Final Technical Report for DOE/EERE

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8/11/2015

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Project objective

The original objective was to enable a high volume, cost effective solution for increasing the amount of light captured by PV modules through utilization of an advanced Light Re-directing Film and to follow a phased approach to develop and implement this new technology in order to achieve an expected power gain of up to 12 watts per module.

After data indicated the Light Redirecting Film material did not meet SolarWorld's reliability specifications, the objective was broadened to include testing other new materials designed to increase the amount of light captured by PV modules. For the materials which achieved the most power gain while being cost effective, the objective was to develop the manufacturing technology to utilize these materials in SolarWorld's high volume manufacturing.

Significant accomplishments

Full size PV modules were manufactured using a new Light Redirecting Film (LRF) material applied to two different areas of PV modules in order to increase the amount of light captured by the modules. One configuration involved applying thin strips of LRF film over the tabbing ribbon on the cells in order to redirect the light that is normally absorbed by the tabbing ribbon to the active areas of the cells. A second configuration involved applying thin strips of LRF film over the white spaces between cells within a module in order to capture some of the light that is normally reflected from the white areas back through the front glass of the modules. Significant power increases of 1.4% (3.9 watts) and 1.0% (3.2 watts), respectively, compared to standard PV modules were measured under standard test conditions.

The performance of PV modules with LRF applied to the tabbing ribbon was modelled. The results showed that the power increase provided by LRF depended greatly on the angle of incident light with the optimum performance only occurring when the light was within a narrow range of being perpendicular to the solar module. The modelling showed that most of the performance gain would be lost when the angle of incident light was greater than 28 degrees off axis. This effect made the orientation of modules with LRF applied to tabbing ribbons very important as modules mounted in "portrait" mode were predicted to provide little to no power gain from LRF under real world conditions. Based on these results, modules with LRF on tabbing ribbons would have to be mounted in "landscape" mode to realize a performance advantage. In addition, modelling showed that under diffuse lighting conditions such as when the sky is overcast, there would be no significant performance advantage for modules with LRF.

Modules were sent to an outside contractor to measure the power performance under different angles of incident light in order to validate the modelling results. The measured data agreed very well with the modelling predictions and showed that the power gain for modules with LRF applied to tabbing ribbons was completely lost at an angle of 25 degrees off of perpendicular. At even larger angles, the power was lower than standard modules. From 35 degrees to 55 degrees off axis, the power loss was about 1.4% or equal to the power gain at the optimum condition of perfectly on-axis light.

The following reliability tests were performed on the modules with Light Redirecting Film (LRF) material: temperature cycling from -40°C to +85°C up to 400 cycles and damp heat testing at 85°C and 85% relative humidity for 2000 hours.

Damp heat testing was performed on modules and after 2000 hours of testing, the LRF material was observed to have become completely transparent in some sections which appeared to be caused by corrosion of the reflective surface.

After finding that the LRF material did not meet SolarWorld's reliability requirements, a new tabbing ribbon material was obtained for testing. This material had a bright white color designed to increase module power by up to 1.3% by diffusely reflecting light normally absorbed by the tabbing ribbon. When this material was used with the high volume manufacturing equipment used by SolarWorld for soldering tabbing ribbon to the cells, a number of major issues were discovered that made this material unsuitable for manufacturing with SolarWorld's equipment.

Exceptional challenges

Early in the project we encountered challenges working with the vendor providing the light redirecting film (LRF). Since this material was a new proprietary material, we were limited to working with one vendor. The vendor was eager to support one mode of application of their material which was applying the film over tabbing ribbons. However, the vendor was not interested in providing support for the other major application that this project proposed to test which was application of the LRF to the spaces between cells. The vendor stated that they did not have enough resources to support additional application needs. As a result, about half of the first phase of the project (tasks 1.3 and 1.4) was delayed for a few months while we attempted to work with the vendor to get custom widths of material and an alternate design with the adhesive material on the front instead of the rear surface. The lesson we learned from this experience is that before committing to doing research on the application of a new material, we should obtain a commitment from the vendor to support our needs in a timely manner. Another option would be to make the vendor a formal partner in the project.

Major technical challenges were encountered during this project as a result of reliability testing. Additional challenges were also encountered with regards to the discovery of significant limitations to the power gains from the application of materials with light redirecting properties due to the geometry effects under off-axis lighting conditions.

