UV Fluorescence for Defect Detection in Residential Solar Panel Systems

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***Abstract*— UV Fluorescence (UVF) is a relatively new "non-contact" method of detecting cracked cells in solar panels with potential high throughput and low cost. We report here on application of a pole-mount UV-flash camera system to the detection of defects on residential rooftops in Boulder Colorado. The majority of tested system exhibited useful UVF images, with most showing cracked cells, and a smaller percentage showing hot spot cells. Junction box heating and sealing problems and possible finger corrosion or encapsulant delamination were also seen. This data suggests that pole-mount UVF system is highly applicable and informative over a wide range of residential panel designs and ages and provides information complementary to that achieved from Electroluminescence imaging.**

Keywords—UV Fluorescence, Cracks, Reliability

I. Introduction

UV Fluorescence is a relatively new characterization method for photovoltaic solar panels to detect defects such as cracked solar cells [1]. The technique involves illuminating the solar panel in the dark with a steady-state or flashed [2] UV light source, and then looking at the fluorescence from the top layer of encapsulant over the solar cells. For new modules, little fluorescence signal is seen, but as a panel is exposed to UV light and heat in the field over a year or more, chemical species in the front encapsulant layer evolve such that a detectable fluorescence image can be captured. On older modules that used polymer backsheets and front encapsulant layers containing additives to absorb UV light, a typical *square-pattern* will evolve where the center of each cell will fluoresce brightly while a ring around the perimeter that is ~ 2-15mm wide appears dark. The dark perimeter ring is due to oxygen penetrating the rear polymer backsheet and rear encapsulant layer, and then spreading laterally a short distance across the front encapsulant layer over the cell. This oxygen can react in a photochemical bleaching process to deaden the fluorescence. In some newer front side "UV-transparent" encapsulants with less of the UV absorbing additives, very weak fluorescence will be seen in the center of the cells, but the chemical additives in the rear layer can still over time diffuse upward into the front layer and then laterally move inward across the top layer. In such *ring-pattern* cases one sees the standard outer dark ring from the oxygen activity, but then an inner fluorescing ring related to the chemical diffusion from the rear layer [1].

Where there are cracks in the solar cells, oxygen can also diffuse through the crack and then spread laterally across the front encapsulant layer to create a dark band in the UVF image some mm's wide. Defects other than cracks can also be imaged as we show below.

In contrast to Electroluminescence (EL) imaging, which is relatively slow and which requires the biasing of the panels with an external power supply, UVF is much faster. A closed crack in an EL image will show up as a dark line <0.5mm wide, but these same cracks will show up in a UVF image as a band >2mm wide. Thus, the number of panels per image can be greater with UVF, further increasing the throughput. If there is a question about whether a recent event such as a storm or people walking on panels has created new cracks, one could do EL and UVF testing of the panels within some days or even weeks of the event. The oxygen bleaching effect takes some time to evolve, and should EL show cracks but weak and narrow dark bands are seen in UVF, one can conclude that the cracks are new. If strong and wide dark bands are seen in UVF, one can conclude that the cracks are old [3]. Table I compares the relative strengths of each technique.

TABLE I. UVF vs EL Comparision

Factor	UVF	EL
Compatible with new modules	No	Yes
Tells how "bad" a crack is	No	Yes
IEC Standard exists	No	Yes
Need to bias panels	No	Yes
High Throughput	Yes	No
See cracks under wires	Yes	No
See hot spots	Yes	No
Tell "when" cracking happened	Sometimes	No
See delamination	Maybe	No

Prior work has focused on application of pole-mount UVF to utility scale field testing [2]. The technique also has application for residential and commercial rooftop applications. Here we show the results of several tests performed on residential systems in Boulder Colorado during 2020 with the goals of 1) aiding product development of a commercial tool for sale by BrightSpot Automation, 2) providing data as to the percentage of systems tested which show useful UVF images, and 3) better understanding what types of defects can be seen.

II. UVF Test Procedure

The testing equipment consisted of prototype BrightSpot Automation UV Flash Camera system containing a lightweight mirrorless camera, a modified flash system that emits both UV and visible light, a custom filter enclosure housing to absorb the visible light from the flash, a tall carbon-fiber pole to hold the camera up high to image panels on the rooftops, and a manual remote trigger attached near the bottom of the pole. While for utility scale systems with large numbers of similarly oriented panels to test, we have a found a shoulder harness with a support cup to be useful for supporting the pole, on the smaller residential systems with more frequent focusing, we found it more convenient to not use the harness, and to use a shorter pole held up high during imaging. 50 and 28mm focal length lenses were used depending on the height of the systems and other factors. All imaging took place at least 45 minutes after sunset.

