DISSERTATION

EXPLORATIVE DESIGN METHODOLOGY APPLIED TO THIN FILM PHOTOVOLTAIC PRODUCT DEVELOPMENT AND SUSTAINABLE PRACTICES

Submitted by

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In partial fulfillment of the requirements

for the Degree of Doctor of Philosophy

Colorado State University

Fort Collins, Colorado

Spring, 2016

Doctoral Committee

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ABSTRACT

EXPLORATIVE DESIGN METHODOLOGY APPLIED TO THIN FILM PHOTOVOLTAIC PRODUCT DEVELOPMENT AND SUSTAINABLE PRACTICES

Design is a fundamental aspect of engineering. In contrast to its importance, the understanding and the teaching of a formalized theory of design is not a focus of the engineering discipline. Therefore, developing a more rigorous understanding of the actual design process is beneficial. This study of design presents the opportunity to improve the design process and to develop a common language that facilitates communication. A variety of different theories have been developed in an attempt to model design processes. Because many are either observational or model design as a search process, they inadequately account for knowledge generation and innovation development. The design as exploration (DAE) theory accounts for knowledge generation, provides explicit terminology, and offers a promising approach to expanding the understanding of design. However, the capabilities of the DAE theory have not been broadly researched, particularly for innovative design, for design environments that are heavily constrained as found in early stage technology companies, or for the development of sustainable products.

A thin film solar photovoltaic (PV) module packaging technology was developed and commercialized by the startup company Abound Solar. Approximately one million modules were manufactured and sold in the US, Asia and Europe. The design activity was started as a research effort at CSU and then advanced to large-scale production. It was conducted without a clear design predecessor and with limited available starting knowledge. The early stage company environment with limited resources and funding and a compressed schedule further impacted the design efforts. This module design effort is used to analyze the application of the DAE theory and its utility for early stage technologies and design environments that require innovation.

Key outcomes of this research are the further development of DAE theory, including expanding the understanding of knowledge generation within DAE during real world design. For early stage companies and for innovative designs, the generation of new knowledge is needed before the development of credible problem statements and requirements can be developed. The requirements imposed by sustainable design and iterative product design cycles are also researched thus enabling the extension of the theory's applicability. By investigating cradle-to-cradle sustainable design and iterative product design cycles, a forward-looking, anticipatory component to the DAE process was developed. An updated graphical representation of the DAE theory is presented. It shows the expanded opportunities for knowledge transfer, incorporates knowledge levels, refines the role of R&D and prototype development, and accounts for multiple design cycles.

Details of the module product realization including the materials, construction and manufacturing processes are described. The results of the development included a nearly 6 times reduction in capital costs, reduction in cycle time from 13.5 minutes (currently industry standard) to 30 seconds and significantly improved module durability to moisture ingress (the dominant failure mechanism). The new architecture and associated manufacturing technology can enable lower cost modules with higher reliability and durability which will help to achieve the near term DOE cost goals of 6 cents/kWh and ultimately 3 cents/kWh for solar generated electricity.

ACKNOWLEDGMENTS

I offer my special thanks to Wade Troxell. I have truly enjoyed the breadth and content of our conversations. I have appreciated your encouragement to investigate new intellectual avenues. Your understanding of design theory as applied to engineering and research has been very insightful. Thank you for the opportunity to explore these avenues of thought.

I sincerely appreciate my 25-year friendship with W. S. Sampath. We have partnered on a truly vast array of successful projects, including the founding of Abound Solar. I look forward to new challenges as we work to make solar electricity an energy solution.

My committee members, Louis Bjostad and Gearold Johnson have provided meaningful insights and I am thankful for that input derived from their rich experience. I want to acknowledge the contributions of the Abound Solar product development team who helped bring the module designs described here to commercial fruition. I want also acknowledge my colleagues and collaborators with the Next Generation PV Center at CSU and Direct Solar. Lastly, I offer my love and appreciation to my friends and to my family who have been the source of endless encouragement and support.

Kurt L. Barth

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1 INTRODUCTION

1.1 Overview: Different theories have been developed in an attempt to model the design process. Many are either observational or model design as a search process and either don't cover or inadequately account for knowledge generation, creativity and innovation within the design process. The design as exploration (DAE) [Smithers 1990, 1992] theory was developed to overcome these limitations. The explorative nature of design is abstracted where knowledge of both the broader context and the specific design under development is increased while design requirements are refined.

The "module package" is the physical structure that encapsulates the semiconductors and provides mechanical protection and a means of transporting and mounting the PV device. A new PV module packaging technology was developed and commercialized by the startup company, Abound Solar. The product was a new design that demonstrated superior reliability to environmental conditions with reduced materials, capital, and equipment costs when compared to the industry standard. The design activity started as a research effort at CSU and was then developed through to large-scale production. The effort was initiated without a clear predecessor and with limited available background knowledge. The startup company environment, with limited resources, funding, and a compressed schedule, further impacted the design efforts. A new company, Direct Solar, has since been formed and is continuing to advance the module packaging technology.

The environment of a startup company introducing a new, high technology product, provides an ideal backdrop to extend the understanding of the DAE theory. The new module design is novel, and the development was being conducted in a very young company in a fledging industry that was experiencing rapid expansion. At the start, there were no experts in the company and there was minimal industrywide knowledge, along with a lack of well-defined best practices. Though innovative design, by its nature, requires the generation of knowledge, the success of this design (and the product introduction) in this circumstance required the generation of a particularly high level of new methods and understanding. In this dissertation, the novel module package development is used to illustrate the DAE theory's application and utility for early stage technology development. The DAE theory is explored in design environments that require innovation and have poorly understood knowledge domains. Methods to expand and better utilize design domain knowledge are presented. The DAE theory's applicability is extended to environmentally sustainable design, where a broader understanding of how the product will be used and processed at the end-of-life is needed. New understandings for applying DAE to continuing design cycles and the simultaneous development of multiple related designs—areas where DAE has been previously identified as insufficient—are presented.

Solar photovoltaic (PV) modules, also known as solar cells, are solid state devices that directly convert sunlight to electricity. A PV module is comprised of semiconductors, encapsulation, and a junction box with leads. Internal interconnections connect the semiconductors to the junction box. The module is the "package" that protects the semiconductor from mechanical harm, prevents damage from environmental factors, and provides electrical safety when the PV is installed and operational. The details of the systems approach used to develop the new module architecture are presented. The design features, manufacturing process development, and product testing performed at Abound are described and the results of recent developments, funded by the US Dept. of Energy, are included. Realized outcomes of this product development, including reduced manufacturing, capital, and product costs, along with increased product reliability, are presented. Approximately one million modules were manufactured and sold in the US, Asia, and Europe.

1.2 Thesis Topic Overview: The PV module technology development will be used to demonstrate and explore the DAE methodology. Two key aspects of this design effort will be investigated within DAE: a) the development of a new innovative product where there is limited or conflicting industrial knowledge and b) the experiences within a startup company with significant non-technical or business constraints, such as accelerated time to market requirements influencing the design effort. The DAE theory will be further investigated by exploring sustainable, "cradle-to-cradle" design cycles and product design in which multiple designs may be undergoing simultaneous development at different rates. The ongoing technical research effort to refine the technology to improve module reliability and reduce costs is presented in conjunction with demonstrating the DAE theory. The R&D and engineering processes to develop the new module architecture will be described in detail.

The outcome of this dissertation will be insights into the applicability of the DAE theory for innovative product design and the extension of DAE into design that includes simultaneous lines of exploratory investigation where one line can influence or initiate other lines. This is an area where DAE had been previously described as insufficiently developed by the theory's originators [Smithers 1992].

2 BACKGROUND

2.1 Solar Photovoltaics: Solar PV panels are used terrestrially for residential and commercial rooftop installations and most commonly for utility scale deployments for solar power plants. PV modules are assembled together to form "arrays." Although size varies with manufacturers, the typical modules for utility grid connection are around 120 x 60 cm [FSLR 2013] or larger, such as 196 x 92 cm [Suntech 2013]. The number of modules assembled in an array is determined by physical necessity (how many can fit) or, for utility installations, arrays are configured to achieve the maximum voltage allowed under regulation (typically 650-1000 V in the US and 1000-1500 V in Europe). Figures 2.1 and 2.2 show utility deployments of modules using thin film semiconductor technology.

There are two main semiconductor technologies for terrestrial PV: thin film and crystalline silicon (c-Si). Crystalline silicon PV has been the dominant technology, with market share varying between approximately 90% and 95% over the last decade. Modules are assembled from individual cells made from either mono-crystalline or polycrystalline wafers. These are tabbed together and laminated between layers of ethylene vinyl acetate (EVA) and tempered glass, which act as the encapsulation. A perimeter aluminum frame provides mechanical support and the means of mounting.

Thin film PV is significantly different from c-Si and involves depositing 1-4 micron layers of the semiconductor material on a substrate, often glass. The most successful fabrication methods are vacuum vapor deposition. Many of the manufacturing systems are proprietary and process specific. Because thin film PV uses up to 100 times less semiconductor materials and more streamlined manufacturing processes, thin film PV holds the potential to be less expensive than c-Si. With these benefits, the US Dept. of Energy has focused development efforts on thin film PV.

Figure 2.1: Utility scale installations of PV modules of First Solar Agua Caliente CdTe thin film PV Plant.

Figure 2.2: Utility scale CdTe thin film PV modules produced by Abound Solar. Multiple two row tables are shown in the lower picture.

The largest PV module producer, First Solar, utilizes thin film CdTe semiconductors, paired with CdS as the heterojunction partner. Modules using the $CuInGeSe_2$ absorber (often paired with n-type CdS) are being researched by a number of groups and have been commercialized by Solar Frontier of Japan.

2.2 PV Module Architecture[1]: The photovoltaic module is the package for the PV semiconductor and includes the leads, encapsulation, and any structures internal to the module, such as buss bars. The module architecture must fulfill a number of key requirements:

1. Provide environmental protection to the semiconductor materials, including protection from moisture ingress
2. Provide mechanical protection to the semiconductor materials
3. Provide electrical safety isolation for the module
4. Provide a means of mechanically mounting and interconnecting the modules in the field

There are a number of requirements that the module package must fulfill for customer and regulatory agency acceptance. Industry standard photovoltaic warranties are for 20 to 25 years. The encapsulation and module structure must resist a number of stresses during transport, installation, and operation over the life of the module. Modules are tested for certification using testing standards such as the American National Standards Institute/Underwriters Laboratories (UL) 1703 and International Electrotechnical Commission (IEC) 61646 [IEC 2008] and 61730 for c-Si. Passing these standards is mandatory to sell and install modules in most of the world, including the US. In order to pass the tests described in these standards, the module encapsulation must protect the photovoltaic structure from moisture, UV radiation, and other potential sources of environmental degradation. The front substrate and the back substrate must provide significant mechanical strength to withstand mechanical loading from wind and snow. Additionally, the module must withstand impacts from hail and windblown debris while providing electrical isolation and safety.

[1] A high level description of the PV module, the importance of the module reliability to the PV industry and a description of Abound Solar are presented here to enable the design theory investigations. The technical details of the new module architecture are the focus of section 5.

2.3 PV Costs and the Impact of Reliability: For solar, cost is the key market driver; reducing costs enables more installations to be economic and expands the usage / market. PV costs include the manufacturing cost of the module, the installation costs, and other balance of system (BOS) costs such as racking, power conditioning equipment, and interconnections. The US Department of Energy (DOE) has initiated the "SunShot Initiative" to advance PV technology to reach installed costs of less than $1/Watt [SunShot 2013]. According to the DOE, solar energy systems at this price would be broadly economic in the U.S. and the rest of the world [SunShot 2013]. The solar industry is rapidly advancing, and for utility scale applications PV is *currently* economically competitive, unsubsidized, with coal and nuclear and significantly more economic than natural gas in many parts of the US [Lazard 2014].

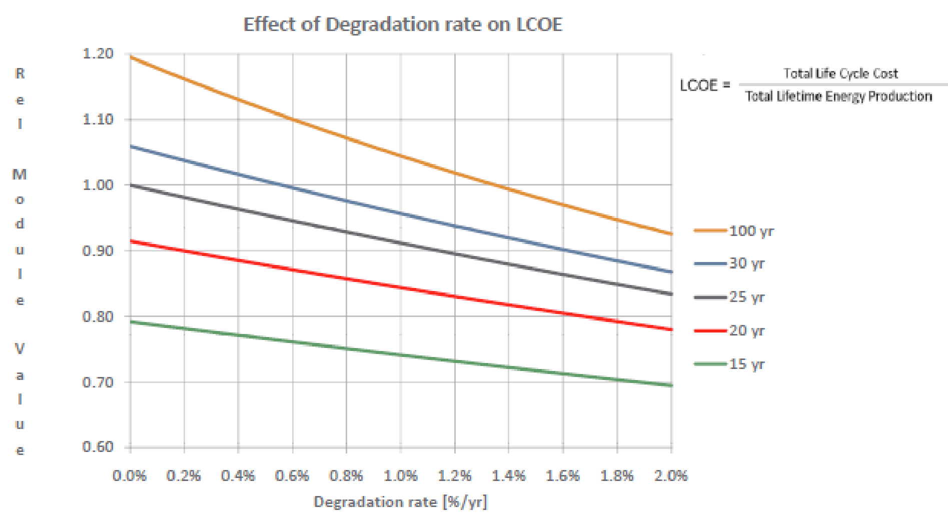


Figure 2.3: The negative impact of reduced module reliability on PV energy costs [Beck 2011].

The CdTe thin film PV provides the lowest documented production cost per watt (< $0.40) [Wessoff 2014] of any PV technology. The CdTe thin film technology's cost structures are well below the full production cost of its overseas competitors. Furthermore, thin film's effective efficiency under field conditions, typically with higher temperatures and lower solar intensity than standard rating conditions, gives it an additional competitive advantage of up to 10% over the silicon technology for average power production [Huld 2010].

Reliability is critically important, as it affects the operation and maintenance costs for the solar installation. Module reliability has a direct impact on the levalized cost of energy (LCOE), or the cost of the energy produced by the PV system. Figure 2.3 shows that the relative module value decreases significantly with increased module degradation rates. Lowering the degradation rate and increasing the reliability of modules in the field directly reduces the cost of PV generated energy. Figure 2.4 shows that for the same LCOE and efficiency, a module with a 50 year life is over two times more valuable than a module with a 30 year life.