Extended damp heat testing results showed that the LRF material severely corroded even though it was completely sealed within the modules. This indicated a material incompatibility with the EVA used in SolarWorld modules.

Modeling results, confirmed by third party tests, showed that the performance of modules with LRF was severely compromised under off axis lighting conditions including a performance penalty when the incident lighting was more than 25 degrees off axis.

Based on the damp heat results and the performance issues caused by off-axis lighting conditions, SolarWorld determined using LRF to increase the power output of PV modules would not provide enough benefit to justify the increased cost and would not result in a reliable product. As a result, further work on developing LRF manufacturing equipment was cancelled. In addition, other technologies which used patterned reflecting surfaces to redirect light were also dropped from consideration for use in SolarWorld modules due to the performance losses under real world conditions.

One additional technology was tested which consisted of a new tabbing material with a white coating designed to increase module power by up to 1.3%. However, this material did not work with the soldering equipment used in PV module manufacturing by SolarWorld.

Progress against award milestones

Task 1.1: The evaluation of the performance of the original Light Redirecting Film (LRF) on tabbing ribbons was completed during the 3rd quarter of 2014. The average power gain from this material was 1.4% (3.9 watts) when measured under standard conditions which included direct on-axis light. Figure 1 shows the power measurements for 3 groups of modules. The LRF group shows data from the original 15 hand built modules with LRF applied to the tabbing ribbons. The LRF-R group shows data from 2 additional modules that were built after optimizing the soldering process. Group C shows data from the control modules which were built with the same lot of cells but with no LRF applied to the tabbing ribbons.