The imaging procedure entailed the following steps:

- Tilt the LCD camera display downward so it is viewable when raising the pole up above
- Raise the pole up high while looking at the LCD display and choose the distance to stand from the residence and the pole angle. Take a first image.
- Lower the pole end to the ground tilted at an angle with the camera at face level, and adjust the distance to the panels to maintain roughly the same camera to center panel distance as when held high. Adjust camera tilt if necessary.
- Adjust the ISO (camera gain) as is needed to achieve a sufficiently bright image. In the case of a brightly fluorescing system, improved focus can be achieved by closing down the aperture (higher f-stop). On weakly fluorescing systems, the lowest f-stop is used to maximize signal strength.
- Point the camera toward the panels and manually focus while zoomed in using the ambient light available
- Raise the pole and image the lowest set of panels while looking at the LCD screen. Move to the left or right and continue imaging the bottom rows of panels allowing for some overlap of images.
- Refocus if necessary for imaging other portions of the system
- Later download the images from the memory card, and correct for lens distortions and enhance the image contrast using BrightSpot Automation's IMPEL software.

Fig. 1. UVF pole-mount system

III. Results

Due to the limited reach of the flash, the majority of tested systems were on single-level houses, although a few higher up systems on double-level houses or larger structures (churches) were tested. Of the 42 systems tested, 67% showed fluorescence of sufficient brightness to be useful. This may have been greater if a taller pole or ladder or drone had been used to bring the flash closer to the panels. Of the useful group, roughly 86% exhibited *square-pattern* fluorescence, with the remainder exhibiting *ring-pattern* fluorescence.

Roughly 2/3 of the systems with useful images showed significant levels of cracked cells (see Fig. 2). The dark bands corresponding to crack locations varied from <2mm to >2cm. Some cells with apparently high levels of cell cracking appeared entirely dark. In contrast to EL imaging which cannot detect cracks that are located underneath the busbars and interconnect wires, with UVF we saw that cracks in these locations were quite common. Although such cracks do not cause an immediate problem, they do represent a possible source of new branching cracks as the panels are further stressed with mechanical loading events and thermal cycling. Modules with *ring-pattern* fluorescence are more challenging to interpret, but breaks in the bright rings clearly correspond to cracks that intersect the ring. In a system that contained 2 different type of panels, both pattern types were seen. In a ground mounted system, we observed snail trails in cells during daylight, and these corresponded perfectly with the crack locations seen by UVF as is seen in Fig. 3.

Roughly 20% of the systems with useful images showed scattered cells which fluoresced much more brightly than neighboring cells, appearing either white or orange in color (see Fig. 4). We interpret this to be due to cells which have run hot at some point during their history due to entering reverse bias from shading events, or cracked cells with reduced active area, or interconnect wire bonding problems. The higher temperature operation can accelerate the reaction which causes the encapsulant to fluoresce, and if the encapsulant yellows or browns, this can impart an orangish color to the UVF image of these cells.

Another defect seen in one system (see Fig. 5) had dark lines branching along the finger directions, perpendicular to the busbars. The cause of the pattern is unclear, but could be linked to silver finger corrosion [1] or delamination of the front encapsulant along the finger that allows oxygen from an intersecting crack to travel along the linear delamination void. If this is true, UVF could prove to a valuable tool for detecting such defects.

A variety of other curiosities are seen in Fig. 6. In some cases brighter regions are seen near junction box locations, possibly indicating hot-running bypass diodes, and in other cases darker areas are seen by the junction boxes, indicating seals which allow more oxygen to enter the module. In one case a dark area is seen around a cell, indicating possible repair/rework performed during manufacturing.

