TWELVE YEAR EVALUATION OF A NOVEL ICPC SOLAR COLLECTOR INSTALLATION: THE ROLE OF FAILURE MODES IN CHANGING OPTICAL AND THERMAL PERFORMANCE

William S. Duff
Jirachote Daosukho
Department of Mechanical Engineering
Colorado State University
Ft. Collins CO 80523
e-mail: bill@engr.colostate.edu

ABSTRACT

A novel integral compound parabolic concentrator evacuated solar collector (ICPC) array has been in continuous operation at a demonstration project in Sacramento California since 1998. An ongoing study addresses the impact of optical, thermal, material degradation and component failure factors on array performance over the twelve years of operation.

The paper will include a review of collection system performance and reliability over the twelve years of operation, the design of the simulation, snapshots of animations of rays striking at various angles and the modeling and the analysis of the ray tracing for the vertically and horizontally oriented fins. New results in this paper are 1) the modeling and analysis for longitudinal off-normal incident rays for both fin orientations, 2) the reflectance measurement results, 3) the tube-by-tube reflectance degradation map and 4) an analysis of the of the effects of the two fin orientations and two failure modes on optical performance.

1. BACKGROUND

1.1 Development of the Novel ICPC

Research on CPC solar collectors has been going on for almost thirty years. See Garrison [1] and Snail et al [2]. In the early 1990s a new ICPC evacuated collector design was developed. The new ICPC design allows a relatively simple manufacturing approach and solves many of the operational problems of previous ICPC designs. The design and the fabrication approaches are described in Winston et al [3] and Duff et al [4].

1.2 Sacramento Demonstration

A 100 m^2 336 novel ICPC evacuated tube solar collector array has been in continuous operation at a demonstration project in Sacramento California since 1998. The evacuated collector tubes are based on a novel ICPC design that was developed by researchers at the University of Chicago and Colorado State University in 1993. The evacuated collector tubes were hand-fabricated from NEG Sun Tube components by a Chicago area manufacturer of glass vacuum products.

From 1998 through 2002 demonstration project ICPC solar collectors supplied heated pressurized 150C water to a double effect (2E) absorption chiller. The ICPC collector design operates as efficiently at 2E chiller temperatures (150C) as do more conventional collectors at much lower temperatures.

This new collector made it possible to produce cooling with a 2E chiller using a collector field that is about half the size of that required for a single effect (1E) absorption chiller with the same cooling output. Data collection and analysis has continued to the present [5, 6, 7. 8]

As can be seen in Fig. 1, the non-tracking ICPC evacuated solar collector array provided daily solar collection efficiencies (based on the total solar energy falling on the collector) approaching fifty percent at the 140C to 160C collector operating temperature range. Instantaneous collection efficiencies of about 60 percent were achieved at these operating temperatures. Also, daily chiller COPs of about 1.1 were realized.

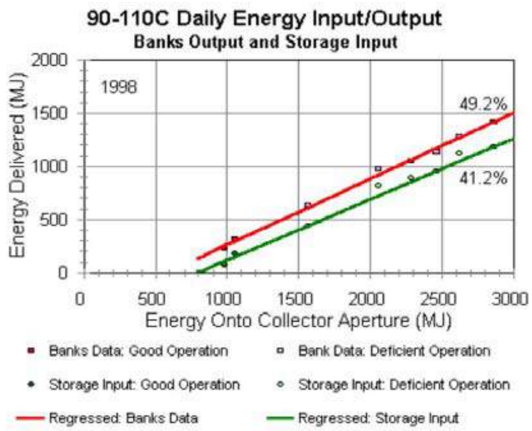

Fig. 1: 1998 Daily Collection Performance for Operation at 90 to 110C Collector to Ambient Temperature Differences.

The ICPC array has recently been operating at the lower temperatures that are required to drive a single effect absorption chiller. The ICPC array has provided daily solar collection efficiencies approaching fifty-five percent at the 80C to 100C collector operating temperature range.

1.2.1 Array Layout and Absorber Orientation

The new ICPC evacuated tubes were fabricated with two absorber orientations, one with a vertical absorber fin and one with a horizontal fin. A cross-section of the collector tube illustrating the two orientations is shown in Fig. 2.

