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LLNL-TR-827405

Non-Destructive Testing of Water in PV Modules, Final Report for CRADA No. TC02255

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NON-DESTRUCTIVE TESTING OF WATER IN PV MODULES

Final Report
CRADA No. TC02255
Date Technical Work Ended: September 19, 2018

Date: December 5, 2018

A. Parties

This project was a relationship between Lawrence Livermore National Security, LLC (LLNS) and DNV GL PVEL, LLC

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B. Project Scope

This was a collaborative effort between LLNS, as manager and operator of Lawrence Livermore National Laboratory ("LLNL"), and DNV GL PVEL, LLC, through its wholly-owned subsidiary of KEMA, USA, Inc., operating as a wholly-owned subsidiary of KEMA N.V., Arnhem, Netherlands, a Dutch company, which is a wholly-owned subsidiary of DNV GL, Høvik, Norway, a Norwegian company ("Participant"), to test a water measurement instrumentation developed by LLNL in support of a DOE-funded award.

The project was originally designated as a twelve (12) month project, and consisted of four (4) major tasks and the following four major deliverables:

TASK	DELIVERABLE	RESPONSIBLE PARTY	DUE DATE
1.1	Property Loan Agreement	LLNL	Month 3
1.2	Standard Operating Procedures for the Instrumentation	LLNL/Participant	Month 3
2	Spectroscopic Data from Tested Modules	Participant	Month 12
3	Efficiency Data from Tested Modules	LLNL/Participant	Month 12
4	CRADA Final Report and Abstract	LLNL/Participant	30 Days from End of Project

Deliverables 1.2 and 2 were successfully completed.

Deliverable 3 was not completed. The original concept for the statement of work was formulated in September 2016 when the approach for measuring water in photovoltaic modules was based on Fourier Transform Infrared (FTIR) spectroscopy. In the previous approach LLNL measured samples that were approximately 2 by 2 inches in size due to size limitations of the sample compartment in the FTIE spectrometer. To overcome this limitation for this CRADA we proposed a new approach based on using an optical fiber bundle made of seven zirconia multimode fibers arranged in a hexagonal structure. The center fiber acts as an illumination source and is coupled to a tungsten filament light source, while the periphery six fibers would collect back reflected light towards a detector whose responsivity covers the water absorption band from 3000 to 4000 cm^{-1}. This setup would enable measurement of large structures such as photovoltaic modules, however there was a requirement that the section of the module measured was reflective such that some of the light from the center fiber will be reflected into the collection fibers.

During the negotiation period for this CRADA, a new and improved approach for detecting water in photovoltaic modules was developed at LLNL. The method is based on the same spectroscopic principles outlined above, but it aimed at capturing mapping information on the water content by acquiring an image of the module section, instead of probing a single spot with the fiber bundle. A uniform large area black body acted as an illumination source and a liquid nitrogen cooled band pass filter was used to select only the portion of the spectrum that is relevant for water content testing. Silicon infrared optics with broadband coating (1-5 um) were integrated in the system. An additional calibration procedure, focal plane array non-uniformity correction, common for mid infrared imaging was implemented. The system consists of a camera and a black body with the sample being inserted in between these components to determine transmission over the entire sample area. Representative data for water ingress mapping is presented in Figure 1. The benefits of this new approach were recognized as having a potential for a greater impact and the research direction of the CRADA was adjusted accordingly. For LLNL deliverables remained the same, except the team would use a different instrumentation to accomplish the same goal.

The instrument was not loaned to the Participant as originally planned, due to the need for a liquid nitrogen supply that wasn't available at DNV-GL premises. Instead the samples were sent to DNV-GL for damp heat accelerated testing and returned to LLNL for spectroscopic testing. A property loan agreement (Task 1.1) was not needed to perform the work. The tested sample consisted of a double glass module received from Canadian Solar. Water ingress results showed that during 1000 hours of damp heat testing (the current certification standard) the ingress depth was approximately 5 mm from the edge, showing that the construction of the module was sufficiently robust to prevent water ingress. Because of this finding, efficiency testing on the module was not performed since the ingress profile did not reach the photovoltaic cell area.