Reliability issues for thin film PV have been consistently reported [Whitfield 2010, Beck 2011, FSLR 2012, PVRW]. The leading thin film producer in the world, the US based First Solar Inc., has had significant reliability issues and has over $200 million in warranty expenses in late 2011 and 2012 alone [FSLR 2012, Montgomery 2012]. A Credit Suisse analysis of First Solar's business in 2012 stated that, "It's (reliability is) the most important metric for the company's long-term survivability" [Montgomery 2012]. This is a profound statement considering the number of thin film module producers—such as Unisolar, Abound Solar, MiaSole—that have gone out of business or been acquired at "fire sale" prices citing predatory pressure from off-shore producers during that period.

Thus, reliability issues were a more dominant business concern than the current influx of heavily subsidized Chinese silicon modules. It is noted that First Solar is the most advanced and successful of the thin film PV manufacturers in the world, further highlighting the significant impact that module reliability has for all producers. Since the CdTe PV technologies are the cost leaders and have demonstrated module reliability issues, improved module reliability would enable further reductions in LCOE from PV.

There has been significant R&D efforts by both US and European institutions [for example see Sample 2009] for improving module performance. The US DOE and NREL sponsor annual PV reliability workshops [see PVRW]. The author gave a plenary invited talk to this conference in 2008 [Barth 2008]. There was a recognized need in the thin film PV industry for improving module packaging reliability, manufacturability, and cost [Jones-Albertus 2015]. That need is ongoing but was particularly acute during the 2007 to 2010 time frame when the initial design efforts described here were performed. Although there has been much study of the industry standard module architectures and materials, there has been an absence of novel, new solutions.

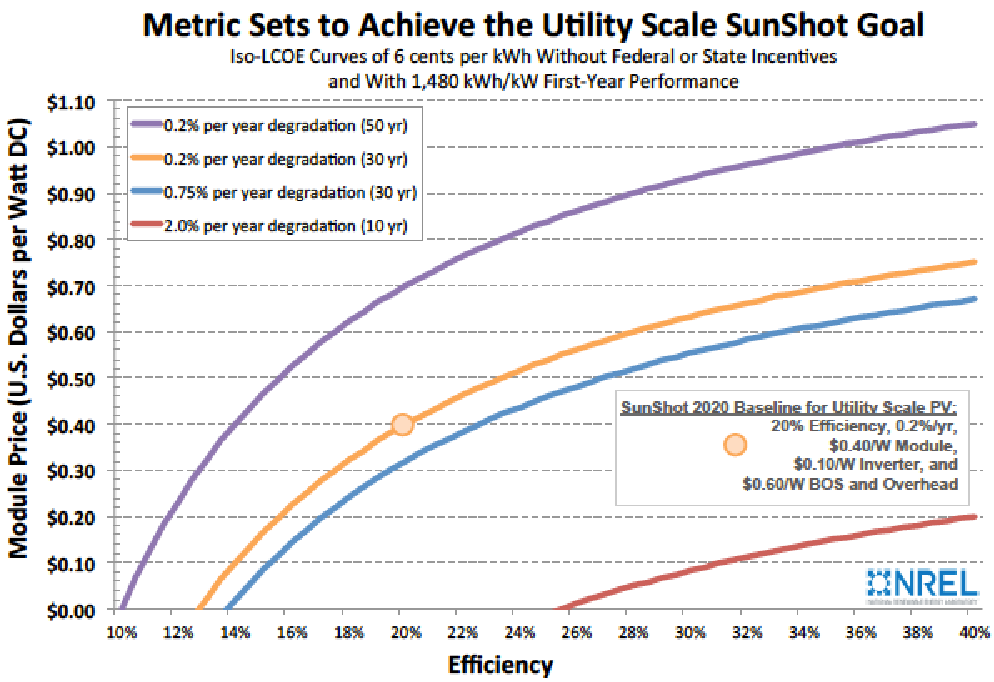


Figure 2.4: Impact of module life and degradation rate. All curves show $0.06/kWhr LCOE. A 16% module can be sold for $0.20/W if it has a 30 year life, and the same efficiency module can be sold for over double ($0.50/W) if it has a 50 year life; both provide the customer with the same energy cost (LCOE) [chart from Jones-Albertus 2015].

2.4 Abound Solar and Business Environments: In 2007 AVA Solar was formed to manufacture CdTe based thin film PV utilizing technologies developed at CSU by the author, R. A Enzenorth, and W. S. Sampath [Barth 2002, 2007, 2009, 2011]. AVA Solar was later renamed Abound Solar.[2] The author was a founder of Abound Solar and a founding director on the Board of

[2] The renaming of AVA Solar to Abound Solar happened during the period that the design efforts describe here were being conducted. For simplicity, the company will be referred to as "Abound Solar" or "Abound" throughout the document even if some of the activities described were performed while the company was still named "AVA Solar."

Directors. He developed the initial business plan and helped drive the equity financing which eventually totaled over $300 million. The author was involved in all startup business decisions, technical strategy development, and resource hiring. As the company matured, his contributions included technical due diligence, intellectual property (IP) strategy development, and IP competitive analysis across the company.

Abound Solar produced over one million modules and became a leading domestic manufacturer of CdTe PV, with customers in the US, Europe, and Asia. Abound's manufacturing technology is highly automated and remains state of the art. Abound Solar was recognized as one of the nation's leading startups [Business Week 2008, Entrepreneur 2009, Cleantech 2010].

The author was intimately involved in Abound's module product development, including driving the early design efforts described in this dissertation [Barth 2009, 2010-2, 2011, 2011-2, 2012]. He was responsible for identifying and driving research needs, developing the conceptual design of the module through specification for production, and aiding the manufacturing processes and equipment development. He developed resource plans for hiring the product development and reliability team, initiated the construction of the world class reliability lab, and developed Abound Solar's module certification and reliability program. He developed partnerships with NREL, Cardinal Glass, Sandia National Lab, TUV Arizona, and Underwriters Laboratory (UL). The Abound team developed a module product that addressed key reliability issues seen in the industry [Barth 2009, 2010-2]. The module development resulted in the filing of two US patents [Barth 2015, 2015-2], both pending, and two international patents [Barth 2011-2, 2012].

When Abound exited the PV manufacturing business, a new company, Direct Solar LLC, was formed. Founded by the author, Direct Solar LLC is a technology engineering firm focused on developing methods for improving solar module reliability and reducing costs. Direct Solar obtained the US module architecture intellectual property and has continued the development of the technology. Direct Solar has support from the US Department of Energy and has collaborations with the National Renewable Energy Lab and SEMATEC-PVMC in New York [Direct Solar 2013]. Using the Abound Solar experiences and learning as a starting point, Direct Solar has continued to advance the module architecture development. For this dissertation, results from these recent developments will be included.

3 DESIGN THEORY

Engineering design can be considered the process of evolving a series of specifications to develop a process, item, or method that fulfills requirements. The design process combines the incorporation and generation of knowledge with an iterative aspect to develop the appropriate outcome.

3.1 Motivation to Study Design: In a broad sense design is a critical human endeavor. "The ability to design is what creates civilizations" [Smithers 1992, p. 2]. Architectural or stylistic design elements are often used in defining different cultures. Designing is a fundamental aspect of engineering and is at the heart of most engineering effort. In contrast to its importance, understanding and teaching design is not frequently a focus of engineering education. Traditionally, design skills are taught in an informal manner using examples or case studies. Alternately, skills are developed through experience with little formalism: design is taught by having students practice design. Other approaches to discuss and teach "design" focus on the steps of organizing a design process, such as the "stage-gate" process or systems engineering methods [Kossiakoff 2011]. These are effective tools for overseeing product introduction or even shepherding the outcomes of the design process to commercialization. However, these approaches do not address the actual design process; they don't describe the creative, knowledge-based iterative development. They are more business management tools to facilitate the interaction of different groups (engineering, R&D, marketing) and business activities (scheduling, budgeting, etc.). Because of the importance of design, developing a more rigorous understanding of the actual design process is an asset. There are key benefits to investigating the design process and trying to develop a structure that describes real design. The first is that the greater understanding developed through the study presents the opportunity to improve the design process. By investigating something, more knowledge is developed which can be used to improve the method. This can range from advancing how design is approached, performed, and taught as an engineering discipline, down to facilitating an individual designer in organizing and executing a specific design effort. The second is that through rigorous study, a common language with well-defined terms is developed. This enables more effective communication between designers and provides a foundation for teaching design. Lastly, the study and development of design theory may enable the development of algorithms that enable the development of automated design tools.

3.2 Design as Search: Existing theories have defined design as a dynamic mapping of actions between required functions and selected structures [Hatchuel 2009]. Early research in design was often investigated in conjunction with artificial intelligence (AI) research. Those efforts focused on defining a structured method where the prescribed design space was the output of a search type algorithm [Smithers 1990-2 and Simon 1996]. For a “search” to be "successful," what is being searched for must be known and quantified. This requires that the starting point and end objective be known and relatively well specified. This conceptualization has inherent limitations. The "search" method is more similar to a mapping exercise surrounding well-known options, determining where there is the best "fit." This definition does not accommodate key aspects of real design, including the creation of new knowledge and innovation. A design solution may be well known in another industry or discipline outside the initial search space. Simon [Simon 1996] describes a "general problem solver," or GPS, which may broaden the search methodology to more general cases, but it still requires that the solution be in the current domain where the problem solver is operating.

3.3 C-K theory: The C-K theory of design [Hatchuel 2009, 2003] proposes that design involves interplay between the concepts, or ”C space,” and knowledge, represented by "K space." The C space contains entities which are weakly defined and which can only be searched or explored [Hatchuel 2003]. A concept in C space is an entity that cannot be determined to be "true" or fully described in K space. The K space contains more well-defined or partially known objects and relations between the objects. A positive aspect of the C-K theory is that the K space (and C space) can grow over time as more knowledge is acquired and the design activity progresses. For the C-K theory, the design activity progresses when concepts generate other concepts or are developed and converted to knowledge. Design involves stating concept proposition, C_i: *there exists an x with a set of attributes* A_o [Hatchuel 2009] *and design parameters, D*. The process involves adding and subtracting attributes and parameters and evaluating if the C_i is true, false or neither. "True" means that the concept Ci with attributes A and parameters D is true K space; this represents a design solution. "False" means that A and D need to be changed. "Neither" represents a new concept, and design iteration needs to continue. Design is the expansion of C and K spaces through four operators—C to K, K to C, Cto C, and K to K—each utilized depending on the design situation.

Hatchuel and Weil contend that the C-K theory allows for innovation through the interplay of the weakly defined entities in the concept space. However, the level of innovation is restricted by the initial definition of the concept space and has dependence on prior existing knowledge. In this manner, the C-K theory has some limitations for describing real design. The C-K theory places emphasis on knowledge. The ability for a design theory to address knowledge generation and account for and categorize existing knowledge is a key for success.

3.4 Design as Exploration: A more comprehensive theory of design is to view design as an "exploration" (or even an adventure) [Smithers 1990]. In the design as exploration (DAE) theory, the type and nature of the potential solutions are not fully defined at the outset. The initial requirements for the design are also vaguely defined at the outset. The design activity involves an exploration in which knowledge is generated to refine and ultimately define the requirements and design specifications.

DAE theory allows for the generation and accumulation of knowledge. This is in contrast to "the solution is already there, it just has to be found" concepts embodied in the design as search theory.

A brief summary of how a design may move through the DAE construct follows. Designs start with a weakly defined set of initial requirements, Ri. Knowledge from broader fields or a body of knowledge in the design space is known as Kdm or domain knowledge. Specific knowledge of the design is Kdn. Through the exploration process, Ed, knowledge is created and the initial requirements are developed into a design description document (DDD) which includes the design specifications, Ds, the final requirements, Rf, and exploration history, Hd.

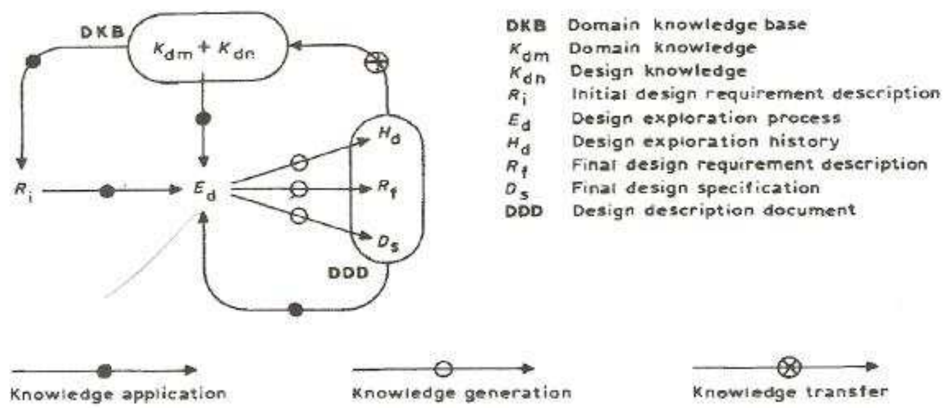


Figure 3.1: Design as exploration theory [Smithers 1990].

The process is iterative, and as a design progresses, new knowledge is generated in Kdm and Kdn that can aid the future designs. This knowledge also enables the generation of initial requirements, Ri, for the next design. The design as exploration method captures key aspects of knowledge generation. The key aspect of the dissertation will be to demonstrate the design as exploration theory in the PV module package development.

Design for DAE is the "incremental extension of problem statements and associated solutions" [Corne 1994]. In most design processes, an ambiguous, poorly defined initial requirements set (Ri) and problem description (Pi) are posed (figure 3.2). As the exploration process (Ex) is conducted, there is an iteration and refinement of different problem statements

(Px, Px+1 ... Px+n), requirements (Rx, Rx+1 … Rx+n), and design description (Dx, Dx+1 ... Dx+n). Any one of the incremental conceptual designs (Dx) likely do not fulfill all the requirements (Rx) or satisfy the problem statement (Px), but through the exploration process, the R, P, and D converge, reducing the unsatisfied aspects until there is final design, tightly worded requirements, and a clear problem description. The more clearly defined the parameters are at the outset, the more "routine" the design. Designs with very clear requirements and problems statements in mature industries are said to be "cook book" designs that can be fulfilled without significant knowledge generation. A more thorough understanding of the DAE theory will be developed in subsequent sections of this document through the use of the Abound Solar examples, in which there are very open ended requirements and poorly understood problems statements.