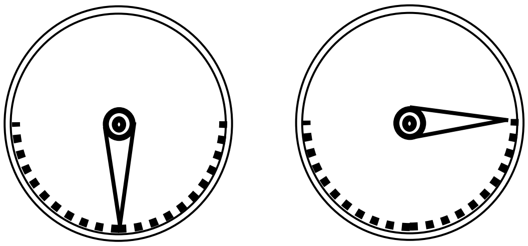

Fig. 2: Novel ICPC Design Showing Vertical and Horizontal Fin Orientations.

The collector array is made up of three banks. The north bank consisted initially of all horizontal fin tubes, the middle bank consisted of all vertical fin evacuated tubes and the south bank included an even mixture of the two types. In a series of experiments in 1999, the two differently oriented fined collectors were found to yield essentially identical performance. The flow pattern through the 112 evacuated tubes in each bank is parallel and the three banks are plumbed in parallel.

1.3 Evacuated Tube Reliability

After a year of operation several distinct patterns in the development of cracks in the evacuated tubes emerged. One of these involved the production sequence or, equivalently, the fin orientation and the other, the end of the tube where the crack occurred.

Vertical and horizontal tube absorber orientations were produced in the first and second halves of the ICPC tube production run respectively. One year after installation 1.2 percent of the vertical fin orientation tubes and 9.8 percent of the horizontal tubes had developed cracks. This strongly suggests that there were distinct differences in the longevity of the vertically finned tubes versus that of the horizontally finned tubes (or, equivalently, of the first half of the production run versus the second half). Statistically, if one assumes that the entire production run is characterized by the overall fraction of cracked tubes of 0.05865 then the likelihood that the first half of the production run came from such a process is less than 0.003. Moreover, after six years of operation only 3.6 percent of the vertically finned tubes had developed cracks, whereas the horizontally finned tubes continued to develop cracks at a much higher rate. Since the evacuated tubes were essentially hand built, this 3.6 percent failure rate is about what one would expect.

The end caps of each end of the evacuated tubes were identical, each consisting of a dish shaped piece of glass and a metal cap bonded to the glass. At the top end, a metal tube was brazed to the metal cap to provide flow of heated fluid. At the bottom end a metal tube was brazed to the metal cap to provide a means to evacuate the tube. Thus, only the top end was subject to both thermal stress (the 155C fluid) and mechanical stress (partial support of the fin and heat transport tube). One might expect the failure rates due to cracking to be higher at the top end of the tube than at the bottom. In fact the opposite occurred. Out of 19 cracked tubes after one year, 7 were cracked at their tops and 12 at their bottoms. Statistically, if one assumes that the true proportion of cracks at the top to be 60 percent, then there is only a 0.001 chance that one would observe seven or fewer cracks out of 19 at the top end.

2. OPTICAL PERFORMANCE MODELING AND EXPERIMENTATION

2.1 Graphical Ray Tracing

Fig. 3 depicts the results of an animated graphical ray tracing simulation that has been designed to investigate the optical performance of the ICPC. See Duff, et al [7]. Factors incorporated are the transmittance of the glass tube, the reflectivity of the reflective surface, the gap between the tube surface and the fin and the absorptance of the fin. The sun rays are simulated as discrete uniform rays over a range of incident angles from 15 degrees to 165 degrees. The rays are followed through the glass envelope, to the reflector and to the absorber fin. The number of rays absorbed is recorded. The collector efficiency graph of Fig. 4 shows the amount of energy absorbed during a typical daytime period.

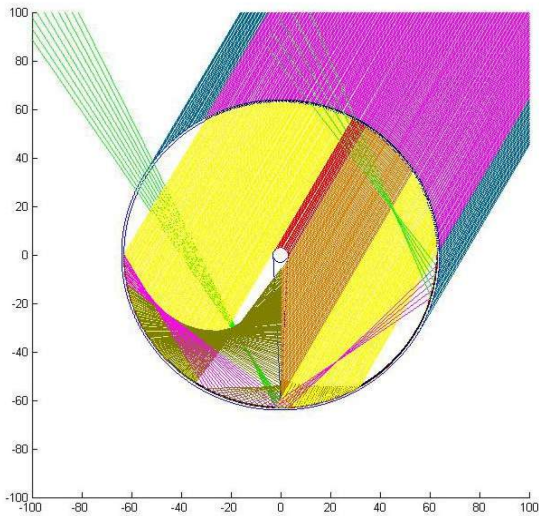

Fig. 3: Rays Striking the Vertical fin ICPC at a Nominal Angle of 44 Degrees.