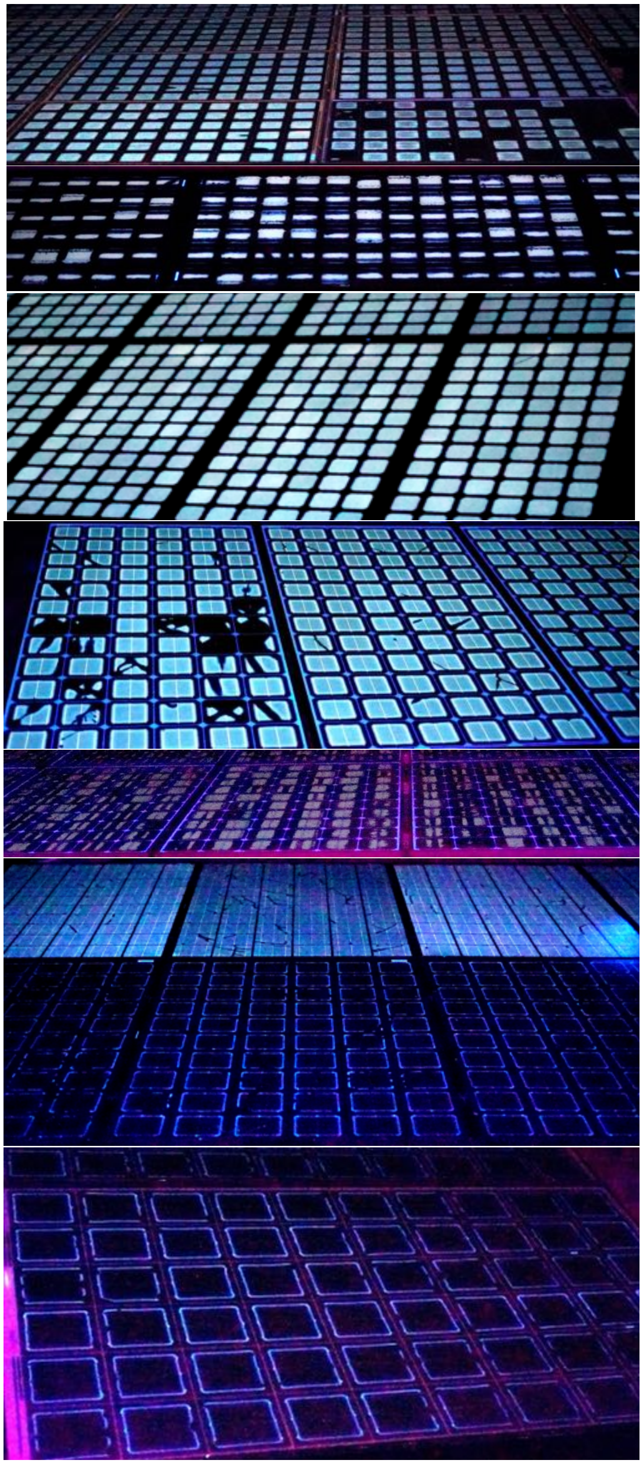

Fig. 2. UVF images showing cracked cells

Fig. 3. Daylight photograph (left) showing snail trails, and a UVF image (right) showing cell cracks in identical locations.