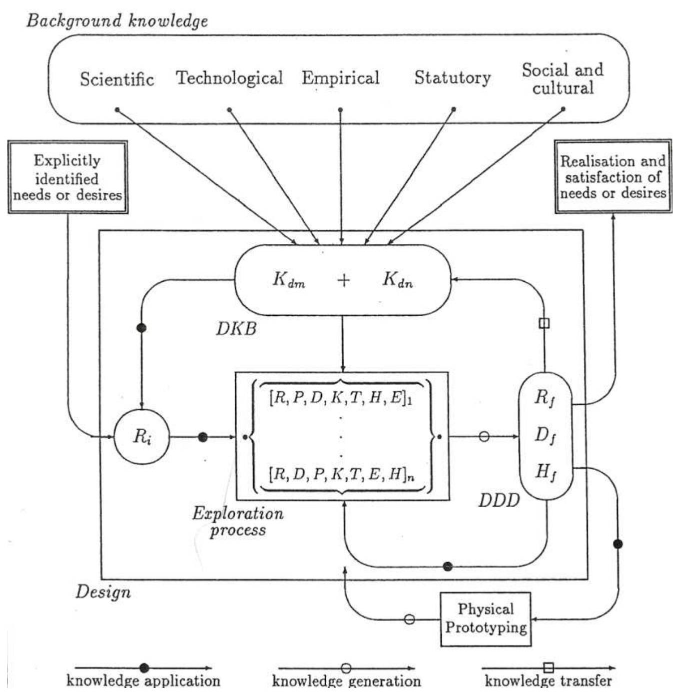


Figure 3.2: Extension of the DAE theory highlighting the iterative exploration process and sources of design knowledge [Smithers 1992].

4 RESULTS / DISCUSSION

4.1 Thesis Statement: This dissertation will show an integrated design methodology based on the design as exploration theory to illustrate early stage innovation and cradle-to-cradle sustainability. The PV module technology realization will be used to demonstrate and explore the design as exploration methodology. A systems approach to the design resulting in the technology realization of a thin film photovoltaic product will be developed.

Outcomes will include insights into DAE applied to a) design development for early stage innovations where there is limited or conflicting industrial knowledge; b) design in a company startup environment with significant non-technical or business constraints, such as accelerated time to market requirements and c) sustainable design and how cradle-to-cradle design thinking can be incorporated into the frame work of the DAE method. Currently realized outcomes of this product realization, including reduced manufacturing, capital, and product costs, along with increased product reliability, are presented.

4.2 Overarching Constraints Encountered During the Design Efforts: During the technology developments described here, Abound Solar was a startup company with both financial and engineering resource limitations. There was minimal institutional knowledge of the industry since none of the early participants had been involved directly in the PV industry. Since there were no products developed, little product specific knowledge was available. The thin film PV industry was growing and did not have the established, knowledgeable vendors or equipment suppliers seen in other high tech fields (for example Applied Materials support of the microelectronics industry). Even the customers were on a learning curve and only beginning to develop an understanding of their requirements.

Technology realization in a startup, new business environment, and for the introduction of a new technology product, is fundamentally different compared to an established company in a mature industry introducing the next generation in a product line. This goes beyond having a poorly populated domain knowledge database, DKB, and a thin Kdm and Kdn (see figure 3.2). There may be no appropriate DKB; there may be little or no existing knowledge of the product or design space. This then requires that the DKB for the PV (DKB_{PV}) be created (not just expanded) for the design effort. Creating DKB_{PV} (or any specific DKB) can be done through experimentation and research, which is conducted not as a direct design activity, but simply to increase understanding and build knowledge. Additionally, the DKB's for other, nominally unrelated domains (industries or technologies) can be investigated and key knowledge brought over to the DKB_{PV}. However, if it is not immediately clear what if any DKB would be appropriate to utilize, the challenge is then to investigate and identify DKBs that may be useful and to pull knowledge. This broad multi-industry review further expands the knowledge development efforts required before initiating the actual design.

A key aspect for classic design is a thorough review of the predecessor design. Often deficiencies or opportunities with the predecessor are the motivation for the new design effort. The predecessor is important as it gives a starting point for the new design and allows for an initial determination of the requirements, Ri, that enable some definition of the design space. The predecessor design is regarded as one of the most critically important factors and forms a key entry point in systems engineering methods [Kossiakoff 2011]. In a new technology development, or for a startup company, there may be no direct predecessor. This was the case at Abound Solar's start.

For the Abound module development, multiple different technologies were initially investigated. There was some minimal commonality, primarily in Ri. An example of common Ri across the different tech options was the requirement to meet the externally imposed IEC and UL certification standards, but the fundamental methods of achieving those requirements were different for each technology. Each module technology option had DKBs and Ri's specific to that technology. Thus there were multiple different design options being investigated simultaneously, each with significantly different underlying technology. The design process requires multiple iterations through the DAE process (Figure 3.1).

4.3 DAE Applied to an Early Stage Company

4.3.1 Startup Company Environment: Abound Solar was started at the beginning of the year 2007. Initially there were only three members: two technical founders (including the author) from CSU who went with the company when it spun out of the university, and a business leader who was not involved in day-to-day activities. The team was later augmented with a CEO. This lean founding team was responsible for all initial business planning, business development, building leasing and site selection, early hiring, and company financing. In February of that year, $3.7 million of equity capital was raised. By May 2007, an additional $30 million was raised from the noted New York private equity group, Invus Group, LLC. An additional tranche of funding was available from Invus upon completion of key technical milestones within a specified time.

During this startup period, there were three key aspects that impacted the early company development. The first issue was the very lean staff; particularly lacking were resources with technical / engineering and design experience. An early focus for the founding team was to increase the technical staff. However, it was quickly apparent that there were very few if any engineering candidates with experience in PV module design, even when the search was extended nationally. The second issue was the number of significant *non-technical* but needed business development and funding activities that required attention. These were critical to the success of the company and required focus of all members of the founding team. The author was surprised at the time and effort required to perform these duties. These responsibilities included developing job descriptions for the critically needed additional engineering staff and interviewing candidates, in addition to meeting with and preparing presentations / updates for investors. Even aspects that were more technical and associated with the module engineering design activities required additional effort because Abound Solar was a new company and did not have the established relationships and accounts with potential supply chain members. Examples included identifying, vetting and then developing business relationships with materials suppliers, testing services, and other vendors. The third key aspect was the immediate need to minimize the development timelines and schedules. This was being imposed from different directions. On one hand, expanding the engineering staff was needed to adequately complete the technical aspects of the manufacturing process development, including the design of the module architecture. However, additional staff salaries depleted investor cash more quickly, which was particularly true for high caliber engineering talent. Although Abound had raised significant equity funding extremely rapidly, this was insufficient to fully develop the technology, set up a manufacturing process, and enter the market with a competitive product. Follow on funding would be needed. This drove the need to show substantive, consistent progress to investors to secure future funding. Also, there was the specific technical milestone requirements required to receive the additional funding tranche from Invus. Thus, if the company economized on talent, infrastructure, and other resources, the favorable second Invus investment would be missed. However, adding engineering resources too quickly added salary load, diverted time and effort away from design, and was difficult because of the lack of local engineering talent with PV experience (not to mention PV *design* experience). Educating and training new technical staff members to bring them up to speed further impacted schedules. This concern over "cash burn," combined with the investor requirements and the need to hit milestones, imposed the need to minimize the module design timeline. Based on the author's interaction with other entrepreneurs and technologists, these constraints are not unique to the start of Abound Solar, but are commonly experienced by high technology early stage companies.

The foundational technology behind the formation of Abound Solar was for high throughput, rapid fabrication of the PV <u>semiconductor</u> device (the solar cell). This was the focus of the nearly 15 years of effort at CSU prior to the formation of the company [Barth 2002, 2002-2, 2005, 2007, Sampath 2009]. The focus was intentional, as the semiconductor fabrication was the most critical technology needed for making a successful venture. At the start of Abound Solar, little effort had been directed on the development of the module package.

These three aspects—limited knowledgeable resources, the very rapid growth of the company, and the need to achieve milestones now driven by the investors (not necessarily technologists)—were powerful drivers for the early company and provided dominant constraints on the PV module design processes.

4.3.2 DAE to Understand the Impact Of the Startup Constraints: Design activities are driven by requirements and constraints. Requirements are aspects of the design that are needed or essential to carry out the function. The item being designed may need to fit into a specific dimension or be less than a certain mass. Requirements define the functionality and form factor of the design and are the technical focus of the designer's effort. Constraints are restrictions to the design or design activity. Constraints may be external to the technical design activity. Examples include availability of manpower, budgetary considerations, customer acceptance, or time to market limitations. These "soft" constraints are often as impactful to the designer's efforts as the technical requirements and constraints. The reality of limited time and budget considerations in real world design can easily drive the design process more than the quest for a technically elegant solution.

The startup company environment, particularly the constraints experienced in Abound, had real impact on the PV module design effort. The company was manpower and resource limited and without revenue; the time to market (and achieving revenues) was critical to minimize cash burn. Though these externalities were nontechnical, they dominated much of the thinking on design activity. At Abound, the design activity was initiated without a clear definition of all the requirements, technical objectives, or even the end goal. As a startup company, there was no predecessor product and there was no imbedded company knowledge about past design. Additionally, since the company had minimal technical or engineering staff at that point (and the founders were experts in the semiconductor processing rather than the module design), there was no one in the company who had detailed knowledge of the module design process. This meant that there was very minimal domain knowledge, Kdm (referring to figures 3.1 and 3.2), and particularly design knowledge, Kdn, within the company. In the 2006-2007 timeframe, the PV industry was still quite small but going through exponential growth. This meant that there were few true PV industry experts and those with experience were quickly taken. The author tried unsuccessfully on multiple occasions to "headhunt" engineers with even low-level PV industry specific knowledge. Consequently, Abound was not able to hire in PV industry specific Kdm or Kdn expertise; this had to be developed.

In order to obtain knowledge, the first set of design activities was solely to gain a broader knowledge of the general field. Two avenues were pursued. The first was to broadly investigate what the competitors were using for PV module designs. This was conducted at the highest level of what can be physically observed from fielded modules and reported on data spec sheets. This gave no specific design information, such as polymer or materials formulations. The second avenue was to conduct a broad based academic and trade journal literature review and to contact people familiar with the industry. These two efforts were to start to develop a domain knowledge, Kdm, for the design effort (and for the company).

Expertise for the narrowest but directly useful set of skills was unavailable: CdTe thin film PV module architecture and encapsulation domain knowledge ($Kdm_{CdTe\ PV}$).[3] This knowledge was specific enough that there was only minimal research literature (let alone broader industry knowledge) available. However, there were reports and publications [for example see TamizhMani 2008] available for PV reliability test results that were not specific to the thin film product Abound was developing (Kdm_{PV}). Though this was not directly applicable to the design effort at hand (product development narrowly focused the thin film, CdTe device), the information

[3] Thin film PV is ~10% of the market. There was more information on the industry standard c-Si encapsulation architecture.

did provide general insight. As the information gathering efforts continued, domain knowledge from other industries was studied: in particular, the practices of the insulated glass (IG) window industry. The IG industry had developed technologies for sealing glass substrates, was concerned with moisture ingress into the package, and their products had a 20-30 year design life, factors that were very similar to what was now forming as Abound's product conceptualization (Rx and Px). This domain knowledge, $Kdm_{glass\ product}$, was very useful. Lastly and more generally, textbook methods of designing and testing products, including reliability engineering, design for manufacturing, and other methods, were investigated and utilized ($Kdm_{general\ product\ design}$). Eventually, Abound was able to hire engineering resources with these more general design skills, including reliability engineering, accelerated life testing and product qualification testing (to achieve UL and IEC certifications).

As the company matured, significant knowledge was accrued. Domain knowledge was expanded first, by developing an understanding of the more general, encompassing aspects of the domain, and then, as more research and design explorations (Ex) were completed, more specific, narrowly focused knowledge was developed. Understanding of PV industry was added and finally, the most narrowly focused and most applicable understandings, specific to Abound's product ($Kdm_{thin\ film\ PV}$), were developed. In this manner, *the module product design experience within the startup environment at Abound demonstrates the importance of knowledge development.* With no imbedded knowledge of the product design and minimal domain knowledge, the most critical early design activity was educational. This knowledge had to be sought out, and in many cased developed. The generation and application of knowledge is a defining aspect of DAE in this environment.

4.3.3 Insights to Knowledge Use in DAE: In Smithers and Troxell's 1990 paper, the "knowledge process" is stated to underlie the entire design process [Smithers 1990]. Referring back to figure 3.1, knowledge is described as "Kdm + Kdn," which feeds into the exploration process (as "knowledge application"). A description of the dependence and linkage between the domain and design knowledge is highlighted. Smithers later expands on the knowledge concept (see figure 3.2) by including types or sources of knowledge under the headings of "scientific, technological, empirical, statutory and social and cultural," which can apply to either / or both Kdm and Kdn [Smithers 1992]. The combination of Kdm and Kdn is referred to as the "Design Knowledge Base," or DKB. Knowledge is shown to flow or to be *applied* from the DKB to the exploration process (Ex). Knowledge is *transferred* from the final "design description document" (DDD) to the DKB.

The early Abound design experiences provide opportunities to refine the understanding of how knowledge is both used and generated in DAE. For the young company, the most important aspect of the module design process was the expansion of the knowledge. Not only was new knowledge needed to develop an actual design, new knowledge was required prior to any generation of feasible design descriptions (D), and was needed to develop suitable requirements descriptions (R). At the onset, the team didn't know enough to credibly begin developing a module architecture. Only after a specific level of knowledge about both the general domain of PV, Kdm, and the developing design, Kdn was developed, could the exploration process (Ed) be expanded to where incremental potential solutions were researched and developed to incremental extensions of problem statements [after Smithers 1992]. In this manner, knowledge flows both from the DKB to the exploration process (Ed), but also from the exploration process to the DKB during the design process. The knowledge generation efforts were part of the design exploration process and were as critical as, for example, developing component specifications (perhaps more so).

Smithers et. al correctly show knowledge transfer from the final DDD to the DKB, but, in the case where there is a thin DKB, as in a startup company, the knowledge flow *from the exploration process back into the DKB* to advance the process is more significant to the ongoing design than the final accounting. Knowledge is not just generated as a result of the overall process, and learning is critical to initiating and sustaining the exploration. It is noted that "K" (figure 3.2) is a component of the exploration process but is described as "domain and design knowledge available to support the exploration" [Smithers 1992, p.8]. This definition is expended here to now include "available to support *and generated by* the exploration". It is noted that in subsequent articles, Smithers clearly describes that knowledge is generated during design but this was not in the context of DAE. The new distinction presented here is that knowledge is generated during exploration, which is then used to benefit subsequent explorations in the same design.

At the onset of the design process, there was minimal foundational knowledge available, and, as the process progressed, the knowledge was consistently expanded and refined. Referring to Kdm and Kdn as "Design Knowledge Base" (DKB) [Smithers 1990, 1992, Logan 1992] and knowledge as "background knowledge" is limiting based on the startup company experience. Knowledge generated during the design exploration is critical to the process and is neither "background" nor foundational to the current exploration. Thus, a more appropriate description is "design knowledge resources" (DKR), which accounts for knowledge flow both ways between the DKR and the exploration process, Ed.