2.1.1 Vertical Fin Ray Trace Analysis

The optical efficiency based on surface reflectance measurements is 0.94, the gap between reflective surface and the absorber fin is 4 mm and the absorptance is 0.95. The first gap loss (green rays) is detected at an incident angle of 44 degrees which is depicted as a decrease in the optical efficiency seen in Fig. 4.

In Fig. 4 gap losses separate into roughly two ranges. A flat response occurs between 80 and 100 degrees and an abrupt efficiency drop occurs at 44 degrees. To illustrate that the gap loss is the cause of the optical efficiency drops, another simulation is run in which there is no gap loss. See Fig. 5. The graph depicts a rounded distribution with no abrupt jump in efficiency at any nominal angle.

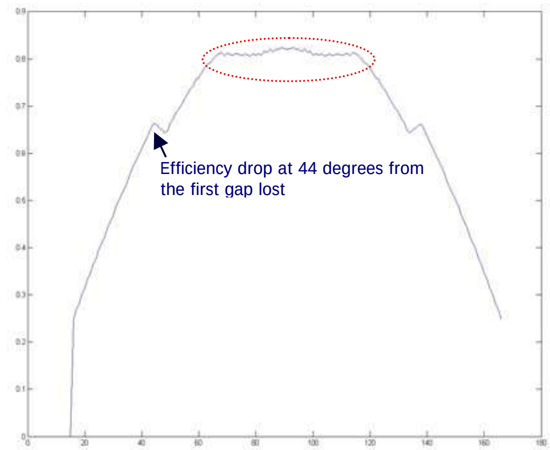

Fig. 4: Optical Efficiency (Vertical Fin) from Nominal Angles of 15 to 165

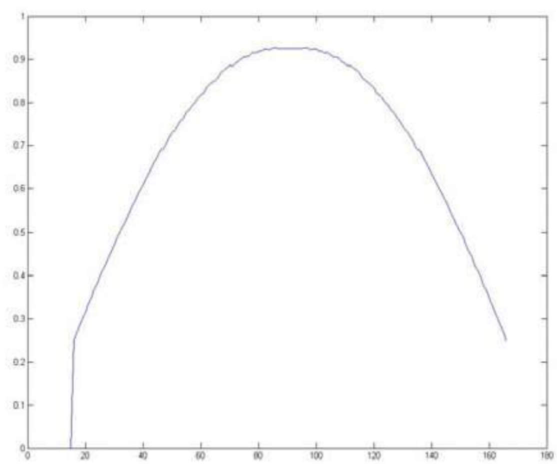

Fig. 5: Optical Efficiency from Incident Angles of 15 to 165 Degrees with No Gap

The reflectivity is now changed to 0.7 to achieve an optical efficiency curve that has a shape that is more of a dished appearance around the 90 degree incident angle. See Fig. 6.

2.1.2 Horizontal Fin Ray Trace Analysis

An example of the ray tracing analysis for the horizontal fin is shown in Fig. 7. In Fig. 8 the optical efficiency plot for the horizontal fin ICPC shows an unbalanced curve skewed to the right. The plot shows that the horizontal fin ICPC has greater energy collection efficiency in the afternoon than in the morning. As seen in Fig. 7, at an angle of 30 degrees, reflected ray striking the fin are both single and multiple reflections. As shown in Fig. 9, at an angle of 150 degrees, the only rays that are reflected to the fin are single reflection rays.

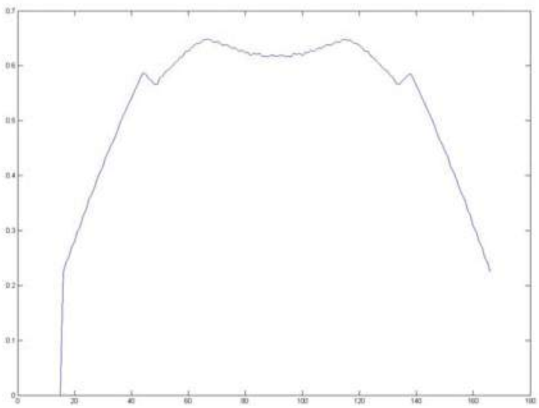

Fig. 6: Optical Efficiency with 0.7 Reflectivity at 15 to 165 degrees.