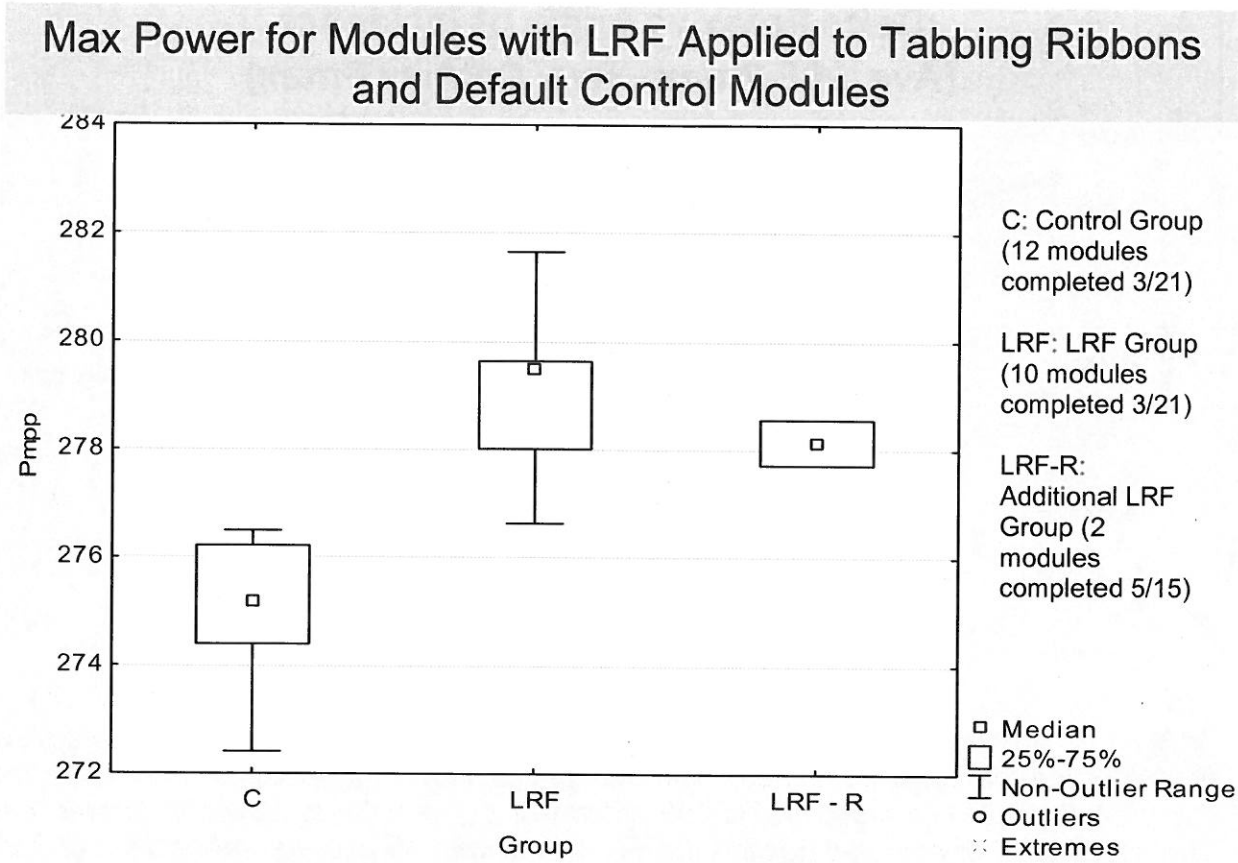

Figure 1

While the peak power improvements achieved by the application of LRF were much as expected, modelling results indicated that the real world energy harvest from this technology would be significantly reduced due to the response of LRF to off-axis lighting and indirect lighting effects. In particular, modeling showed that mounting modules in portrait orientation greatly reduced performance. Because of this concern, additional testing was commissioned from an outside contractor, Fraunhofer, to gather data on the off-axis lighting effects for modules mounted in a portrait orientation. This data showed the performance gain from LRF remained high when the angle of incidence was within about 10° of being normal to the module. However, as the angle increased from 10° to 25° the power gain decreased rapidly all the way to zero gain at about 25°. At even more oblique angles of incidence, the LRF material actually reduced the module power output below the power that was produced by modules without LRF due to shading effects from the LRF material. Figure 2 shows the power gain (or loss) from LRF vs the angle of incident light based on the data from Fraunhofer.