4.3.4 Knowledge Levels in the DKR: The early design efforts and the technical staff recruiting highlighted that knowledge, particularly domain knowledge, has different levels of specificity to the design. Using the Abound examples, the general textbook type knowledge ($Kdm_{general\ product\ design}$) was useful and needed, as was the knowledge generated during the exploration process specific to the CdTe PV ($Kdm_{CdTe\ PV}$). However, the latter is clearly more technically specific to the Abound module design effort. In a setting where there is a more developed DKR, such as a more mature company that has an established product line, knowledge gaps that can adversely impact a specific design effort are more difficult to identify. The knowledge gap may be a narrow region, specific to the particular design, which is obscured by a generally well-populated DKR.

Having this understanding, the different knowledge levels aid in identifying knowledge gaps. It enables the design team and management to review the DKR and then target efforts to fill in key gaps. This could be accomplished through research, targeted hiring, or retaining consultants. This was done at Abound out of necessity; the management had to design a plan to internally develop this knowledge.

There is a need for hierarchical categorization of the available knowledge to facilitate targeted knowledge generation efforts (either R&D tasks or targeted hiring of experienced resources etc.) within the design process. Invoking different knowledge levels in the DKR will facilitate conducting targeted, learning-focused design explorations. The DKR can be expanded to multiple tiered Kdm and Kdn's. Each level would represent a subsequent increase in the level of specificity relative to the design being explored. Table 4.1 shows some simple examples from the Abound development of how knowledge levels can be broken down to benefit the design explorations. Knowledge levels could be identified differently for each industry, company, and design effort. The number of levels would depend on the complexity of the design and could be tailored to the design team's experience. More levels would facilitate the identification of knowledge gaps, while a highly knowledgeable design team may require fewer levels due to their experience. It is noted that the same knowledge is present in the DKR independent of the number of levels.

This concept of specific "knowledge levels" presented within broader domains has been described by Allen Newell [Newell 1981] in other contexts, specifically for coding hierarchy in artificial intelligence research. Smithers describes and extends Newell's concepts to design but does not put the concept into the DAE theory [Smithers 1996, 1998, 2002]. Smithers goes so far as to introduce a complete design theory based on "knowledge levels," which is described in detail in his 1998 paper [Smithers 1998]. The emphasis on knowledge, both in the generation and application, is useful and required for the understanding of real-world design.

Table 4.1: Tiered knowledge levels for Kdm with examples from the module development.

Current DAE	Abound module example	Generic level	Comments
Kdm	$Kdm_{\text{general product design}}$	$Kdm_{\text{general product design}}$	Generalized design methods, textbook
	$Kdm_{\text{glass product}}$	Kdm_{Industry}	Industry best practices, certifications standards, trade group or engineering society (ASME, IEEE) knowledge
	Kdm_{PV}	$Kdm_{\text{Product Family}}$	Product expert knowledge, not proprietary
	$Kdm_{\text{CdTe PV}}$	$Kdm_{\text{Specific product type}}$	Product specific, possible proprietary, significant crossover with Kdn

In contrast to DAE, knowledge level theory of design converts all aspects of the design process into "knowledge levels." This includes the requirements description (R in DAE), and design history (H). While it is clearly true that R and H describe some level of "knowledge" in a general sense, there is a fundamental difference in what the DKR represents compared to the design requirements during the design process. This is seen by contrasting the different design actions associated with each of these segments. The requirements at the initiation (Ri) and during the exploration process (Rx) are the *motivators* for the designer to develop the next solution (Dx) via the exploration process. The DKR are the resources, tools, and opportunities which feed into the exploration process (Ex); the DKR seed the creative process. In the knowledge level design theory, innovative design can be seen as more of an iteration of routine processes. "It has a form like that of routine design, except that rather than just one problem statement being synthesized from the initial ... requirements description, a number of different problem statements are formed, and solutions to each of them investigated and assessed [Smithers 1998, p. 13]. True innovation is by definition the development of something unprecedented and new and requiring creativity.

The DAE method, with an expansive and hierarchical accounting for knowledge, can more easily accommodate high levels of innovation.

<u>4.3.5 Documentation:</u> The accelerated schedule for product introduction and resource limitations during Abound's startup impacted the design documentation in ways that can be highlighted using the DAE theory. The documentation of the interim design iterations (Dx), the refinement of the requirements (Rx), and the design exploration history (Hx) were not sufficiently captured during this period. As a result, there was an incomplete design description document (DDD). Deficiencies in the DDD then led to insufficient documentation of the now expanded design knowledge, Kdn. The emphasis here is the documentation: the Kdn was developed and expanded as the design matured (explorations, Ex, advanced) and company developed. This Kn knowledge resided with the early core design team and was documented sufficiently for this very early R&D phase. However, as the company grew and moved into a manufacturing / execution phase, different functions, such as process engineering, manufacturing equipment developers, and production teams, needed access to the knowledge. Findings were stored in notebooks, in personal computers, and as "knowhow." This was a barrier for transferring knowledge and communicating within the company. Though Abound was able to develop, manufacture, and deliver a product, the inadequate documentation of the design efforts resulted in two key outcomes. The first was that there was minimal institutional understanding of the motivations behind the module design decisions. The members of the company, including some management, understood "what" our product was and "how" it was manufactured, but there was poor understanding of the underlying "why." The second outcome was that knowledge was lost and had to be redeveloped. After Abound, the early team members no longer worked together in the same company. Notebooks, databases, and memorized knowhow were not readily available. The original DKR had been "split up." Subsequent module encapsulation design enhancements

further developed by Direct Solar (after Abound) were hampered. This was overcome through contacting the early design team members and reviewing their personal notes from this period.

As Abound grew, there were sufficient resources to develop a few prototype designs for the module encapsulation. This architecture was innovative, with unique characteristics that facilitated long term durability in the field and significantly improved manufacturability (See module design description in section 5). The design relied on high performance edge seal materials that functionally replaced the lamination materials that were traditionally used in both crystalline silicon and other thin film module designs.

As would be expected, the product specifications were well documented and controlled but the explanation history of the design choices were not. The "what" (Df) was documented, not the design "why" (Hf). As the company expanded, new product development resources were added to the design team. These new engineers were not present when the initial design explorations (Ex) were executed to develop the edge seal concept and did not understand the decision points that resulted in the new innovative architecture. This was particularly the case when manufacturing and process engineering resources were added who were not there during the early design effort. They came with a different perspective and familiarity with different knowledge domains. Some difficulty and delays were seen with developing and optimizing the manufacturing process tools, and later when product improvements were proposed.

The startup company environment is not conducive to the documentation tasks. But as demonstrated above, the development of knowledge, both Kdm and Kdn, is perhaps the most critical aspect to the ultimate success of a venture. Implicit in the DAE method is the need for robust documentation, particularly as a means of capturing knowledge generation. If the effort is not expended to capture the expansion of Kdn and Ex, the overall design effort, including placing the product into manufacturing, product improvements, and developing end of use strategies (sustainability), is compromised.

4.4 DAE Applied to Innovation

4.4.1 Innovation Opportunities for CdTe PV Modules: The module package is responsible for the protection of the semiconductor films and provides mechanical integrity to the module.[4] When starting the module architecture development for the Abound product, there were no commercially available encapsulation materials or technologies optimized for the thin film PV. The crystalline silicon PV dominated the market. The industry standard encapsulation materials were ethylene vinyl acetate (EVA) film sheets. To form a module using this technology, the front glass substrate, an EVA encapsulant film, silicon PV wafers, an additional EVA film, and a back sheet (either glass or another polymer) were "laid up" in sequence (figure 4.1).

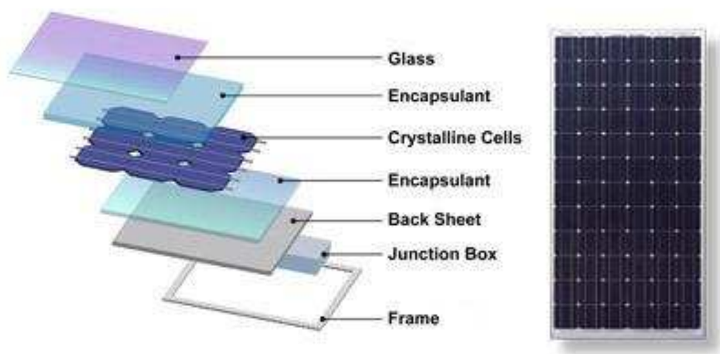


Figure 4.1: Schematic of typical crystalline silicone module structure (image source: Dow Corning).

Then the stack would be placed in a vacuum / thermal laminator which would require approximately between 13 to 20 minutes to remove the entrapped air and soften, then cross-link, the EVA polymer to adhere all the components. This lamination process was developed to surround the fragile silicon wafer and adhere the wafer to the protective front glass. Good EVA transparency is needed; light must go through the encapsulation before being absorbed by the silicon PV device.

[4] A brief description of the module structures are presented to aid in the DAE exploration. A more through, architecture centered description of the design is presented in section 5.

The CdTe thin film PV semiconductor was deposited on a glass "superstrate" which then faced the sun in the field (figure 4.2). The glass formed the front of the module and encapsulation materials covered the back, adjacent to the semiconductor. No light passes though the encapsulation for CdTe technology and the encapsulation did not need to be transparent.

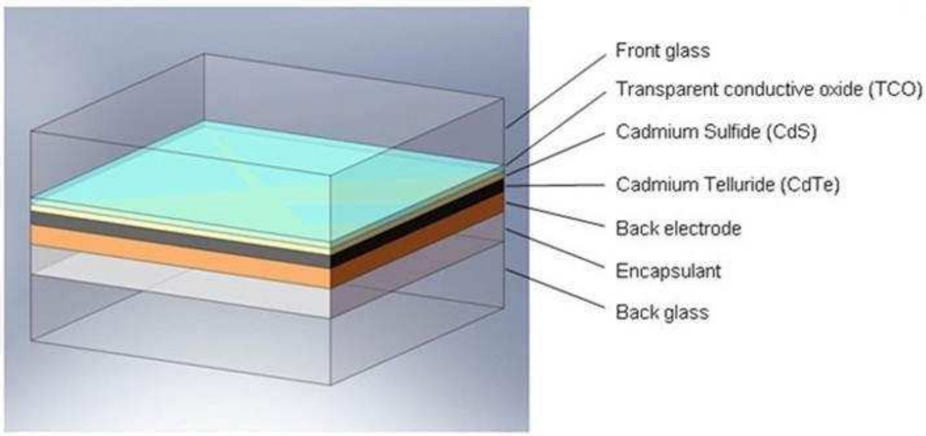


Figure 4.2: Typical CdTe PV module configuration, simple edge seals are often used at the module perimeter (not shown).

PV encapsulation has a number of requirements to be effective. These include (but are not limited to): adequate mechanical adhesion, minimal creep, UV radiation resistance, ability to withstand ambient temperature extremes (including 100 C), low materials cost, ease of manufacturing, and materials availability in square kilometer areas. PV modules are typically warranted for performance for 25 years and have a design life of 30 years or more. The EVA encapsulation films for crystalline silicon must also maintain good optical properties for transmitting light to the PV device over this time frame. This is not a requirement for the CdTe PV module. Maintaining the EVA transparency over the design life was a major issue in crystalline silicon encapsulation development [Pern 1997]. Polymers that are transparent to visible light over the course of a 30 year life in field conditions are not common and are expensive. Removing this constraint offered significant opportunities for reducing cost and improving performance of Abound's module through the use of more commonly available, durable non-transparent materials. This was one of the key drivers for the development of Abound's innovative architecture. However, moving away from the industry standard PV encapsulation method toward a novel architecture, even one that potentially used more commonly available materials, meant that significant knowledge development, specific to the CdTe PV application, was needed; the Kdn for c-Si encapsulation was not applicable.

There was no existing body of knowledge either in the PV field or other disciplines that covered Abound's new design. Because the design and many of the materials were new to the PV field, there was limited domain knowledge (Kdm) available for the development; additional Kdm would have to be developed (as well as the more obvious need to develop the product specific Kdn). The impact of this is similar to that of a startup environment on the design environment: both environments were knowledge poor, particularly for domain knowledge, requiring a focus on learning (knowledge generation) as the first series of exploration processes (Ex).

<u>4.4.2 Knowledge Development, Routine Through Innovative Design:</u> The module package design effort was initiated with a very broad review of the literature. Product spec sheets from other producers and DOE publications were reviewed. Materials samples for reproducing the industry standard lamination based encapsulation method were obtained. Samples with intentional variations in processing and geometry were fabricated with these "off the shelf" materials. Durability testing, including rigorous "damp heat" (85 degrees C, 85% relative humidity, 1000 hours) [IEC 2008] exposure, was initiated with help from the DOE's National Renewable Energy Laboratory (NREL).

From a design perspective, these initial efforts were more "routine design" [Logan 1992, Smithers 1992]. The initial requirements (Ri) were to reproduce the industry standard architectures (figure 4.2) using standard materials and methods. The exploration process (Ex) was to iterate around small variations in materials, vendors, and lamination recipes to develop a final design, Df, using industry best practices, Kdm_{PV}. The design document description (DDD) that was being developed by perusing this "routine design" would have included the specific selection of the "off the shelf" materials (part numbers), component configurations, and process hardware "dial" settings.

Because of the differences in the technologies, the thin film PV semiconductor devices are more susceptible to moisture degradation than crystalline silicon devices [Kempe 2014]. While the industry domain knowledge (Kdm_{PV}) was being reviewed for best practices and methods, it was found that the standard encapsulation technologies were susceptible to moisture ingress. During the time of the Abound product development, TamizhMani et. al. [TamizhMani 2008] published the cumulative results of past UL and IEC qualification testing from across the PV industry. The results from thin film PV were included. This represented a detailed new set of thin film PV specific domain knowledge ($Kdm_{thin\ film\ PV}$). The report showed that for the then current thin film architectures, 70% of the designs submitted for certification testing were failing the damp heat test! It is noted that this qualification testing program is expensive and can take months; it is the final qualification prior to UL / IEC certification and is typically performed at the conclusion of the design process. This type of certification testing is not experimentation to aid the design process, but as a capstone qualification to enable product introduction into the market. This makes the extremely high failure rate even more noteworthy. Although there were thin film products in the field that had achieved certification, the moisture ingress concerns, combined with the design latitude afforded by not needing a transparent encapsulation, compelled the investigation of new innovative options.