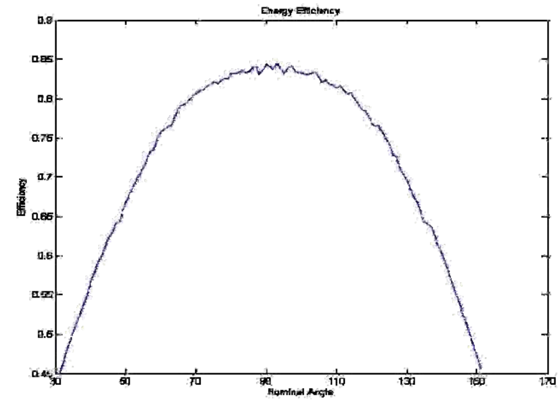

Fig. 8: Optical Efficiency (Horizontal Fin) from Incident Angles of 30 to 150.

Fig. 10 shows efficiency effects of three different reflectivities of 1.00, 0.94, and 0.70. Efficiency is reduced for the smaller reflectivity values. The curve also skews more to the right for the smaller values of reflectivity.

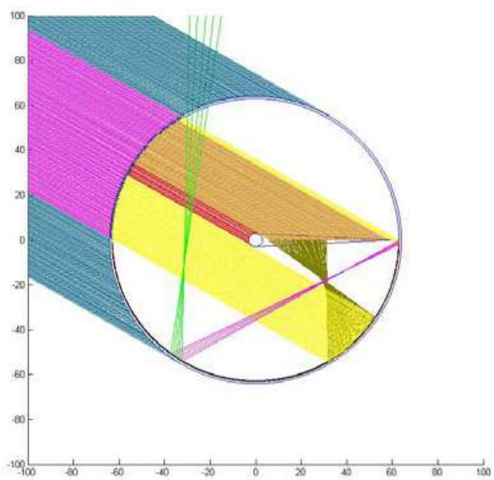

Fig. 7: Rays Striking the Horizontal Fin ICPC at a Nominal Angle of 30 Degrees.

Comparisons of different gaps between the absorber fin and the cover glass were analyzed by setting the reflectance to 1.00. As shown in Fig. 11, the efficiency is reduced as the gap between the absorber fin and the glass enclosure increases.

2.1.3 Three-Dimensional Ray Tracing

The projected solar radiation is analyzed in the terms of both longitudinal and transverse incident angles to the tube. The reference axis is adjusted to be the same plane as the collector plane. As shown in Figure 12, ray tracing projects the suns ray into longitudinal (side view) and transverse (front view) planes of the ICPC arrays.

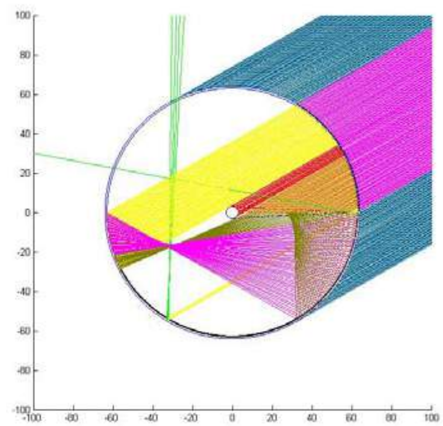

Fig. 9: Rays Striking the Horizontal Fin ICPC at a Nominal Angle of 150 Degrees.

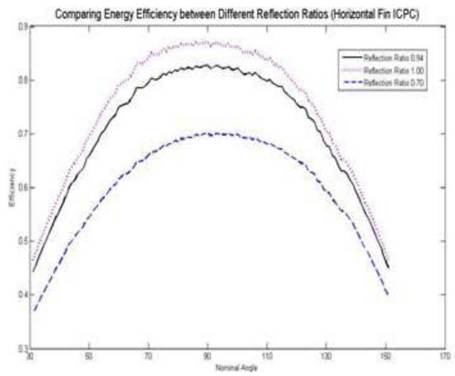

Fig. 10: Comparing Energy Efficiencies for Different Reflectances

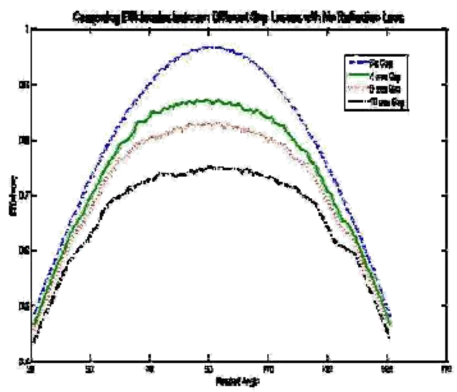

Fig. 11: Comparing Optical Efficiencies for Four Gaps of 0, 4, 6, and 10 mm (Horizontal Fin ICPC).