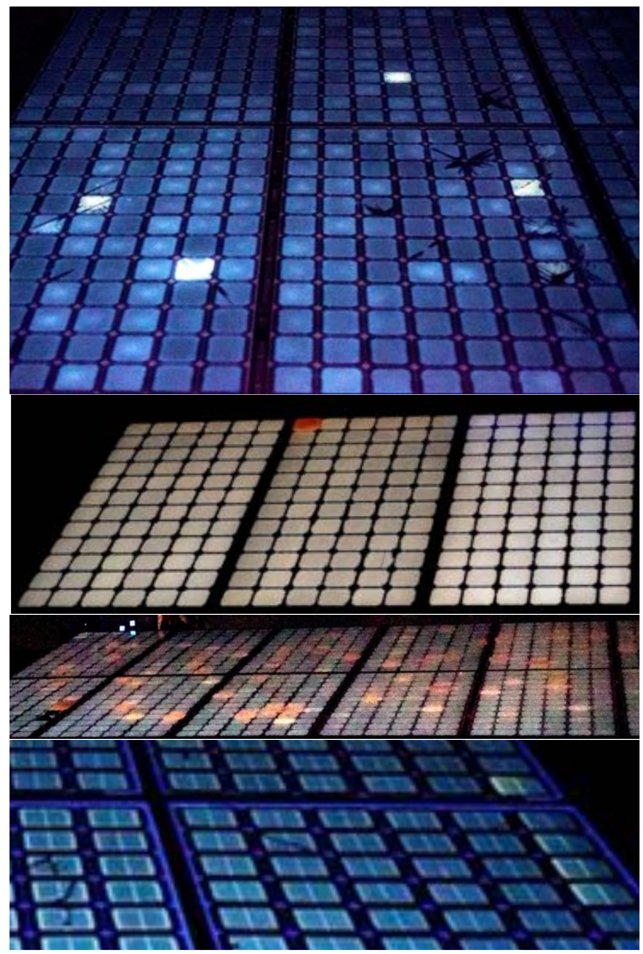

Fig. 4. UVF images showing cells with hot spots

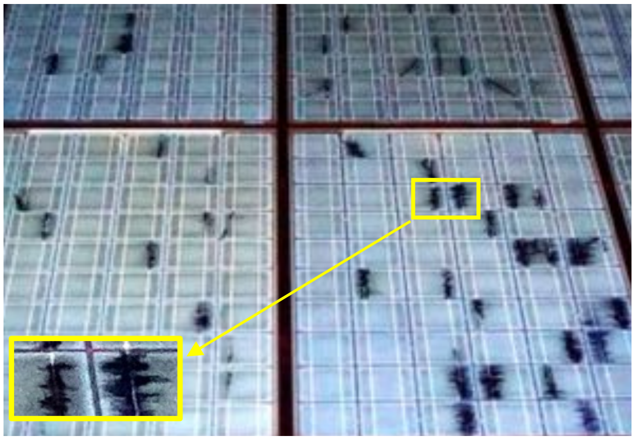

Fig. 5. UVF image exhibiting possible finger corrosion or delamination

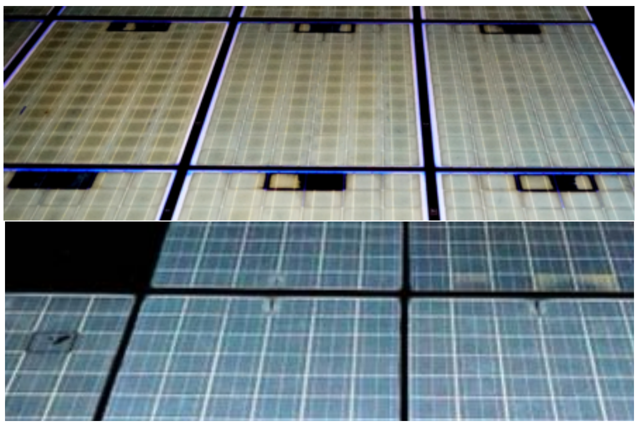

Fig. 6. UVF images exhibiting other interesting patterns

IV. Post-Test Improvements

Automatic enhancement of images through BrightSpot's IMPEL software is demonstrated in Fig. 7. Enhancement steps include in order, vignetting correction, barrel distortion correction, contrast improvement, and perspective adjustment. Note that IMPEL was developed for enhancement of single module EL images. Customization of the software for UVF specific requirements will be implemented in the future. In addition to these image enhancements, we will also implement machine learning based approaches that will likely include the segmenting out of individual modules images and cell images, and automatically detecting and quantifying different defect types. Some possibilities for defect categories include:

1. Cracks (in increasing severity)
    a. Under busbar
    b. Single (between busbars)
    c. Drag mark (across multiple cells in a line)
    d. Multiple (between busbars)
    e. Large dark area (hail, shattered)
2. Hotspots
    a. Cell
    b. By junction box
3. Sealing problem
4. Finger problem
5. Soiling

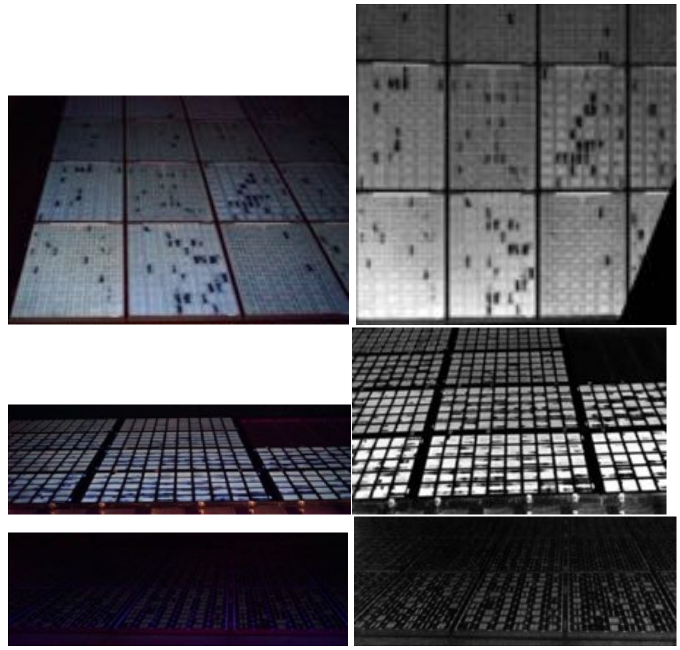

Fig. 7. Examples of automatic UVF image enhancement through the unoptimized IMPEL software.

We found alignment of the camera to the panels to be challenging due to the poor view of the tilted camera LCD display when it was high overhead. To aid in the alignment, we have since added a remote display at eye level as is shown in Fig. 8. We are also designing an interface to allow focusing of the camera while it is being held overhead.

Fig. 8. Remote display improvement to aid alignment

V. Conclusions

We have demonstrated how a hand-held pole-mounted UV Fluorescence system can be effectively used to detect a wide variety of defects on residential rooftop systems, and we believe this to the first published study of its kind for residential systems. We found 2/3 of the systems tested from the ground had sufficiently bright fluorescence to be usefully characterized. Of these systems, roughly 2/3 had high levels of cracked cells, and 1/5 had some level of "hotspot" cells. Other defect types were also seen. Such high levels of defects are worrisome for the health of this market segment.

We believe UVF can be an important tool for the emerging area of residential O&M, and can provide feedback regarding best module designs and installation approaches. The core components of the UVF system are also compatible with drone-based imaging [4], and such an approach may be advantageous in some residential scenarios and most utility scale scenarios.

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