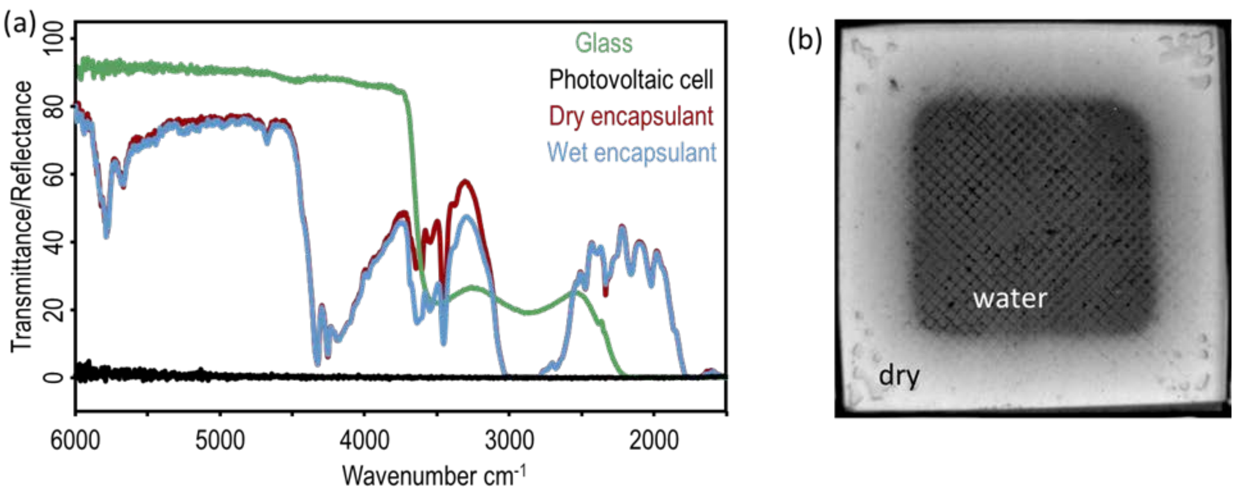

Figure 1. (a) Changes in the spectral absorbance (4000 to 3000 cm^{-1}) of EVA encapsulant when exposed to water ingress. Lower transmission indicated higher absorption from the water content. Partial transmission shows that it is possible to image through glass sheets (b)Image of an EVA laminate sample that highlights regions with high (dark shade) and low (light shade) water content.

C. Technical Accomplishments

In this research project we have demonstrated the use of the water ingress imaging technique on production photovoltaic modules that were fabricated using a double glass design. It was the first demonstration of applicability of our methodology for an industrial application. Technical limitations made did not allow for transfer of the imaging system to the Participant, however, additional technological development at LLNL will result in a system equipped with closed circuit cooling that will eliminate the need for a liquid nitrogen supply. It is expected that when the new system is complete (January 2019) the operation and ease of use of the system will be improved significantly.

The specific technical accomplishments were:

Standard operating procedures for the instrumentation

The typical operation procedure for the setup is described in this section. Although exact details on how the system is setup can differ depending on the properties of the sample under analysis, this section captures the typical interaction between the user and instrument.

In its simplest operational architecture, the system is composed of a light source and a detector (Figure 2). The sample will be inserted in between the two elements to measure transmission. To operate the system in background (non-uniformity correction) mode no sample is placed between the source and detector. To improve accuracy, the background is measured at two temperatures, ideally approximately 10 ˚C above and below the apparent temperature of the sample under analysis.

The light source is a black body system composed of a head (a textured aluminum surface covered by high emissivity paint) and a heater that will control through a thermal sensor feedback loop the head temperature. The user interacts with the black body control through an interface that contains two switches (main power, and power on for the black body head) and a touch screen where the temperature set point entered and where the actual temperature is displayed. When the actual temperature is stable in time (as determined by the controller) and within 0.01 °C of the set point the user is notified with a visual signal on the touch screen interface. To turn off the black body the user changes the set point close to room temperature (20 °C), waits for the temperature to be stable, then turns off the power on the head and on the controller and mounts the cover on the black body emissive surface.

To operate the system in the imaging mode, the detector is arrayed in individual pixels (640x512 pixel resolution) such that transmission in multiple points in the sample is measured at the same time. To accommodate the larger area the light source (black body) is extended to cover the entire sample and a lens is introduced to produce an image of the sample onto the sensor (focal plane array).