The simulation program evaluates each single ray from transverse view in a uniformly distributed set of rays, as shown in the longitudinal view. A ray striking the collector at a given angle and in given location is monitored as to how it responds at various surface orientations of the collector. A color code is used to illustrate how simulated rays respond at surfaces as shown in Table 1.

Table 1: Color Codes to Illustrate Ray Action.

Color	Code
Pink	Ray Enters Outer Glass Tube
Red	Ray Hits Heat Transport Tube
Blue	Ray Missing Aperture Area
Yellow	Ray Hits Reflective Surface
Brown	Ray Hits Absorber Fin
Green	Ray Is Reflected Out

Figure 13 shows a traced individual ray in the transverse plane projected to the longitudinal plane as an array of uniformly distributed rays. The ray tracing procedure is set up to trace individual rays and their intensities until one hits the absorber plate or is reflected out. The direction of the ray traveling in the ICPC tube will be recorded and projected to both transverse and longitudinal views.

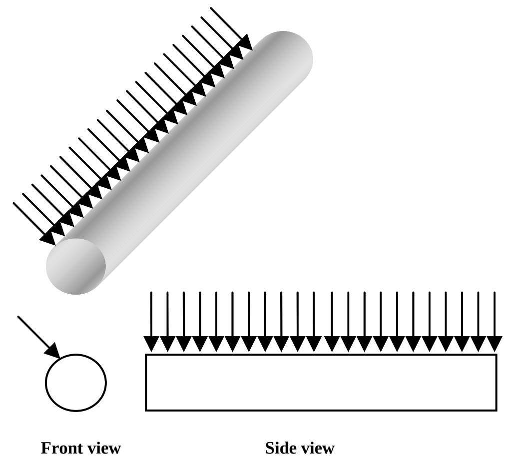

Fig.12: Projections of sun radiation to longitudinal (side view) and transverse (front view) planes

When each ray is traced on the transverse plane, the uniform distribution of rays is analyzed throughout the longitudinal view. Each ray is followed starting from where it enters the tube in the transverse plane. The pink color code will mark the ray from outside glass cover to the entrance point. After the rays (pink colored) enter the tube longitudinally, each ray will be followed to see if it hits or misses the reflector. The rays that miss the reflector or absorber are then colored blue. The rays then hit the reflector, perhaps multiple times, before hitting the absorber or being reflected out.

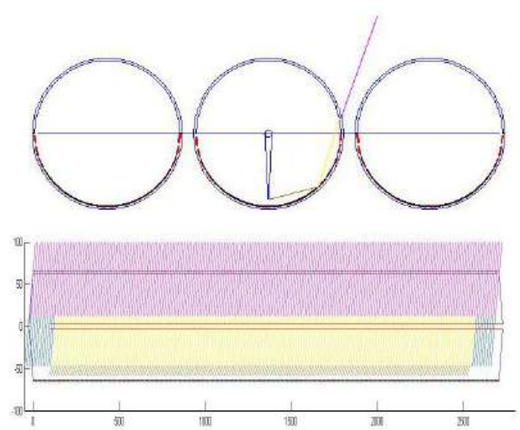

Fig.13: Projected rays on both transverse and longitudinal views on vertical fin ICPC

The reflected angle in the longitudinal view is calculated by using the predetermined reflected position from the transverse view that is applied to the longitudinal view. Each reflection ray is colored yellow. After its reflection, each ray in the array will be investigated to see if it hits the absorber (brown) or is reflected out (green). See Fig. 14 and 15.

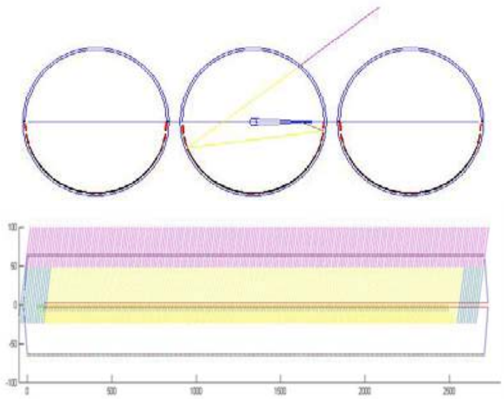

Fig.14: Projected rays on both transverse and longitudinal views on Horizontal fin ICPC