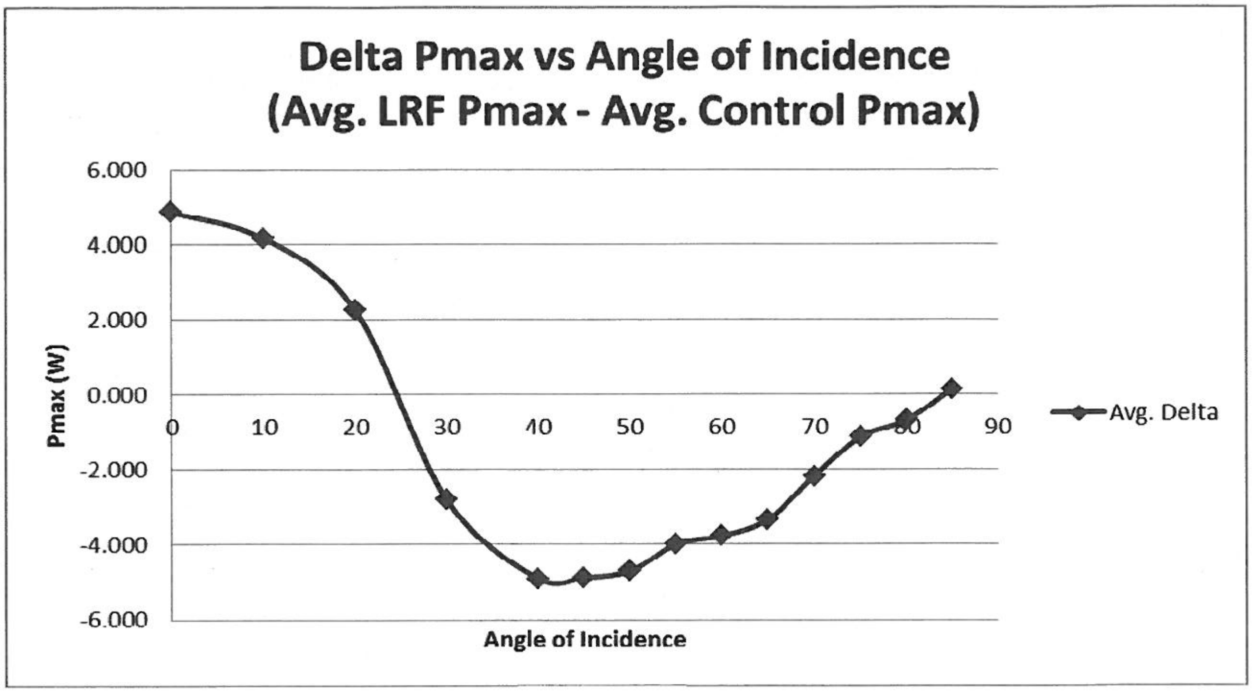

Figure 2

<u>Tasks 1.2:</u> 400 hour thermal cycle testing was completed on the original LRF prototype modules and the control modules. The results are shown in Figure 3. They show that the modules failed to meet theTC-200 criteria of 5% maximum allowable power loss. The second set of modules passed the TC criteria with an average power loss of 3.2% at TC-200 and 4.2% at TC-400.

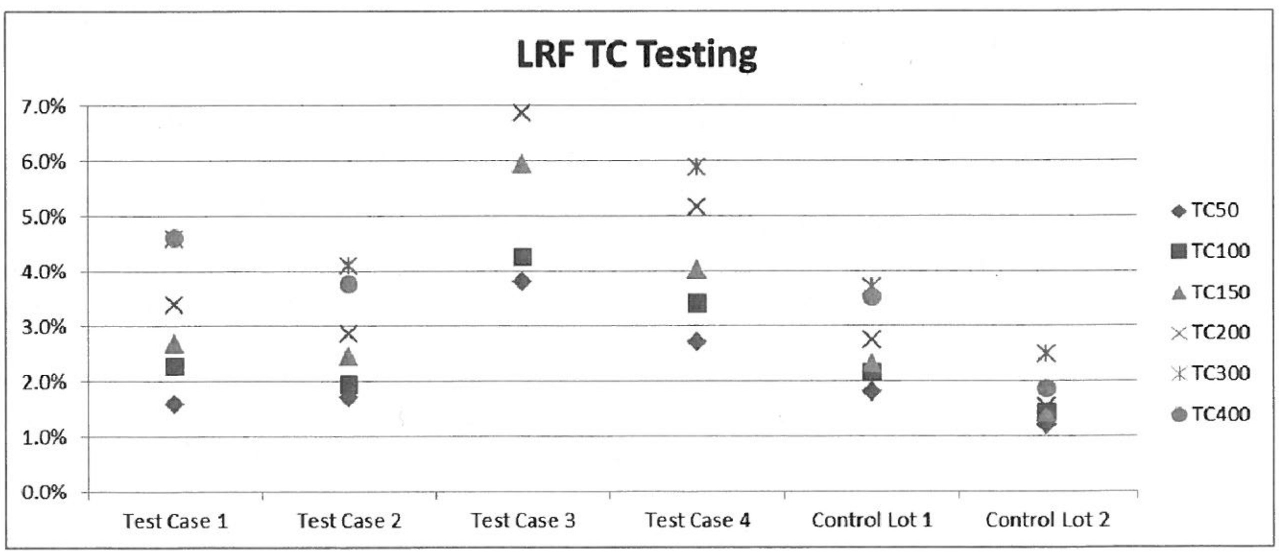

Figure 3

Damp heat testing was completed on two modules with LRF applied to the tabbing ribbons. These modules were first used for thermal cycle testing to 400 hours and were then subjected to damp heat testing. The two LRF modules averaged 6.2% power loss at DH-1000. After 1250 hours of damp heat testing, both modules still had functioning LRF material as verified with a laser pointer. However, the LRF was no longer shiny. It looked cloudy and did not reflect an image of the grid lines which indicated that some of the light redirecting function was lost. After 2000 hours of damp heat testing, the LRF material became transparent in some areas with the ribbon visible beneath the LRF and in these areas there was a complete loss in the capability of the LRF to redirect light as verified with a laser pointer. In other areas there was still some functional effect from the LRF but the effect was dramatically reduced. See the photo images below which illustrate these effects.