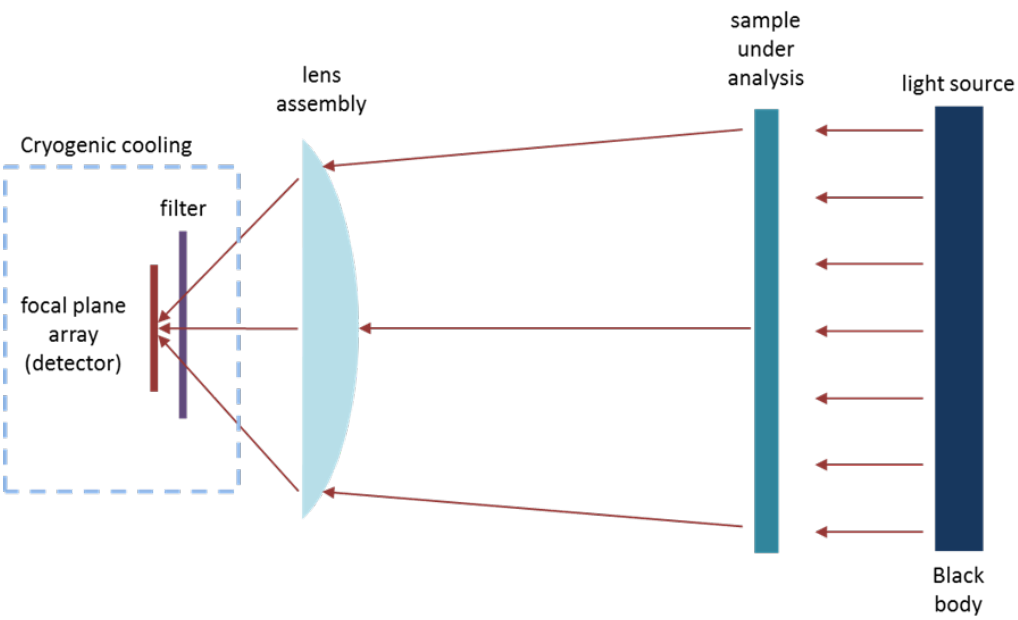

Figure 2. Operational architecture of the imaging system. The light source is composed of a back body that emits isotropic radiation. The detection sub-system is an infrared camera composed of a lens assembly that will project an image of the sample unto a focal plane array (detector), a bandpass filter that is only transmitting light that overlaps with the water absorption band (partially or totally), and a cryogenic cooling sub-system that lowers the temperature of the focal plane array and filter.

For improving signal to noise a filter is placed before the focal plane array to transmit only light that covers the water absorption band (approximately 2.7 to 2.9 microns). The filter and sensor are assembled in closed circuit cooling enclosure that lowers the temperature of these two elements to that of liquid nitrogen to increase the signal to noise in the focal plane array and to decrease the background resulted from thermal emission of the filter.

During the calibration procedure (two point non-uniformity correction) the user will start the procedure in the desktop application, define the camera acquisition parameters (integration time and frame rate), put the lens assembly on the camera, bring the black body to the first temperature point, wait for the temperature to stabilize and follow the prompt from the software to record an image while the entire field of view of the camera is covered by the black body. The process is repeated for the second temperature set point and the software will adjust the camera settings to output a flat response when imaging a uniform surface. For the sample measurement the user will place the sample in between the black body and the camera, manually adjust the location of the sample and the focus of the lens assembly to achieve the desired magnification and a sharp image, while observing the camera output on the screen in live video mode. If a result is deemed acceptable the user will freeze the live video feed and save a picture of the sample for later use.

Spectroscopic data from tested modules

For the initial characterization coupon samples were received and tested from Canadian Solar, the manufacturer of the module. The samples consisted of front and back side glass, encapsulant, backsheet, bus bar and tabbing. The goal of this initial testing was to characterize the materials that were used for module construction and to verify that the technique is applicable to the double glass photovoltaic module.

For a second set of experiments we evaluated changes in transmission for the encapsulant under dry (laboratory) conditions and after immersion in water at room temperature for 24 hours to allow for complete saturation. A change in transmission upon water uptake by the encapsulant film is observed around 3500 cm^{-1}, a previously identified absorption band. Results are consistent with data presented in Figure 1, taken from an EVA encapsulant laminate sample fabricated with sapphire for good transmission in the infrared. The Canadian Solar sample transmission is lower due to film texturing that contributes to optical scattering. The spectroscopic data is presented in Figure 3.