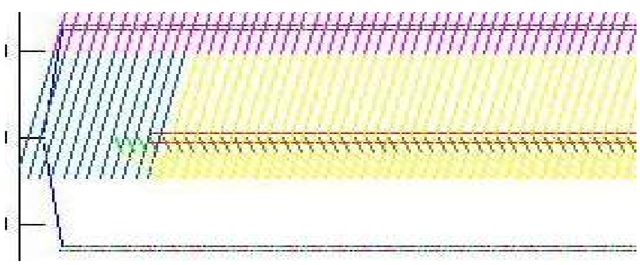

Fig. 15: Closed-up projected rays on longitudinal view with multiple reflections

2.1.4 Blocking effect from Adjacent Tubes

In the morning and the evening, the incidence angle of rays to the array is small and some of the beam radiation is partially blocked by adjacent collectors. The blocked rays are transmitted through the cover from the adjacent tubes and lose some intensity due to reflective losses of the glass cover. In the simulation the transmittances from blocking is calculated based on the incidence angles of the rays hitting and passing through the glass cover of the adjacent tube, Fig. 16.

The incident angle modifier is also adjusted by the blocking effect. The blocking effect is also presented in the form of a proportion of the beam intensity that passes through the glass cover.

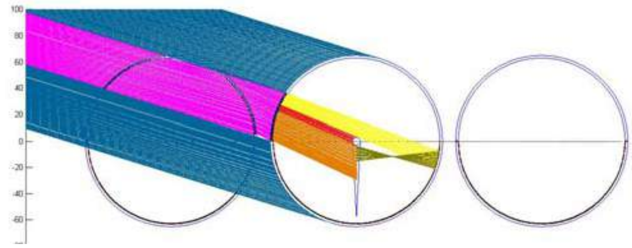

Fig. 16: Partial Blocking Illustration

Figure 17 shows how the blocking reduces the overall optical performance of the ICPC as the optical efficiency of both fin configurations drops in the time ranges 8:00 to 9:10 and 13:50 to 16:00.

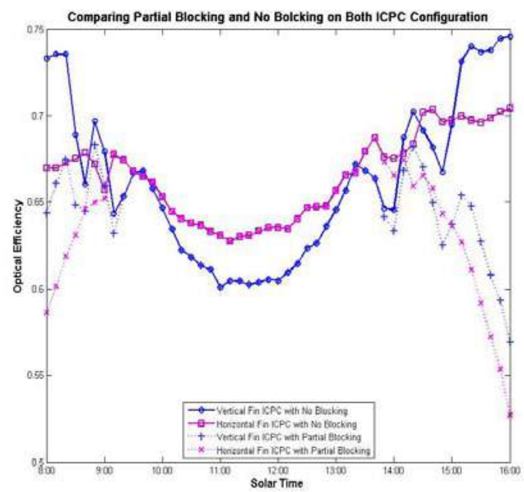

Fig. 17: Partial Blocking Effects on Both Vertical Fin and Horizontal Fin Configurations.

2.2 Reflectivity Measurement

A device, consisting of a laser and detector mounted on a support structure is used to measure reflectance of mirror surface samples from the ICPC. Using this device, a map of reflector performance that is keyed to the appearance of the reflective surface for the tubes in ICPC array has been generated.

Four levels of reflectance degradation are identified for the Sacramento site by the appearance of the reflective surface. At level 1 the reflector still performs well and only a minor change in the reflector appearance is observed. At level 2 there is some whitening of the reflector. At level 3 there is a substantial amount of degradation of the reflector. At level 4, shown in Fig. 18, most of reflector is gone and you can easily see through it.

At the site, all 336 tubes were categorized, one-by-one, by the above reflectivity appearance levels, existence of a glass crack, surface temperature, water leakage, and fin orientation. Each tube was divided into ten sections along its length. Degradation levels were identified and marked for each of the ten sections. Fig. 19 shows a color mapping of tube degradation information for a portion of the array.