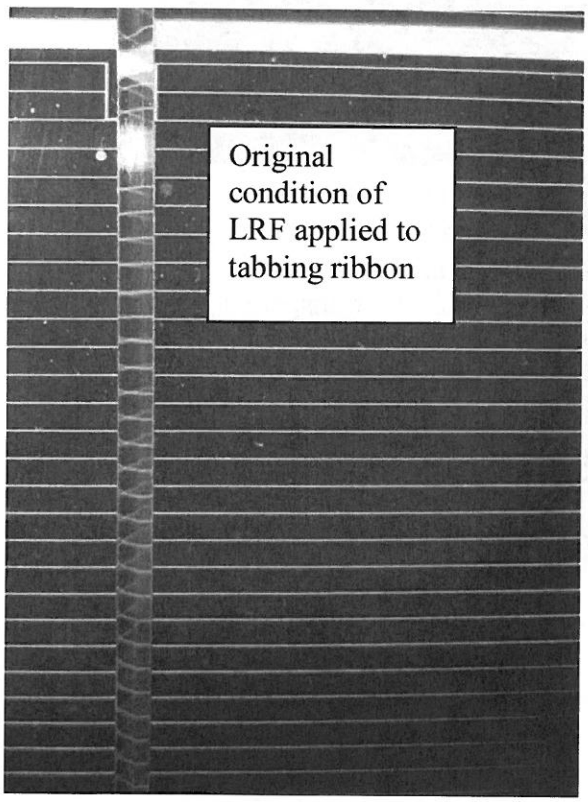

Figure 4

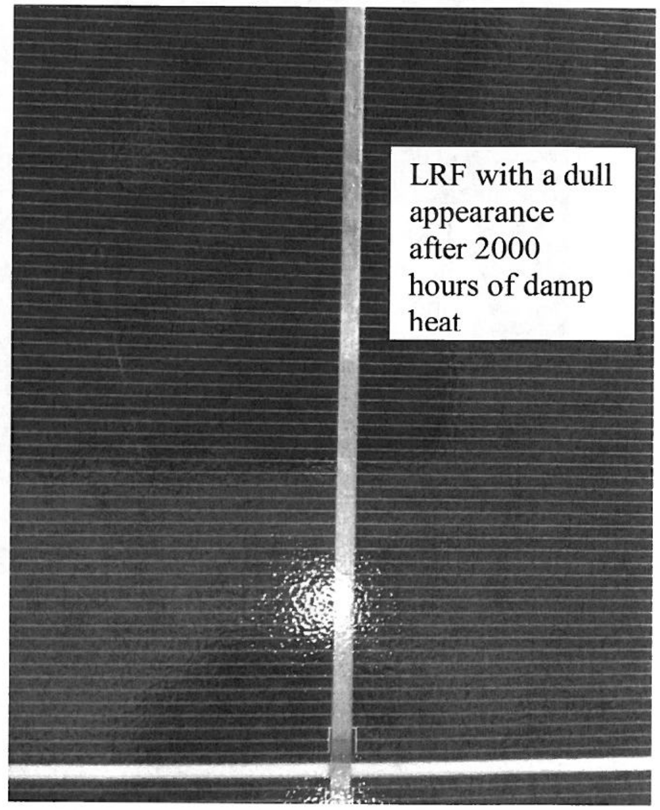

Figure 5

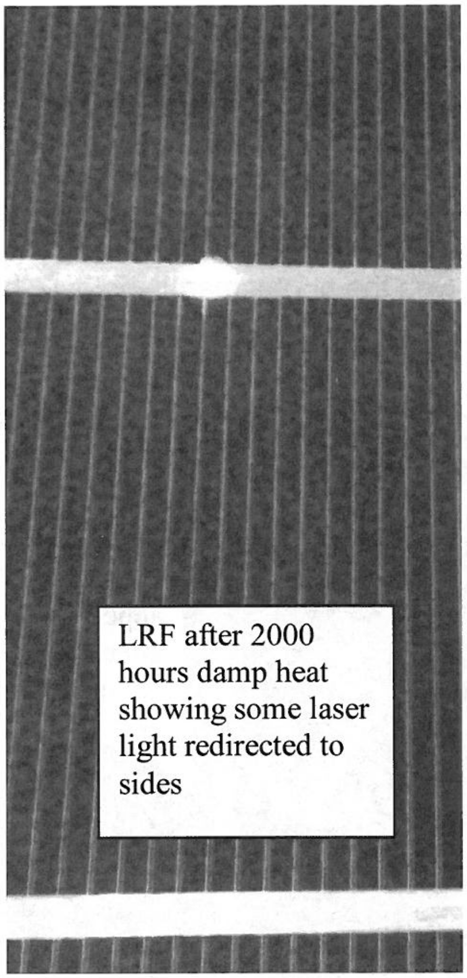

Figure 6

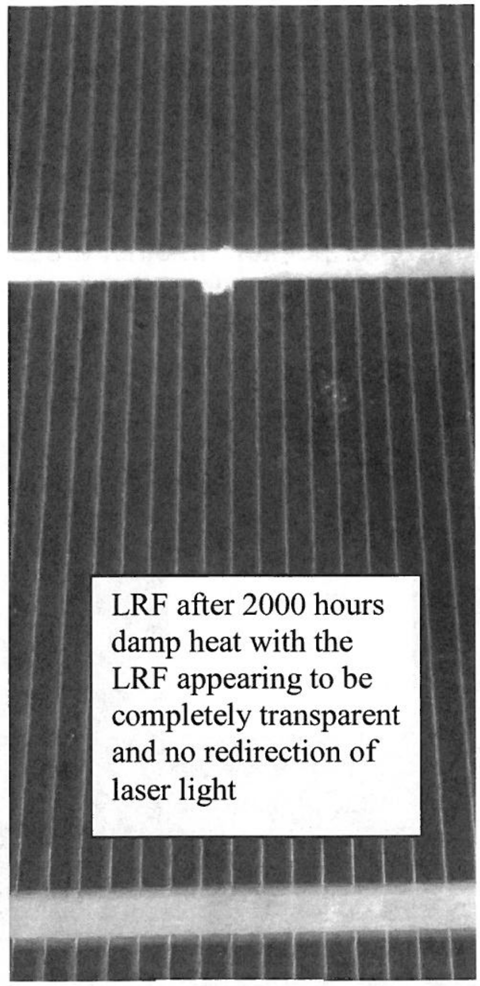

Figure 7

<u>Tasks 1.3:</u> The task of measuring the power gain from the application of LRF to the spaces between cells or between the cells and frame of a module was started a few months late due to difficulties in obtaining the necessary form factor of LRF material from the vendor. Once we obtained the required materials, we built test modules with LRF applied to the vertical spaces in two configurations, in front of the cells and behind the cells. Preliminary power gain results for this task were obtained from a small number of hand-built modules but further work was cancelled due to the reliability results obtained from Task 1.2. The limited results indicated that applying the LRF in front of the cells provided significantly better results than applying the LRF behind the cells. The data showed that LRF in front of the cells increased the power output by about 1.1% (3.2 W) compared to only 0.47% (1.3 W) when the LRF was applied behind the cells.

Tasks 1.5: This task was added to the project in December 2014 as an alternative technology to pursue after the initial work on testing and developing manufacturing capabilities with LRF was cancelled due to the reliability failure results. The technology being investigated by this task was the use of a newly developed tabbing ribbon with a bright white coating to enable capturing the light that is normally absorbed by conventional tabbing ribbon. Modelling results showed that this technology would not suffer from the performance reduction of LRF due to off-axis lighting or diffuse lighting conditions.