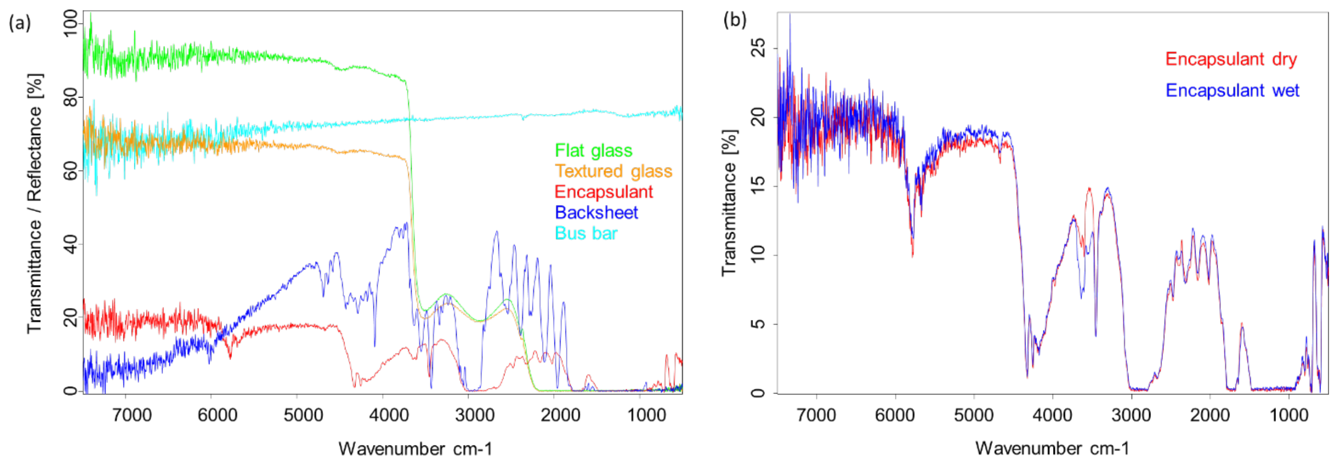

Figure 3. (a) Spectroscopic characterization of module materials: flat glass (front of the module), textured glass (back of the module), encapsulant, backsheet and bus bar. Transmission or reflectance over 10% in the 3000 to 4000 cm^{-1} band is observed for all tested materials. The effect of scattering for textured glass and encapsulant (equivalent decrease in transmission) is not present in laminated samples doe to filling of interface gaps. (b) Spectroscopic testing of Canadian Solar encapsulant before (red) and after immersion in water (blue) at room temperature for 24 hours. A significant change in transmission of observed at the location of water absorption band. This property will be used to test for water ingress in the double-sided glass module.

The tested type of module was with a double glass design, with a white encapsulant layer on the back side. We were unable to verify what king of materials that were used for module fabrication. The accelerated testing was performed at DNV-GL under damp heat conditions (85 °C, 85% relative humidity). The testing was done in increments of 192 hours (8 days) so we could test in intermediate steps for moisture ingress in the module. After the first round of 192 hours the module was taken to LLNL, but no ingress was detected. To troubleshoot this issue, an EVA sapphire laminate witness sample was prepared to verify humidity and ingress conditions during accelerated testing. Based on our previous experience, moisture ingress in EVA is typically 1 inch per day under damp heat. After the second 192-hour exposure at DNV-GL both the witness sample and the module were taken to LLNL for analysis. The witness sample showed water ingress evidenced both by spectroscopic data and its light scattering appearance, however no water was detecting using the imaging technique. Finally, the module was left under damp heat testing for 576 hours and subsequent edge imaging demonstrated an ingress profile of approximately 5mm.

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Figure 4. Water ingress imaging of double glass photovoltaic module. Left: front side image of the module showing the edge. Middle: back side image of the module. Right: bandpass infrared image of the module imaged from the front side after 1000 hours of damp heat testing. Note the water ingress profile from the side as evidences by the dark spots corresponding to water accumulation in the encapsulant pattern. Ingress distance is approximately 5 mm.