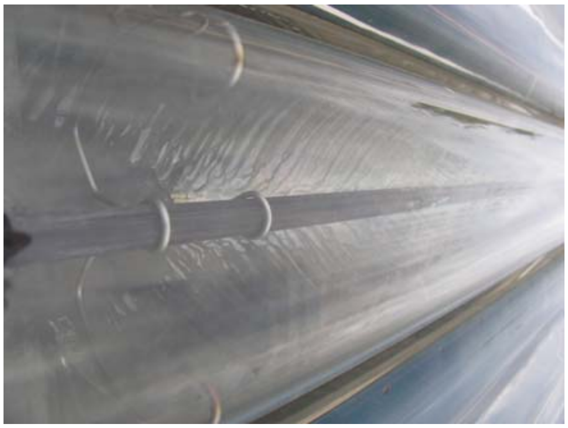

Fig. 18: Fourth Level Reflectance Degradation.

Reflector samples representative of the four different degradation levels were taken from the Sacramento site for measurements in the laser laboratory at Colorado State University. The samples for the four levels of degradation and good reflector samples were measured for their reflectivity by the laser detection device.

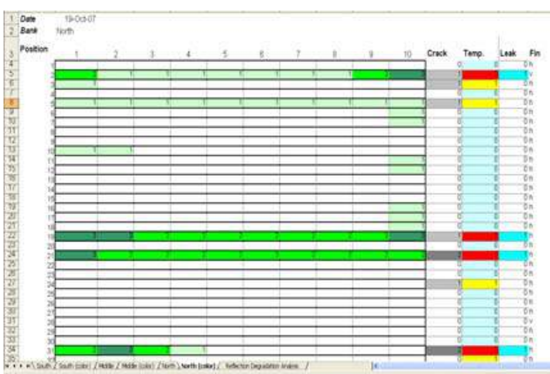

Fig. 19: Map of Tube Degradation

Using this device, a map of reflector performance for the ICPC array is being generated. The reflectance results are shown in Table 2 for each level of degradation.

2.3 <u>Effects of Two Fin Orientations and Two Failure Modes on Performance</u>

Reflectivity degradation plays an important role on the performance of the evacuated tube. As reflectivity degrades, the performance of tubes with the two fin orientations falls off in different ways.

<u>Table 2: Measurement of Reflectivity</u>

Degradation Level	Percent Reflectivity
Good	93.48
1st	79.66
2nd	38.46
3rd	22.93
4th	1.24

For the vertical fin, performance drops rapidly for incidence angles close to 90 degrees. This behavior is as expected since the vertical fin receives radiation mostly from the reflector. The horizontal absorber fin performs better than vertical absorber fin when the reflector degrades since the horizontal fin absorbs some of the radiation directly, Fig. 20 and Fig 21.

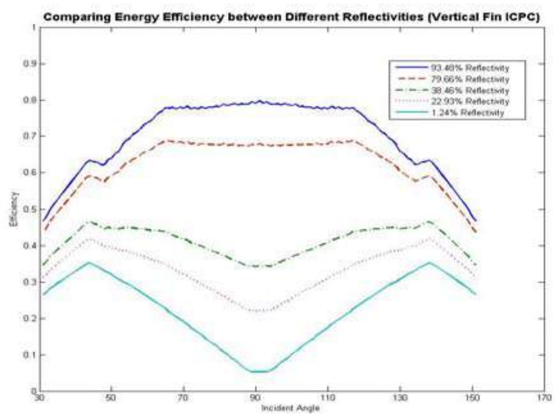

Fig. 20: Comparing Optical Efficiency between Different Reflectivity Ratios (Vertical

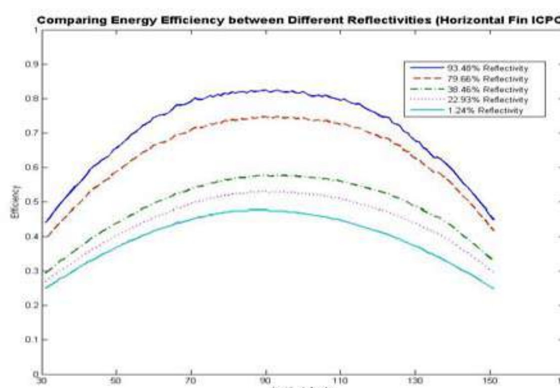

Fig. 21: Comparing Optical Efficiency between Different Reflectivity Ratios (Horizontal Fin).

3. CONCLUSIONS

A detailed ray trace analysis for characterizing the optical performance of ICPC evacuated tubes has been described and its results illustrated. As a consequence of the ray tracing, it was found that reflectivity degradation will play a significant role in the reduction of array efficiency. The nature of reflectivity degradation depends on fin orientation and the type of failure, such as water leakage from the heat transport tube or cracks in the cover glass. Overall performance is also degraded by the loss of vacuum in the tube. An analysis of the performance consequences of reflector degradation and loss of vacuum is currently being incorporated into the reliability study and will be compared with performance data.