An initial manufacturing trial was conducted which demonstrated that it was not feasible to solder this tabbing ribbon using the high volume manufacturing equipment employed by SolarWorld due to the following:

1. *The white surface of the tabbing ribbon was damaged slightly during feeding*
2. *The white surface of the tabbing ribbon was severely damaged during the soldering process as material was transferred to the solder heads.*
3. *The white material on the surface contaminated the contact soldering hardware which severely degraded the soldering process leading to unacceptably low adhesion force.*

During a test where 10 solar cells were soldered, the first cell showed a pull-force which was about 35% of the normal control cell pull force. The cells at the end of the test showed a pull force of about 10% of the normal control cell pull force. During the test, the control cells showed a 5% decrease in pull force from the beginning of the test to the end of the test while the white ribbon pull force decreased by 71%.

Tasks 2.1 and 3.1: These tasks were put on hold due to the reliability concerns raised by damp heat test results and the performance concerns resulting from the off-axis power measurements. There was only a very small amount of preliminary work done on these tasks in regards to developing initial tooling concepts and preliminary tooling specifications.

Subject inventions developed under this award

None

Other results from this award

Highly Automated Module Production Incorporating Advanced Light Management: Conference paper and poster presented at the SunShot Grand Challenge Summit and Peer Review, May 2014, contributors: M. Perelli-Minetti, K. Roof, C. Rischmiller, A. Razo