The first innovation resulting from the new module design effort was one specific to moisture ingress testing. A means was developed to test the permeation of moisture into the encapsulation. Cobalt chloride (coated on calcium sulfate or gypsum) was powdered and placed inside a moisture test coupon. This material changes color from blue to rose / pink with exposure to moisture. The $CoCl_2$ was used to indicate moisture ingress in different encapsulation configurations and is more sensitive and useful than other methods, including simply evaluating materials adhesion. Though this is not a part of the actual module architecture that would have been used in manufacturing, the development of a testing / evaluation method is an example of how R&D focused design explorations (Ex) are needed to increase knowledge to enable the "actual" module design effort. These methods are expanding the Kdm for this encapsulation development, $Kdm_{\text{Specific product type}}$.

Exploring non-lamination module architecture solutions was a significant shift in the overall direction of the design effort. No longer was the process a routine design; the design effort required innovation. This resulted in a significant expansion of the overall scope: new knowledge and significant changes in the requirements were needed. The existing domain knowledge for the industry-standard lamination encapsulation method was no longer sufficient. The design activity then became a knowledge development effort in which significant expansion of the domain knowledge, Kdm, across nearly all levels, including $Kdm_{\text{Product Family}}$, $Kdm_{\text{Specific product type}}$, was needed before meaningfully descriptive design requirements (Rx) could be developed. As the exploration processes (Ex) were executed, this domain knowledge was expanded, and meaningful requirements, as series of hypothetical designs (Dx), were proposed and tested against the developing requirements. As an analogy, the design was no longer just solving a puzzle but also making a puzzle prior to solving [Smithers 1992].

As the exploration processes to increase the domain knowledge progressed, additional innovative aspects of the design were developed. The moisture indicating materials used to evaluate early test coupons are desiccants. Rather than use these materials simply as moisture indicators, they could be used as desiccators to help maintain a low and controllable moisture level in the module through the entire design life. To implement this concept, a two component (silicone and polyisobutylene) perimeter edge seal was developed to structurally hold the front and back glass together and minimize moisture ingress. The edge seal was the only structural component and replaced the lamination films. (Full design details are presented in section 5). A novel aspect of the design, needed to pass the UL mandated breakage tests, was the incorporation of structures internal to the edge seal that held the glass pieces together under catastrophic shattering. All three of these new design attributes (desiccant deployment, edge seal, and internal breakage retention structures) had to be developed together to form a comprehensive, novel design [Barth 2009, 2010-2, 2014, 2014-2]. There was no predecessor to these designs within the company and they were different in terms of structure, materials, and manufacturing process from what was used in industry (including the IG window industry).

4.4.3 Exploration Process with Innovation: The Abound module development started as a routine effort to optimize a lamination based product. As more domain knowledge was developed, the decision was made to shift the entire effort toward developing an innovative solution to overcome the deficiencies of the current industry standard methods. Since this design was new, the design exploration turned from generally iterating R, P, and D (routine) within a well-defined domain, to a broad exploration process where the initial iterations focused on domain knowledge development. The design effort became a ***knowledge*** exploration process, early on. The knowledge being utilized went from the lowest, most detailed knowledge level (Kdm / Kdn of product numbers specific to vendors for PV lamination films) for the "routine" effort, to the higher, abstract knowledge levels. In the routine design effort, the existing industry Kdm and Kdn, in the form of PV industry best practices, were being explored. For the innovative design effort, a much more general understanding was needed as a foundation before the specific attributes of the design (Dx) could be built. Before any meaningful or relevant potential designs could be iterated within the exploration process, the design team had to first learn about the options and materials available. Now, the moisture performance of different polymer types used across a variety of industries was being investigated ($Kdm_{\text{general product design}}$). For example, a meeting was held with Dow Chemicals to learn about "silicone adhesives and sealants" generally used across all industry.

In many ways this mirrors the knowledge development needed during the startup phase of Abound. The differences are associated with the types of knowledge needed. The knowledge deficiencies due to a startup company were biased to Kdm; innovative designs highlight deficiencies in both Kdn and Kdm. After knowledge was expanded (due to exploration iterations, Ex, focusing on expansion of Kdm and higher levels of Kdn). Knowledge development shifted from Kdm to more Kdn, and the attributes, R, P, and D, were all simultaneously iterated. From this experience for innovative designs, DAE is most impacted in the early explorations (Ex). Initially, an increase in Kdm is developed to account for the novelty, then, as the explorations progress and to incorporate the novelty into the design, development of the higher levels of Kdn are the focus. As the knowledge resources (DKR) develop sufficiently, the innovation driven aspects give way to a balanced exploration mirroring less innovative design explorations where R, P, and D are the focus of the exploration. As the DKR increases, "innovation" becomes more understood and familiar (perhaps only to the core design team). The later iterations of the exploration process trend closer to "routine" design. Finally, if well executed, both "routine" and "innovative" designs arrive at the same point: a strong DDD. The need for new domain knowledge is even more pronounced as the innovation and novelty of a design increase.

4.4.4 Examples of Expanding Knowledge to Drive Design: If an innovative design is new within the domain, knowledge surrounding the novel aspects of design must be developed. For DAE with innovation, domain knowledge generation is needed prior to the development of detailed design knowledge. The Abound module, moved from the lamination encapsulation design (the well known PV industry standard) to the use of edge seals with polyisobutylene (PIB) polymers and structural silicone. This was novel for PV industry encapsulation. For Abound module design, there are many instances where novelty drove the need to expand knowledge. The edge seal example is chosen because, even though PIB and silicones are common materials in the PV industry, significant knowledge generation was needed to use the material in the novel design. They are common materials being used in a novel way to develop an innovative design.

When the innovative edge seal design exploration was initiated, the initial requirements (Ri) were very weak. The Ri included very general, industry standard requirements, such as the need for passing the UL and IEC tests, customer driven 30 year design life, and a general requirement for "low manufacturing materials costs." General domain knowledge of the edge seal materials was needed before there could be any significant advancement of R, D, and P, and design knowledge specific to this architecture could be developed. It was not yet known what PIB or silicone type (chemistry) or quantity / dimensions were needed for the design. Understanding of the application / dispensing, curing, cost, and application specific long-term durability of these materials was needed. Though these are common industry polymers, the development of knowledge levels *specific to the PV edge seal application* was required.

Silicones (and to a lesser extent) butyl rubbers were commonly used in the PV industry for potting back junction boxes. Even though millions of PV modules had been fabricated with silicones or PIB in the bill of materials, that domain knowledge was only minimally useful. The edge seal application had significantly different requirements, including the structural bonding of the two glass surfaces together, UV exposure tolerance (the edge seals do see UV), direct liquid water exposure (back box potting is typically inside the plastic box cover), dispensing over large areas (120 x 60 cm modules compared to a ~4 x 4 cm back box), etc. Understanding curing was a key issue. The two glass plates of the module would be structurally adhered with silicone. The silicone would need to cure quickly or have a sufficient pre-cure strength so that the module could be handled for the final manufacturing processes, testing, and crating. Pre-cure strength was not an issue with the back box potting as long as the material had sufficient pre-cure viscosity to avoid material flow.

Industrial PIB has carbon additives to aid in UV radiation tolerance. Modules can operate at high voltage (600-1500 V) relative to ground, so high potential (Hi-pot) safety testing is conducted on every module. Domain knowledge of dielectric performance of the materials was needed. A R&D program was developed to investigate and build this general knowledge (Kdm) and develop specific solutions (Kdn). It was found that the high carbon content in the industrial PIB reduced the electrical performance under the hi-pot tests. Experiments were conducted with the polymer supplier to vary the carbon content and test dielectric breakdown and UV tolerance of different PIB materials. A formulation was developed that had sufficient UV tolerance and good electrical hi-pot behavior, resulting in the development of specific design knowledge, $Kdn_{PIB\ formulation}$.

4.4.5 Establishing Innovation Level: The concept presented above, that innovative design requires domain knowledge expansion in the initial explorations, can be used to establish the level of innovation in the design. This rating is specific to design and could be used to augment the technology readiness levels (TRL) [TRL 2011] ratings. The complexity or novelty of the design could be quantified by the number of knowledge development exploration iterations, Ex, that were required. Alternately, upon completion, the discrepancy of Ri, Pi, and Di from Rf, Pf, and Df also provides a means of establishing an innovation level. Routine designs have initial conditions that are close to the final design. Innovation requires significant expansion of R, P, and D. Another metric to measure the level of innovation would be the increase in the DKR, or, specifically, the domain knowledge required to complete the design. The more knowledge that was generated further up the hierarchical tree at a higher, more general knowledge level, the more innovative the design. A design that required generation of knowledge, not only of the specific product type but also led to new testing methods and had ramifications to other industries, has greater inherent novelty than a design that only impacted the lower knowledge levels of the DKR.

4.4.6 Role Of Prototypes and Targeted R&D: Prototypes play a key role in innovative design. The utility of prototypes changes over the course of the design process. DAE theory enables insight into their role. Prototypes that are developed early in the exploration process may be less targeted toward developing design specifics but more targeted to develop an overall understanding of the constraints. Early stage prototypes, particularly for an innovative design, are vehicles to extend higher levels of knowledge and are then closely linked to R&D. An example of an early stage prototype used for R&D purposes could be a coupon used to test the moisture vapor transmission rate (MVTR) of a new polymer formulation. The prototype does not emulate a module or develop design specifics, Dx, but does extend the understanding of the polymer behavior for moisture diffusion. In this example, the knowledge is primarily domain knowledge (MVTR specific to a polymer) that will then be used later to influence the R, P, and D as the design progresses. For innovative designs, and for explorations early in the design process, the prototype fabrication / R&D experiments bolster the specific domain knowledge. As the design progresses, later design specific R&D is completed, and prototypes are used to extend the design knowledge, Kdn. Then, as the design nears completion, prototypes may be final mockups to finalize the design, Df and Rf, impacting Kdn.

For knowledge development, prototypes (and R&D) play a key role in extending the DKR primarily through extension of Kdm early in the exploration cycle, and then extending Kdn as the exploration processes near completion. This understanding is a significant expansion of the role prototypes are shown to play with previous DAE treatments [for example see Smithers 1992]. Within those treatments, prototypes are shown as using knowledge generated from the final Rf, Df, and Hf in the DDD (see figure 3.2). In this conceptualization, it is confusing to see how prototypes influence the ongoing design if the knowledge is available only after the design is completed and documented in the DDD. Additionally, no connection is shown between prototypes and expanding the DKR. The understanding presented here is that prototypes and R&D generate knowledge that is fed into the DKR where it becomes available for both current and future design efforts. This is shown graphically in an updated exploration process graphic, figure 6.1.

4.5 DAE and Sustainability

4.5.1 Impacts of Sustainability: Unintended social, environmental, and economic consequences of economic growth and consumption of our natural resources is undesirable and has led to the development of practices promoting sustainability [EPA]. Sustainable development is "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" [Europa]. Incorporating sustainability concepts into design theory has a broad impact. To be truly sustainable, using recycled, renewable, and recyclable materials and methods in a design is an overarching requirement that impacts every other aspect of the design. Even the form factor of the design would be optimized for ease of recycling and re-processing methods.

Within the DAE theory, sustainability clearly impacts the initial requirements (Ri) and problem descriptions (Px). As was seen when investigating other constrained design environments, sustainable design requires an increase in the DKR. Sustainability adds additional constraints into product design, particularly in the selection of materials and / or subcomponents, and requires an understanding of the processing methods. An understanding of recycling methods is needed to develop designs with sustainable end-of-life considerations. As a simple example, thermoplastic polymers that can be re-melted and recast into different shapes are fundamentally sustainable if recycled effectively. Once cross-linked, thermosetting polymers cannot be re-melted. However, some crosslinking polymer materials are shredded and used for other applications (tire pieces are used for playground surfaces and roadbeds). This simple example demonstrates the need for broader domain knowledge such as an understanding of polymer formulation to facilitate recycling, and goes beyond what would typically be required in non-sustainable design (mechanical performance, cost etc.).

Complex designs may need disassembly before recycling / reclaiming or they may use materials that are not easily recycled. Designs may require special handling or processing at the end of service. Nickel cadmium batteries and compact florescent lamps, for example, have specific recycling channels and require special handling. These "problematic" aspects expand the scope of the exploration process, including problem descriptions, Px, to include these considerations. For these complex designs, the extension of the Px requires effort beyond simply substituting in sustainable materials / process in place of traditional options; the entire scope of the design effort increases.

4.5.2 Increase In Documentation Requirements: In addition to the need to specify sustainability as a design requirement in both the problem description and requirements description, other key aspects of the design exploration process need to be rigorously documented during the design process for a true cradle-to-cradle lifecycle. The designer can facilitate the responsible end-of-life reclamation by providing the product user with information on the best manner of recycling. This could be contact information for recycling center locations (such as used for nickel cadmium batteries), markings for the materials used (polymer identification labels cast into the parts), or added guidance in the user documentation. For complex assemblies, there could be instructions included for demounting and separating the components for introduction into different recycling / reclaim channels. These details in the documentation are beyond what would likely be needed for a non-sustainable design, and include specifics of the product construction and materials used.

Sustainability places additional emphasis on the DDD, particularly for complex designs, and forces an expansion of the DDD in terms of both the content and the scope. From the content perspective, the incorporation of markings or documentation to enable the responsible end-of-life handling is a further extension of the initial design requirements. Sustainable design adds the requirements that the design itself needs to be sustainable ($Ri_{sustainable}$) and that documentation on how to recycle ($Rf_{documentation}$) must be available. The details of the final design, Df, now require the documenting of materials specifics to aid in recycling / reuse, including disassembly instructions if needed. The details of the design development history (Hf) are extended beyond how the design achieves the functional specs and now includes a description on how the cradle-to-cradle lifecycle projections influenced the design.

Extending the DDD to document sustainability is a fundamental change in scope compared with design with minimal sustainability constraints. In a "traditional" design process, the final design history (Hf) documents the exploration processes (Ex) of arriving at the final design, Df, to fulfill the final requirements, Rf. This is a chronicle of the past actions. Sustainability adds a future, forward looking aspect to the DDD by anticipating (or even directing) how the product should be handled at the end of the service life. This anticipatory aspect is a significant addition to the DDD. The DDD scope is also extended through expansion of the intended audience. For traditional design, the DDD describes the design and knowledge contributions through the *design* knowledge resources (DKR). The "design" word is emphasized because the DKR is a designer focused resource. Within the DKR, Kdn, is, by definition, design focused. Knowledge added from the DDD to the Kdm is fundamentally a resource for the designer to execute the next design exploration. The design specifics and background knowledge documented through the DDD are inherently slated toward the next design effort, communicating to the designer. For a sustainably focused design, the DDD includes the "end of service life" documentation. These additions are not only communicating with the designer of the next product iteration, but also to those responsible for decommissioning and recycling the product, likely the product user. This is a new target audience for portions of the DDD (and by extension, aspects of the DKR). The time frame for communication may also be significantly extended. For products that have a long service life, the recycle / reclaim portions of the DDD may be needed decades in the future. This is likely significantly longer than the design cycle of the product.