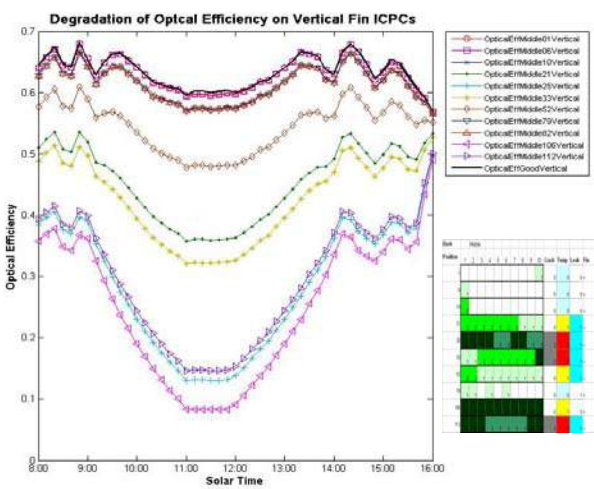

Fig. 22: Matching Optical Efficiency with Degradation Map from Middle Bank (Vertical Fin).

4. REFERENCES

(1) Garrison, J. D., Optimization of Fixed Solar Thermal Collectors, *Solar Energy*, v23, 1979

(2) Snail, J. J., O'Gallagher and R. Winston, A Stationary Evacuated Collector with Integrated Concentrator, *Solar Energy*, v33, 1983

(3) Winston, R, O'Gallagher, J., Mahoney, A. R., Dudley, V. E. and Hoffman, R., "Initial Performance Measurements from a Low Concentration Version of an Integrated Compound Parabolic Concentrator (ICPC)", *Proceedings of the 1999 ASES Annual Conference*, Albuquerque NM, June, 1998

(4) Duff, W. S., Winston, R., O'Gallagher, J., Henkel T. and Bergquam, J., "Five Year Novel ICPC Solar Collector Performance", 2003 American Solar Energy Society Solar Energy Conference, Austin TX, June 2003

(5) Duff, William, Roland Winston, Joseph O'Gallagher, Tom Henkel and Jim Bergquam, "Performance of the Sacramento Demonstration ICPC Collector and Double Effect Chiller in 2000 and 2001", Solar Energy, vol. 76, pages 175-180, January 2004.

(6) Duff, William, Jirachote Daosukho, Klaus Vanoli, Roland Winston, Joseph O'Gallagher, Tom Henkel and Jim Bergquam, "Comparisons of the Performance of Three Different Types of Evacuated Tubular Solar Collectors", American Solar Energy Society 2006 Congress, Denver, Colorado, July 2006.

(7) Duff, William S. and Jirachote Daosukho, "A Performance and Reliability Study of a Novel ICPC Solar Collector Installation", American Solar Energy Society 2007 Congress, Cleveland, Ohio, July 2007.

(8) Duff, William S. and Jirachote Daosukho, "Eleven Year Evaluation of a Novel ICPC Solar Collector Installation: The Role of Failure Modes in Changing Optical and Thermal Performance", American Solar Energy Society 2008 Congress, Buffalo NY, May 2009.

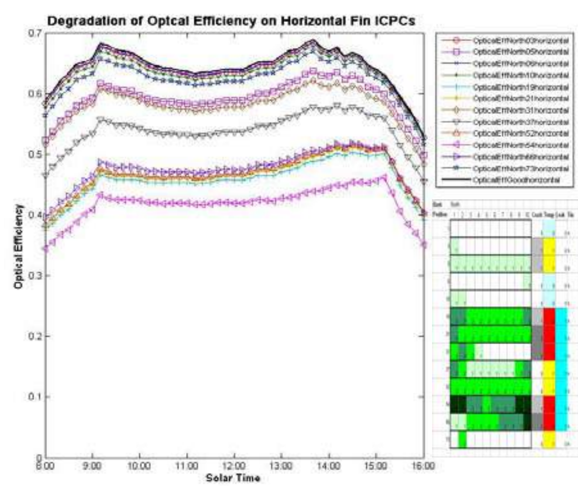

Fig. 23: Matching Optical Efficiency with Degradation Map from North Bank (Horizontal Fin).