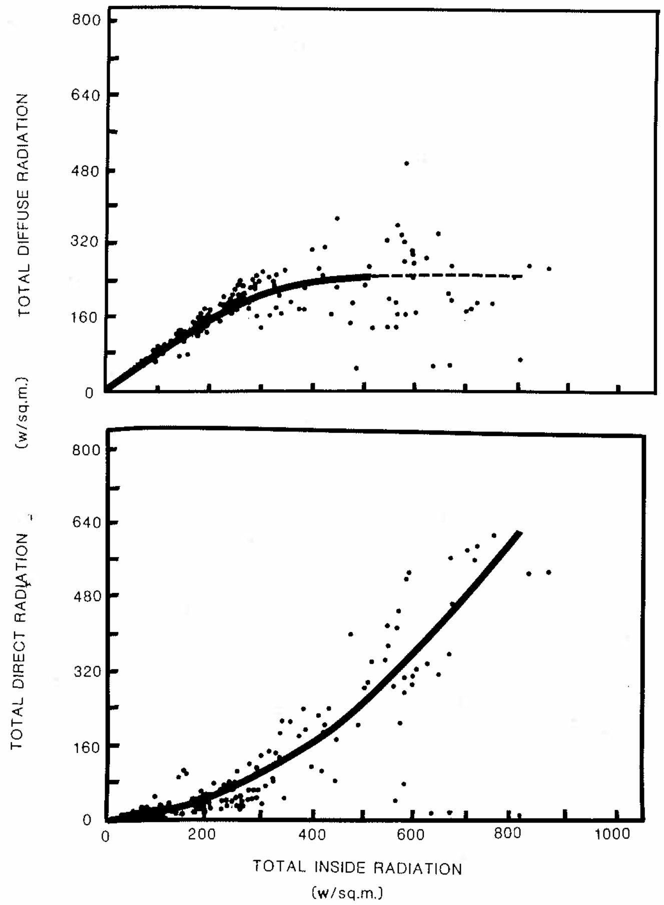

Fig. 7: *Upper:* Scatterplot of absolute diffuse radiation under four coverings as a function of total inside absolute radiation. Correlation = 0.83 for the heavy black curve.
Lower: Scatterplot of absolute direct radiation under four greenhouse coverings as a function of total inside radiation. Correlation = 0.92 for the curve. Coverings were FRP, acrylic, polycarbonate and polyethylene.

Abstracts from the American Society for Horticulture Science Annual Meeting, 1988, Michigan State University

PHOTOPERIOD AND TEMPERATURE INFLUENCE ON TUBEROUS ROOT FORMATION AND FLOWERING IN *ALSTROEMERIA* 'ORCHID' AND *A.* 'REGINA' LINN

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Plants of *Alstroemeria* cultivars Orchid and Regina were grown in rhizotrons to allow non-destructive observation of the development of tuberous roots. Plants were maintained under long days (LD) of 12 hours or short days (SD) of 8 hours at either 11°C or 21°C. After 45 days, all treatments resulted in the commencement of tuberous root development except for the 11°C SD treatment. Tuberous root development was most prolific in the 11°C LD treatment. Although the difference was less pronounced, LD also favored tuberous root formation in the 21°C treatments. 'Regina' formed more tuberous roots than 'Orchid' in all treatments. 'Orchid' flowered after 65 days of LD at either temperature. SD treatment resulted in delayed flowering of both 'Orchid' and 'Regina'. The time between commencement of tuberous root formation and anthesis was much longer for 'Regina' than it was for 'Orchid'. The number of internodes in flowering shoots was monitored to discern any temperature or daylength effect on the height of the shoots.

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