It is recognized that all complex products have a user manual that was likely written with input from the design team and describes how the product should be used. Documenting the end-of-life handling goes beyond the product use. To aid sustainability, the documentation would now include more details of the design specifics (what) and perhaps some aspects of why design decisions were made. The DAE method facilitates this communication; the DDD includes clear descriptions of the final design (Df) and the thought processes beyond the design (Hf).

4.5.3 Expansion Of The Design Scope With Sustainability Considerations: The development of a sustainable product adds constraints and additional activities to the design effort. The R, P, D, and H functions of the exploration process are expanded to ensure that the product is fabricated from recycled and recyclable materials and components, and that recycling and reclaiming are considerations in all aspects of the specification, design, and documentation. This is an expansion of the product design exploration. For many designs, particularly those that use commonly recycled materials or have established recycling / reclamation channels in place, increased documentation and product marking may be sufficient to achieve sustainability. Metal recycling and many types of polymer recycling are commonplace, enabling the sustainability of simple products using these materials. However, many designs are not amenable to existing recycling / reclamation channels, or the methods don't exist. Complex or innovative products that utilize new materials or components may not have existing reclaim pathways. For these cases, the scope of the exploration process will need to include the methods and perhaps even the development of the infrastructure for recycling and reclamation. The development of the recycling infrastructure may be sufficiently complex to a degree that an ***entirely new design exploration*** effort, focused solely on the reclamation, may be appropriate.

This was the case for the thin film CdTe PV products. Abound Solar initiated a program where modules were tracked and, when they completed their service life, would be returned and recycled. A toll free phone number for more information was included on the module identification sticker. This was developed in partnership with the members of Abound's supply chain. Developing this recycling pathway was a significant effort in its own right. First Solar (NASDAQ: FSLR), the leading manufacturer of CdTe PV, has established an even more complete program. They have developed a module recycling technology that operates within their manufacturing facilities. This recycling hardware takes nonfunctional or end-of-life modules and returns raw materials available for reprocessing. Ninety percent of the semiconductor and glass materials can eventually be recovered and reused [FSLR 2015] through this process.

4.5.4 Continuity of Design Cycles: The "cradle-to-cradle" design approach seeks to develop a very high level of sustainability and to minimize waste [Lovins 2008]. Cradle-to-cradle describes how the entire life cycle of the product is considered for sustainability. The design and implementation of the product (the first "birth") is conducted with a requirement that components and materials should be sourced from sustainable materials. Additionally, the ability to recycle or reclaim the components and materials at the end of the lifecycle is a requirement during the product design. The recycling / reclaiming process should exist and be technically and economically feasible. The cycle starts again (second "birth") when the next new design is developed using the recycled / reclaimed materials from the first design. Considering the cradle-to-cradle design cycle, it is difficult to identify where one design exploration starts and ends. There is cross over from one birth to the second. Through the constraints, requirements, and documentation, the initial product design must anticipate aspects of the subsequent designs. This is beyond the purely functional requirements of the product being developed. For sustainability, the second birth considerations are just as critical a set of requirements as the first.

Accounting for design considerations in anticipation of a design effort beyond the current development and not yet underway has not been explored for the DAE theory. As shown in figure 3.2, the multiple iterations required to bring the initial requirements to a final design is demonstrated with the subscripts on the different explorations Ei, E1, Ex+1... Ex+n. Each of these explorations represents an iteration in the design, advancing any of the key design aspects. These include new input from the DKR, advancing the problem statements (Px, Px+1 ... Px+n), requirements (Rx, Rx+1 ... Rx+n), or design description (Dx, Dx+1 ... Dx+n). The exploration process is then incremental movement from problem to solution [Smithers 1992], refining the R, P, and D until the design is complete and Rf, Df, and Hf are fully developed. Thus there is a clear entry and exit point. Explorations with concurrent consideration of multiple designs spread over multiple timeframes are not well defined.

A similar situation arises in rapidly advancing technologies where there are constant inputs of new knowledge (Kdm or even Kdn) from R&D developments. Multiple closely related designs may be under development simultaneously, each awaiting critical new research results or an experimental development to move forward. When the critical piece is delivered, that specific design is able to move forward toward launch. Changing legal or regulatory environments can impose a similar situation where a designer awaits external knowledge or input to complete a particular design among a number of ongoing design options. These other design options may remain under development awaiting new critical information, or may be retired.

At first review, multiple ongoing design cycles, including the extension of the exploration beyond the current product (second birth) or having multiple parallel designs under simultaneous consideration, presents a challenge for the DAE theory. The theory promotes a clear entry (Ri with an existing DKR), a fertile active exploration process, and then a clear completion point with drafting the DDD and "realization and satisfaction of needs or desires" (figure 3.2). Smithers recognized this limitation:

> "The formalisation (sic) presented here is, as it stands, insufficient since it does not capture the fact that different lines of exploratory investigation in a design process are typically related. Development arising from one line can influence or initiate other lines, and convergence can occur between explorations which had different starting points." [Smithers 1992, p 8]

It is proposed that with a subtle expansion, the DAE theory can accommodate the circumstances of multiple design cycles described above. These include design efforts that involve simultaneous exploration of similar or related designs that are maturating at different rates, or explorations that have significant anticipatory aspects that extend the design timeframe into the future. Even with these external circumstances, the actual design process can still be described by DAE. When focusing narrowly on the details of a specific design at hand, the basic exploration process is not changed once the expanded requirements imposed by the design cycles are incorporated. This *local* exploration is universal: incremental advance of R, P, and D with simultaneous development and utilization of the DKR.

There may exist related design cycles that are *external* to the specific exploration process being perused. These design cycles have their own (local) explorations (and associated R, P, DKR, etc.). The key is how to account for the linkage between the different design cycles. The multiple explorations can be visualized as being in parallel with different explorations, each maturing at different rates. Or, less expansive design cycles can be visualized as being nested within a more expansive (either in terms of timeframe or requirements) exploration. In both scenarios, different design cycles may share the DKR.

An analogy is to visualize "trains leaving the station," where the trains represent a particular design and the station exit is the maturation of the design or product launch. When the train is full of passengers it departs. When a particular design receives the needed R&D, software, or regulatory knowledge input, the design can progress. New passengers (input / knowledge or requirements) will continue to arrive at the station and be loaded onto a new train (design exploration conducted) that will eventually depart (local design cycle completion). Multiple trains may be boarding simultaneously with different passengers within a large station (within one shared DKR) and may depart independently of each other. Alternately, the train may not wait for new passengers but may depart based on a predetermined schedule. For example, for the last four years a new Apple iPhone has been introduced every fall, anticipating the Christmas shopping season. This schedule has become critical to Apple's business and drives the product design efforts. The release schedule would not be materially shifted to accommodate a technology introduction; the technology / feature introductions in a particular design cycle are incorporated as available on the schedule. A new technological feature introduction would either make this train or catch the next one. In both scenarios (designs launched based on the arrival of new technologies or design explorations based on a schedule) the explorations are cyclic.

Each design anticipates the next one in an ongoing process. In this manner, *there is effectively a continuous, ongoing exploration process.* Knowledge is continually being developed and incorporated, either through R&D, prototyping, or new external developments. The requirements and problem descriptions are continuously changing, driven by outside factors. These inputs are digested in an exploration process that has a full anticipation of the "next train" or the future second birth (cradle-to-cradle), and a clear understanding of the previous train or the previous birth.

With the multiple explorations either in parallel or nested within a larger design cycle, there are multiple explorations being conducted simultaneously, maturing at different rates. Once a design has matured, the input is closed and the exploration continues until an unambiguous DDD (particularly Rf and Df) can be developed. Unambiguous and detailed specifications must be finalized; the existence of multiple cycles does not alter that necessity. Once the door of the train is closed, the design process is finalized, documented, and placed into production. Any new inputs go on the next train.

4.5.5 Sustainability and Design Cycles: There is strong similarity in how the concept of design cycles and cradle-to-cradle sustainability impact development of the DAE theory. These design environments both require the consideration of design explorations (Ex) beyond the more narrowly focused design at hand (the local exploration), and consider the broader situation and context for the design effort. For sufficiently complex efforts, managing the context of the design iterations becomes more than just an expansion of the local exploration process. It becomes an exploration itself (*external* exploration) where the local exploration is a contributor. Both sustainability and design cycles can be modeled in DAE in a similar local / external iteration or nested exploration methodology. Mapping sustainable design into DAE in this manner also emphasizes the sustainability aspects. A specific local design effort may be the current emphasis of a design team, but it exists as a component to more expansive external exploration. With this local / external understanding applied to the DAE theory, sustainable design becomes an integral part of the product design lifecycle. Ensuring sustainability in the design becomes as innate as anticipating and incorporating the next technological advance for a high tech product.

5 SYSTEMS APPROACH TO PV MODULE ARCHITECTURE DEVELOPMENT

5.1 PV Module Architecture Development Backdrop: Abound Solar was formed in 2007 to commercialize a high throughput manufacturing process for CdTe PV and to supply reliable solar panels to customers. As described in section 4.3, the product design effort was initiated simultaneously with the company founding and was a key focus of the early efforts. Nearly concurrently, independent testing reports documented significant reliability problems with the industry standard module designs [TamizhMani 2008]. Degradation was seen in accelerated testing involving moisture and heat. The encapsulation designs and materials that were being used for thin film PV were originally optimized for crystalline silicon PV. They were high cost and had attributes that were not needed for the CdTe PV, including encapsulation optical transparency. A vacuum lamination manufacturing process was used which required a large footprint, costly equipment, and had a cycle over 25 times the cycle time of the semiconductor processing, the most critical fabrication step for PV manufacturing. These significant limitations with the industry standard materials, designs, and fabrication processes were the impetus to develop a new technology. After significant research and engineering effort, a novel module architecture was designed that was optimized to the CdTe device and that adressed the limitations of the industry standard methods.

The startup company, Direct Solar LLC, obtained intellectual property rights to the Abound developments and then began a program to further improve this module encapsulation technology. US DOE provided funding to support this effort [Direct Solar 2013]. Direct Solar was able to take the learning from the Abound research and production experience and develop a next generation module architecture that further lowers cost and facilitates manufacturability while maintaining the reliability benefits from the Abound design [Barth 2014, 2014-2].

The primary driver for the development of the new module architecture, particularly at Abound, was to improve reliability. That focus was prescient. Since the development of the Abound technology, the need to improve reliability has become more broadly recognized, as there have been warranty claims against reputable module manufacturers [Trabish 2012, FSLR 2012]. DOE has recognized the importance of module reliability and has consistently supported efforts to improve long-term performance. Recently, DOE announced a major new research program to increase module durability and field lifetime [PVRD 2015], motivated in part by a recent DOE and National Renewable Energy Lab (NREL) study [Jones-Albertus 2015] demonstrating the improvement pathways needed to achieve broadly economic solar power.

5.2 Industry Standard Module Designs and Manufacturing Methods

5.2.1 Need for Improved Module Architecture: PV modules are generally warranted for lifetime and reliability for 25 years. A typical warranty is 97% rated power in the first year, and 0.7%/year degradation through 25 years [FSLR 2014]. Two NREL studies have reported the degradation rates of fielded thin film installations at ~1%/year for thin film modules. The CdTe results were between ~0.5%/year to ~1.8%/year [Jordan 2012, 2013]. Recent copper indium gallium di-selenide (CIGS) and amorphous silicon thin film PV degradation rates were higher. Although the industry has made significant strides to improve reliability and warranted lifetime, these results are far short of the 0.2%/year and 50 year life that DOE studies show are needed for solar to be broadly economic across the US [PVRD 2015].

The leading thin film PV producer in the world, the US based First Solar Inc., has had reliability issues and has over $200 million in warranty expenses in late 2011 and 2012 [FSLR 2012. Solar is the most advanced and successful of the thin film PV manufacturers in the world, further highlighting the significant issues that module reliability has for all producers. Since thin film PV technologies are the cost leaders and are demonstrating module reliability issues, without significantly improved module reliability the DOE cost goals will not be achieved. Improved module reliability, combined with reduced materials and manufacturing costs, will lower PV costs, enabling more widespread use. The main factor determining PV operational life is the encapsulation material [Poulek 2012]. Most PV technologies are sensitive to moisture, and thin film materials are especially sensitive to corrosion from water vapor [Kempe 2014]. Thin film modules deployed in hot humid, and maritime climates show greater field degradation than in other areas. This is attributed to fill factor decrease associated with moisture ingress [Jordan 2012]. The ability for the module architecture to withstand UV radiation without degrading the encapsulation is a key requirement. UV degrades the commonly available hydrocarbon-based encapsulations materials used in PV modules [Kempe 2010]. UV radiation has sufficient energy to cleave the C–C bond [Singh 2008], which causes embrittlement and delamination. Encapsulation embrittlement can result in module mechanical failures, while delamination will result in moisture ingress and subsequent failure in the module. It is noted that silicones, which do not have the C-C bond structure, are not susceptible to UV degradation [Wolf 2007].

5.2.2 EVA Issues: Structurally, thin film and crystalline silicon (c-Si) PV technologies are significantly different and impose different requirements on the module package. Thin film PV utilizes a 2-3 micron film of the semiconductor material, which is vacuum deposited on a substrate, most often glass. In contrast, c-Si PV utilizes silicon wafers around 150 to 250 microns thick, which are then tabbed and soldered together into wafer "strings." The strings are then vacuum laminated between sheets of ethylene-vinyl acetate (EVA) polymer, which adhere the wafers to a tempered front glass substrate (figure 5.1, also see figure 4.1). The lamination process involves simultaneously heating the glass/EVA/wafer stack to initiate the crosslinking of the EVA, and vacuum degassing and pressing. The silicon wafers are mechanically fragile when stressed, but, with the modern passivation layers, they are resilient to moisture, oxidation, and other environmental conditions. In contrast, the thin film PV is both susceptible to mechanical damage

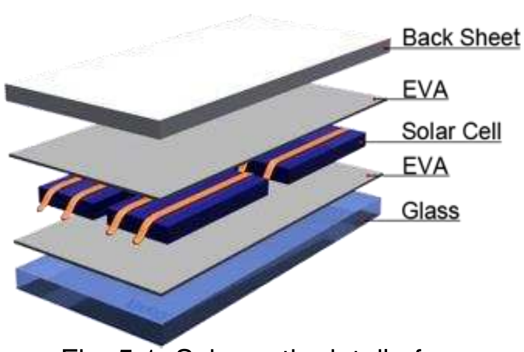


Fig. 5.1: Schematic detail of a typical c-Si laminated structure.

and is highly susceptible to water vapor. Thin film PV can be degraded by prolonged exposure to moisture and requires robust encapsulation to remain reliable [Whitfield 2010].