The discrepancy between expected EVA ingress profile and the actual module profile can be explained by a different formulation of encapsulant. Our results were independently confirmed by the manufacturer (Canadian Solar) using printed circuit board solid state water sensors that were laminated inside the module during fabrication process (data not shown, but was presented at Photovoltaic Module Reliability Workshop, Denver Colorado, February 2018 and is publicly available). Both methods indicated a similar ingress profile and validate the testing performed in this study. The imaging technique has the advantage that it does not require any modification in the fabrication process, it is faster and cheaper on a per test basis. We expect that other stakeholders may adopt this imaging test to improve photovoltaic module performance during qualification testing that includes water: damp heat, potential induced degradation and humidity freeze.

D. Expected Economic Impact

This study showed applicability of LLNL intellectual property on imaging water content in packaging materials to the photovoltaic industry. To enhance the economic impact of the technology in the future, the LLNL team will perform additional research and development activities for fabrication of an alpha and beta prototype with improved characteristics and usability. A second direction will be towards developing methodologies for qualifying and testing other products relevant to the solar industry: encapsulants (ethylene vinyl acetate vs. polyolefin), backsheet, edge seal and flexible front sheet moisture barriers.

D.1 Specific Benefits

Benefits to DOE

The CRADA enhances U.S. competitiveness by utilizing DOE-developed intellectual property and capabilities. Data from the study will strengthen the intellectual property developed at LLNL by correlating water measurement in photovoltaic module with efficiency degradation. It enhances competitiveness of the U.S. solar industry by aiding solar panel manufacturers to design more reliable products.

Benefits to Industry

The results of this study showed the extent of water penetration in double glass modules during damp heat accelerated testing. For modules that fail this qualification standard it is possible to access an investigation tool to provide insights into the failure mechanisms.

The Participant – a global independent testing, certification, and advisory company for the solar industry – benefits by learning a new method for evaluating the reliability of solar panels.

The U.S. Taxpayer benefits by having more reliable solar panels in the future. If this method becomes the standard for measuring the reliability of solar panels, then all parties will benefit.

E. Participant Contribution

The participant performed damp heat accelerated testing of the photovoltaic modules and witness samples. The testing was divided into batches of 192 hours to allow for imaging at intermediate time steps. No subject inventions were created during the CRADA project.

F. Documents/Reference List

Reports

This document is the only report resulting from this CRADA.

Copyright Activity

No copyright activity resulted from this CRADA.

Subject Inventions

No subject inventions resulted from this CRADA.

Background Intellectual Property

LLNL disclosed the following Background Intellectual Property for this CRADA project:

> U.S. Patent No. 9,588,058 - *Non-Destructive Evaluation of Water Ingress in Photovoltaic Modules*; Inventors: Jack Kotovsky, Mihail Bora; Issue Date: 3/7/17 (IL-12947)

DNV GL has not expressed any interest in licensing the invention listed above.

DNV GL did not disclose any Background Intellectual Property for this CRADA project.

G. Acknowledgement

Industrial Participant's signature of the final report indicates the following:

1) The Participant has reviewed the final report and concurs with the statements made therein.
2) The Participant agrees that any modifications or changes from the initial proposal were discussed and agreed to during the term of the project.
3) The Participant certifies that all reports either completed or in process are listed and all subject inventions and the associated intellectual property protection measures generated by his/her respective company and attributable to the project have been disclosed and included in Section E or are included on a list attached to this report.
4) The Participant certifies that if tangible personal property was exchanged during the agreement, all has either been returned to the initial custodian or transferred permanently.
5) The Participant certifies that proprietary information has been returned or destroyed by LLNL.

December 18, 2018

Ryan Desharnais, Head of Section, Engineering — Date
DNV GL PVEL, LLC

12/18/2018

Mihail Bora, LLNL, Principal Investigator — Date
Lawrence Livermore National Security, LLC

12/21/18

Michael S. Sharer, Manager, Technology Commercialization — Date
Innovation and Partnerships Office
Lawrence Livermore National Security, LLC

Attachment I – Final Abstract

NON-DESTRUCTIVE TESTING OF WATER IN PV MODULES

Final Abstract
CRADA No. TC02255
Date Technical Work Ended: September 19, 2018

Date: December 5, 2018

A. Parties

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B. Purpose and Description

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D. Benefit to DOE/LLNL

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E. Project Dates

September 19, 2017 to September 19, 2018

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