Most thin film PV manufactures have utilized module encapsulation architectures, fabrication methods, and materials, borrowed, at least in part, from the c-Si industry. Due to the different physical, structural, and environmental exposure constraints, the module packaging borrowed from c-Si has had reliability issues when used with thin film PV. Additionally, adopting the c-Si packaging methods to thin film has introduced manufacturing processing limitations and other issues. Thin film PV modules are most often constructed with front and back substrates made of glass. With some technologies, metal foils are used as the back substrate with glass front sheets. The front and back glass sheets are laminated together with the EVA covering the whole substrate. Unfortunately, the EVA material has poor moisture vapor transmission (MVTR) properties, allowing moisture to permeate where the EVA is exposed to the elements, along the edges of the module. The moisture can then diffuse and damage the PV structure. Additionally, the EVA / moisture interaction enables the formation of acetic acid in the EVA. Acetic acid can degrade and corrode the PV structures [Kempe 2007]. In contrast to the thin film technologies, industry standard c-Si modules typically utilize a porous polymer back sheet in place of the back glass. Tests at NREL [Kempe 2007] have shown that, in contrast to the impermeable back glass, the c-Si polymer back sheet allows the acetic acid to dissipate, reducing corrosion induced degradation for the c-Si PV structures. However, the permeability of polymer back sheets also enables moisture to diffuse into the module. This is not damaging to the c-Si but prevents these polymer back sheets from being used for thin films. The moisture sensitivity of the thin film PV materials necessitates the use of impermeable materials such as glass or metal.

<u>5.2.3 Edge Seals:</u> The lamination materials used in thin film module manufacturing, particularly EVA, have fairly high moisture vapor transmission rates [Kempe 2014]. In an attempt to overcome the poor moisture performance of EVA, and to improve the performance of other lamination

materials, strips of lower moisture vapor transmission materials are laminated around the perimeter of the module to reduce moisture ingress. These "edge seals" are most often tape strips of polyisobutylene (PIB) mixed with desiccants. Among commonly available industrial polymers, PIB has the lowest MVTR. The PIB can provide moisture control as long as good adhesion is maintained with the glass. This structure is an improvement on the encapsulation without edge seals and has been used in commercial application by companies such as First Solar. However, this architecture still has limitations. Placing polymer strips that are ~120 cm long, ~1 cm wide, and 0.04 cm thick precisely at production speeds is a challenge. Gaps can be present where the strips join each other. The strip material does not bond as effectively to the glass as EVA (which is a strong adhesive). Because the bonding is weak, the adhesive qualities of the EVA bonds the glass plates together and help to mechanically contain the edge seals. The poor bonding of the strips to the glass can lead to bubbles or voids that can facilitate moisture entry into the module. The strips may have a lower moisture vapor transmission than the lamination materials but moisture ingress is not eliminated. Over time moisture can still diffuse into the module.

Delamination has been seen for specific edge seals subjected to thermal/humidity tests; mechanical and UV debonding present an additional failure mechanism [Kempe 2014]. The PIB materials have C-C bonds and are susceptible to UV degradation. The adhesion of edge the seals to the glass may degrade due to UV radiation exposure. Along the perimeter where the edge seals are located, there is no semiconductor film to block the UV. Radiation passes through the front glass and degrades the edge seal / glass interface bonding. Once the adhesion of the edge seal is compromised, moisture can infiltrate along the degraded interface between the glass and seal. If the gap is sufficiently large, then liquid water may infiltrate the module. When moisture does enter into the panel, either through a gap, breach, permeation, or strip degradation, the PV structure will be degraded. It is noted that NREL experts have seen compromised edge seals in fielded modules [Kempe 2014].

5.2.4 Non-EVA Lamination Materials: The limitations of EVA, including the poor moisture performance, long cure times, and acetic acid formation, have driven the development of new lamination materials, notably by Dow Chemical and DuPont. For example, DuPont has introduced new ionomer materials [DuPont 2013]. Although these materials do have better moisture vapor transmission performance than EVA, the edge seal tapes are still required with these non-EVA lamination materials. The new materials are still quite expensive [Hunter 2011] and continue to necessitate the inefficient vacuum lamination process.

5.3 Importance of Encapsulation Moisture Performance: The moisture ingress performance of the module is the most critical of the encapsulation requirements. Moisture can degrade modules in a number of key ways:

1. Moisture can directly corrode PV materials and contacts
2. Moisture + heat can drive oxidation of the semiconductor, contact, and buss materials
3. Moisture combined with the EVA can form acetic acid and drive accelerated corrosion
4. Moisture can degrade the adhesion of contacts and buss bars
5. The electrical integrity of the module can be compromised, causing a potential electric shock or arcing hazard
6. In extreme cases, liquid water ingress and subsequent freezing can cause breakage.

As described in section 4.2, passing the IEC certification tests is a mandatory requirement for module manufacturers and is considered a "qualification" test. They are the minimum level of performance needed. The TÜV Rheinland Photovoltaic Testing Laboratory LLC performs the IEC qualification tests in North America. Figure 5.2 shows the percent failure rate for thin film modules for each of the IEC mandated tests conducted at the time of the Abound Solar development efforts (2007-2008).

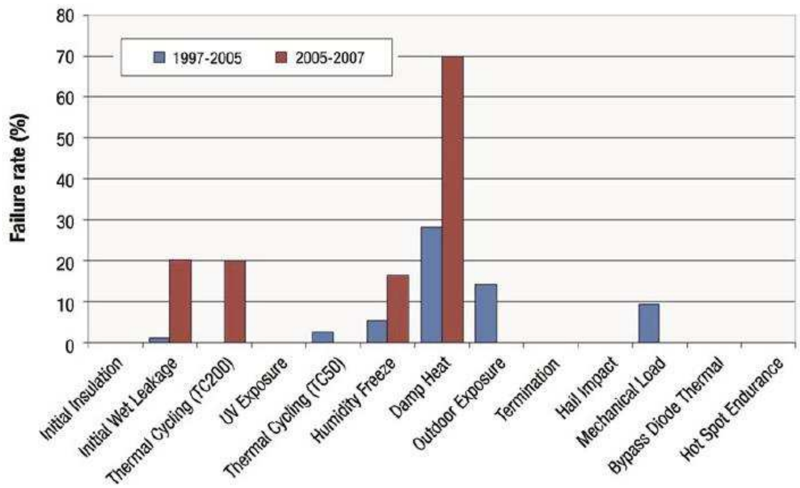
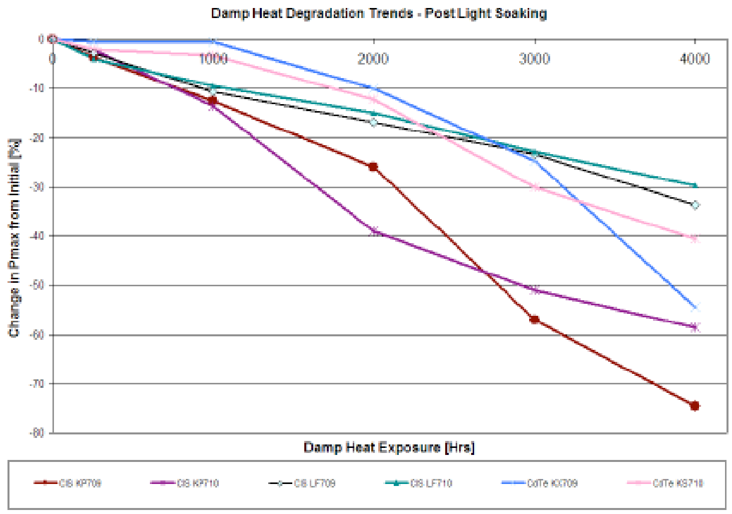


Figure 5.2: Thin film module failures under the IEC 61646 certification tests [TamizhMani 2008].

From Figure 5.2, 70% of all modules submitted during the testing period failed the damp heat test (85C / 85% relative humidity for 1000 hours). A significant number failed the "wet leakage" and "humidity freeze" tests. The IEC tests are expensive and can take up to 3 months to complete. A module manufacturer will not likely submit modules to be certified without the expectation of success. During the time of the Abound product development, the vast majority of module designs, as tested under the IEC protocols, failed the qualification moisture tests.

Sophisticated European and domestic customers of Abound Solar mandated that young manufacturers pass damp heat testing 3-5 times longer than what is prescribed by the IEC tests before large orders would be placed. With 70% of modules failing before 1000 hours in independent testing, 3000 to 5000 hours (approximately 1/2 a year exposure) is a very stringent requirement. Fraunhofer ISE in Freiberg Germany has performed long duration damp heat testing of commercially available thin film modules. The results are shown in figure 5.3. It is noted that all of the modules performed reasonably well up to 1000 hours of exposure (IEC mandated test duration) but had degraded significantly by 3000 hours. Some of the modules were producing less than 25% of their initial power output. When queried, experts at NREL, Fraunhofer, and solar companies believe that 3-5 Khrs of damp heat anecdotally correlates to reliability in the field. The picture in figure 5.4 shows the catastrophic degradation after the damp heat testing.



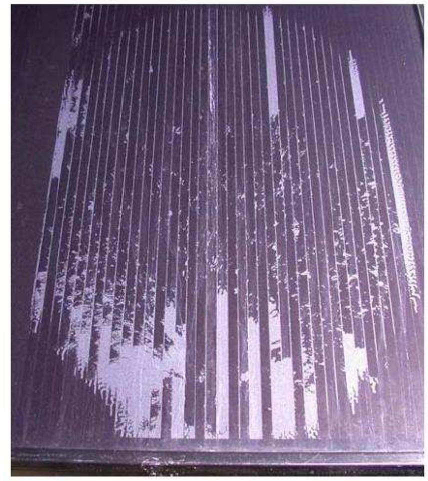


Figure 5.3: Performance of thin film modules under 85 C / 85% relative humidity [Sample 2009 via Whitfield 2010]. All modules were commercially available. Figure 5.4: CIGS module after long duration damp heat [Sample 2009].

5.4 Lamination Throughput and Equipment Cap-Ex: In addition to the moisture performance deficiencies with the industry standard thin film module architectures, there are significant manufacturing limitations. At this time, all common commercially available (thin film and c-Si) modules are laminated, either with EVA or other adhesive films. Lamination is a time consuming, batch type manufacturing process. The lamination process includes the following manufacturing steps: 1) the lamination film material is cut and laid on the front glass plates; 2) the strip seals are carefully positioned; 3) the back glass plate is placed on the stack; 4) this stack is then placed in a lamination machine; 5) a vacuum is applied to remove entrapped air; 6) the stack is heated to soften the lamination film and initiate polymer cross-linking; and 7) pressure is applied to the stack to facilitate adhesion. The vacuum / heat / pressure lamination cycle can takes 13 minutes even for the new advanced lamination materials. Some EVA formulations take up to 20 minutes. In order to maintain production throughput, large vacuum laminators and simultaneously processing multiple modules are required. Batching and queuing of modules in the factory is needed to maintain production flow; most of the other module finishing processes are significantly faster, on the order of ~30-60 seconds cycle time.

Fig. 5.5: Production type vacuum laminator. Note the scale of the people on the right side of the picture [Rimas].

Laminators for high volume PV production have high capital costs and very large factory footprints. Laminators suitable for EVA and other materials are available from a number of vendors; those from Burkel North America (http://www.burkleusa.com) have an excellent reputation and are considered to be of high quality with good value. Figure 5.5 shows the scale and factory footprint needed for a Burkel high volume PV laminator. The capital cost for a similar unit to those pictured is over $12 million for a unit capable of processing ~200 MW/year of modules [Hunter 2011].

5.5 New Module Architecture to Address Limitations: In order to overcome the performance and manufacturing deficiencies of the industry standard module encapsulation, a new module architecture was developed by Abound Solar with increased reliability and manufacturing efficiency. This novel module architecture technology has significant benefits, including:

Extreme robustness to moisture degradation (approx. 4x better than standard methods)

Excellent adhesion, even with UV light exposure

Process cycle time for each manufacturing step is under one minute

Small manufacturing tool footprint (approx. 20x smaller than current methods)

Increased module mechanical strength

Increased process tolerance to glass temper distortion

Reduced manufacturing cost

Reduced capital costs

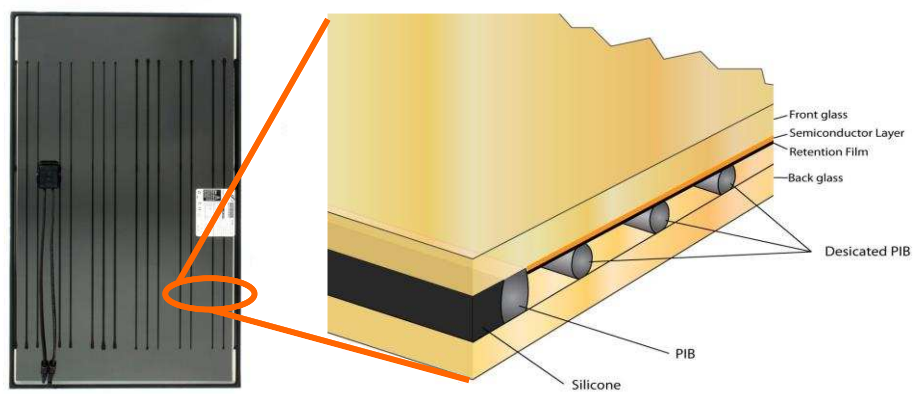


Figure 5.6: Abound Solar module design showing retention sheet. The conformal coat (not shown) is between the retention sheet and the active semiconductor layers [From Barth 2011].

5.5.1 Abound Solar Design: A schematic of the Abound Solar module architecture is shown in figure 5.6. In place of the EVA or other lamination films, the new module architecture utilizes a two component perimeter seal. The strength of the module comes from silicone at the outer edge of the panel. Based on chemistry and materials science principles, one of the most resilient bonding materials for glass is silicone via the repeating Si-O-Si-O bonding across the glass / polymer interface. Silicone is inherently UV resistant [Wolf 2007] and does not degrade when exposed to liquid water. Silicone edge seals are used for the critical application of adhering windows to multistory buildings where bonding failure could cause fatal injuries. Using vendor data augmented with test coupon results, the bond area needed to support the 2400 Pa load required under the IEC certifications tests can be easily calculated. A bead of approximately 1/4 inch is sufficient to carry the load with significant safety.

Inboard from the silicone is an optimized PIB polymer. This material, knows as butyl rubber, has a low moisture vapor transmission rate and minimizes moisture ingress. In contrast to other PIB edge seal configurations used with lamination, the PIB is protected around the edge by the silicone. Even if there is a minor breech of the PIB due to a manufacturing defect, field degradation, or UV radiation, the silicone will prevent liquid water ingress and impede moisture from entering the module. As shown in figure 5.6, the high performance edge seal materials are positioned only around the perimeter of the module, reducing materials usage and cost. No lamination films are used inboard of the edge seal.

As part of the Abound design effort, extensive formulation development on the PIB material to optimize the UV performance in PV applications was conducted. This was done in partnership with the polymer chemical manufacturer. When used in other long life field applications, such as window and spandrel glass applications, the PIB is loaded with carbon particulates to absorb the UV and prevent damage to the C-C bonds. There were issues when prototype modules with un-optimized PIB were subjected to the IEC 61730 "hi pot" safety tests. This procedure tests the modules' electrical safety by applying a high voltage (high potential or "hi pot") to the modules and measuring the leakage current. The high level of carbon in the un-optimized PIB was relatively conductive, which resulted in excessive current leakage. A research program was initiated with the chemical manufacturer, and an optimal carbon level was found that enabled excellent UV performance while passing the required electrical safety tests.

Referring back to figure 5.6, inboard of the edge seal (silicone and PIB), separate desiccant polymer "stripes" are deposited. These are a different formulation of PIB mixed with desiccant. These structures are used to control the level of water vapor exposure for the semiconductor device. The desiccant absorbs any moisture which does diffuse through the silicone/PIB edge seal over the module's life. The desiccant load for the internal stripes can be determined based on the perimeter PIB thickness and bead width (diffusion), and the size of the module. The desiccant quantity is modest. Depending on the module size and configuration, a few grams of desiccant can provide a safety factor to ensure that the semiconductor is protected. This module architecture is particularly suited for addressing the durability, adhesion, and moisture concerns associated with thin film PV. At Abound Solar, over one million modules were produced. Although the modules have been in service for a limited time, the package design showed robustness in the field to moisture ingress and adhesion. The Abound design has passed IEC 61646 and 61703 (UL 1703) certification tests. Additionally, modules have survived 4500+ hours of the rigorous 85 C / 85% relative humidity "damp heat test." This is 4.5 times the duration required by the certification standards. Using this design, Abound Solar was able to achieve UL and IEC 61646 certification in one of the fastest times reported in the industry [Emery 2010]. Figure 5.7 shows the performance of modules fabricated with the Abound architecture and subjected to the "damp heat test." As is shown in Figure 5.2, 70% of all modules submitted for certification testing do not pass 1000 hours of this exposure. Modules with this architecture passed nearly 5000 hours. Compare the moisture performance of the Abound design shown in figure 5.7 to the performance of the then commercial modules show in figure 5.3.

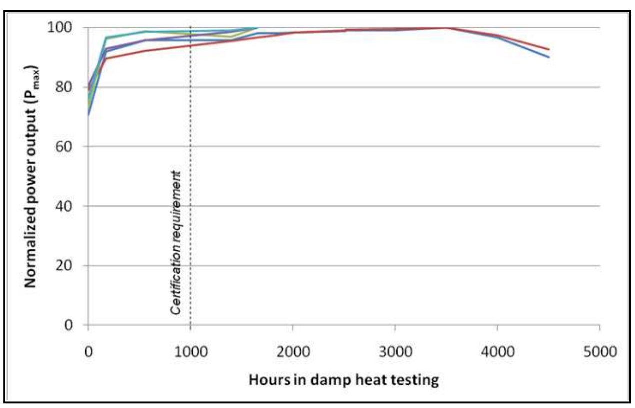


Figure 5.7: Damp heat performance of modules utilizing the advanced "edge seal" and desiccant module package design [Barth 2011]. Compare performance to figure 5.3.

The architecture developed at Abound had significant advantages compared to a laminated structure beyond just durability. It was mechanically effective, facilitated the development of automated manufacturing tools, passed the IEC/UL certification tests, and enabled the introduction of a product into the marketplace by the Abound team. These were the key milestones needed for the startup company. The Abound design used a "retention film" (see figure 5.6) to pass the IEC breakage tests, which mandate that no large glass shards be ejected from the module under catastrophic breakage. The test ensured that there are no large, "knife-shaped" glass pieces present to cause injury. The retention sheet was a polymer film with adhesive on one side that was applied over the semiconductor devices. The sheet was functional and enabled the module to pass the breakage tests by holding the broken shards, but the adhesion of the film was high enough that it could damage or debond the back metallization (back contact) of the PV device under certain circumstances. To overcome this, a polymer "conformal coat" was spray applied to the back of the semiconductor devices prior to the application of the sheet. A hole had to be cut in the retention sheet, allowing access to solder the leads to the buss bar. Cutting a precisely located hole in an un-supported, eight square foot thin polymer sheet at production speeds is a challenge, as was lining up the hole with the correct location for the buss bars and leads. Both the UV curable conformal coating and the retention sheet added expense, and the manufacturing process for installing the sheet was not as elegant as that of the perimeter seal.

As described above in section 4.3, Abound needed to enter the market quickly to generate revenue. Being new to the marketplace, Abound wanted to ensure reliability and to quickly pass the certification tests. The retention sheet and conformal coat were beneficial. The additional complexity and the relatively minor cost of the retention sheet and conformal coating could be absorbed by the high module selling price. At that time, modules were selling for approximately \$2.50/Watt. This is no longer the case; they are currently selling for ~\$0.60/W.

5.5.2 Next Generation Design: Producing over one million modules, passing the IEC/UL certification tests in unprecedented time, and selling modules to customers across the world demonstrated the fundamental benefits of the Abound architecture. However, the learning developed from that high level of implementation, combined with changes in the business environment due to significantly reduced module selling prices, opened opportunities for further innovation. The development of this next generation module design was the focus of the successful program conducted by Direct Solar LLC in 2013 and 2014, supported by DOE [Direct Solar 2013, Barth 2014, 2014-2].

The objectives of the new design effort were to keep the outstanding moisture and mechanical performance of the Abound configuration but develop a new interior structure that combined the function of the conformal coat, retention sheet, and desiccant polymer strips. This new internal structure would be optimized for improved cost and manufacturing efficiencies. A schematic of the next generation design is shown in figure 5.8. The PIB and silicone materials used at the edge seal are common between the Abound and this next generation design. These materials are similar to those used in the construction industry for multi-story commercial building facades and windows. In these applications, the materials have demonstrated greater than 25 year life. The edge seal width (in plane) can be between 12+ mm to between 7 to 10 mm. This is reduced from the Abound design and saves materials costs. The silicone / PIB combo can also be used to isolate the back box penetration inside the module (around the back hole). Similar materials and dispensing techniques can even be used to attach the back box.

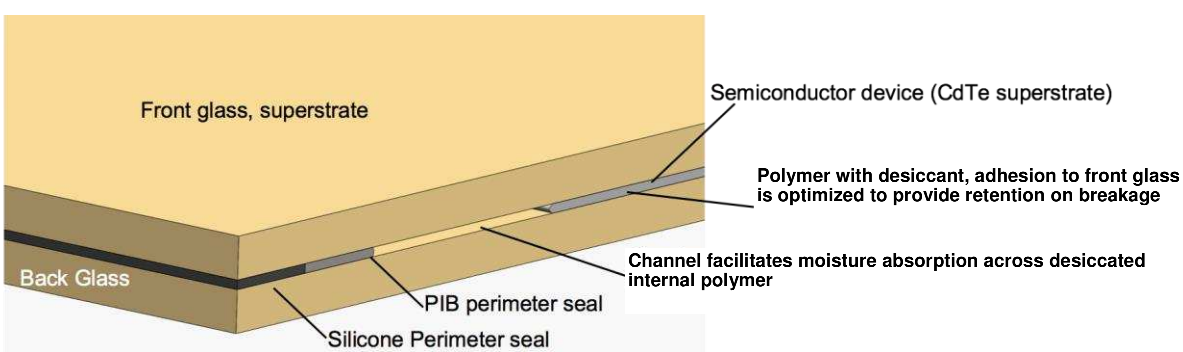


Figure 5.8: Schematic of the next generation module architecture for a CdTe module [adapted from Barth 2014-2].

A key advance of this design is the use of a single polymer, bridging between the substrates. This polymer is a low cost acrylate and replaces the retention film, conformal coat, and desiccated stripes on the Abound configuration. Desiccant is added to the acrylate to absorb moisture that passes through the edge seal and to reduce the cost of the polymer by acting as a filler. The acrylate covers approximately 75% of the inner surface. With the application of the back glass, the structure is pressed, resulting in a total encapsulation thickness of 0.3 mm. This is thinner than traditional EVA (0.4 mm), which is sized for the crystalline silicon wafers and interconnects. This configuration is a low cost solution that still maintains the robust, proven edge seal that was successful in the Abound design.

The acrylate will perform the function of the retention sheet. The polymer will adhere to the back glass and back of the semiconductor device, providing mechanical strength and preventing glass shard ejection (retention) during module breakage to pass the IEC 61730 tests. In addition to minimizing the moisture level in the module, the amount of desiccant can be varied to reduce polymer cost and to change dispensing viscosity. An approximately 1 cm gap is present between the edge seal and the start of the acrylate, and "channels" can be provided in the desiccated acrylate to facilitate the absorption of any moisture vapor that does diffuse past the edge seal. The acrylate does not have to be transparent due to the superstrate configuration of the CdTe devices. Optimization of this next generation design is a pathway for high reliability module architecture with a 50 year life, improved cap-ex, and lower materials costs.

5.5.3 Manufacturing Efficiencies: The manufacturability of both the Abound and the next generation designs are significantly improvements compared to the laminated structures. The modules are fabricated without lamination, vacuum pressing, or module heating. The encapsulation sealants are dispensed through commercially available hot melt injection equipment. Each of the components is applied in under one minute cycle time using tooling derived from production processes used in other industries. This significantly streamlines the manufacturing process, enabling small footprint tools to be located in-line with other module finishing steps, thus avoiding the batching and queuing required for lamination.

The silicone and PIB perimeter seal materials are sourced in 55 gallon drums. A heated platen presses into the drum and extrudes the materials, which are dispensed through specially designed nozzles. The polymer application is controlled by an X-Y motion system (figure 5.9). Control of the pressure, polymer temperature (viscosity), nozzle geometry, and nozzle motion enables precise distribution of the materials. The hot melt systems are used for similar applications in other industries and are extremely inexpensive compared to the capital equipment cost of the lamination systems shown in figure 5.5. The acrylate materials can be dispensed by similar systems but do not require the heated platen to be dispensed. Once all three polymers are applied, the back glass is then positioned and the entire structure is pressed to minimize the distance between the front and back substrates. The application time for the silicone, perimeter seal PIB, and internal desiccated PIB is under one minute for each material for an industry standard 120 x 60 cm module.

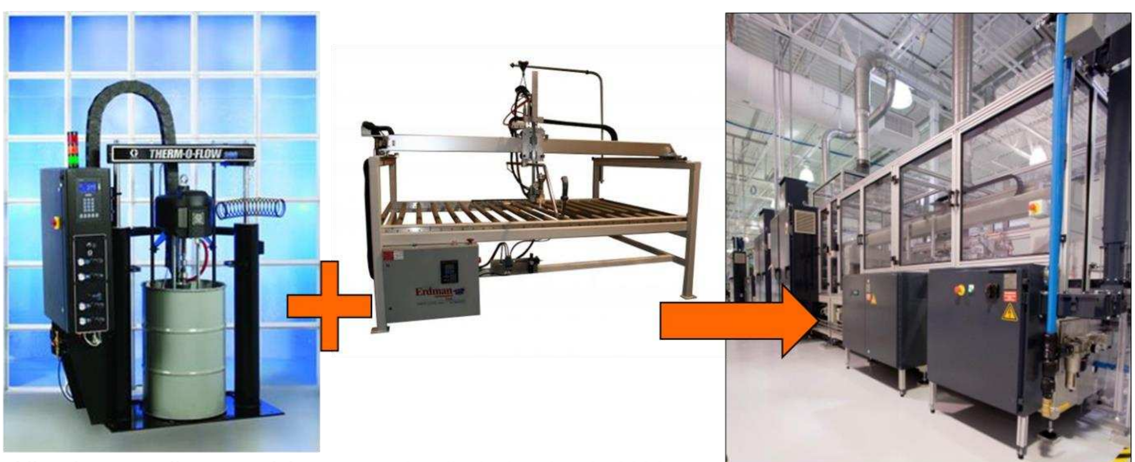


Figure 5.9: Hot melt systems and X-Y motion systems are identified as the most effective manufacturing processes. The image to the right is the production edge seal application tool at Abound Solar. The hardware had a throughput of 30 seconds for a 120 x 60 cm module. This system was integrated into a manufacturing line with other finishing steps module.

The thin film PV industry is moving towards larger area modules, sizes of greater than one square meter. The technology can be scaled to any module size. The production tools need only be incrementally larger than the module size. Additionally, different sized modules could be processed in the same equipment by altering the tool motion program.

Table 5.1: Materials costs savings with new designs [Barth 2014].

Item	Abound Solar design	Next Generation design	Laminate (industry standard)
Conformal coat	$0.34	--	--
Retention sheet	$1.76	--	--
New internal structure design	--	$0.71	--
PIB edge and PIB desiccated	$1.38	$0.70	--
Silicone, bulk strength, water barrier	$0.39	$0.30	--
Laminate edge seal	--	--	$0.60
laminate film (DuPont)	--	--	$3.24
Encapsulation cost	$3.87	$1.71	$3.84
Savings from laminate	-$0.03	$2.13	$0
Est. cost savings for 85W module ($/Wp)	~0	$0.025	--

Table Notes: Cost numbers for 100-200 MW/yr. volume. The next generation configuration uses the PIB/ Silicone edge seal (9 mm wide) but with a low cost acrylate internal fill also with desiccant. For costing, the acrylate internal coverage is approx. 75%.

5.5.4 Materials Cost Benefits: A materials cost model was developed for the standard laminate module (with edge seal), for the Abound configuration, and the next generation architecture. Results are shown in table 5.1. Materials cost numbers were provided by the materials vendors for ~100-200 MW/year production volume. The author's past experiences as a principal of Abound Solar facilitated obtaining valid costs, and are what a sophisticated manufacturer could be expected to negotiate. The numbers were generally not the "list price" and should be viewed as estimates for manufacturing process development. The cost analysis was performed under a DOE SunShot award with input from NREL. Data was reviewed by the DOE program manager. Numbers were peer reviewed and published [Barth 2014]. Cost calculations show an approximately $0.02/W reduction in overall module manufacturing costs [Barth 2014]. It is noted that this is only the materials cost savings, and does not take into account the significant reduction in capital equipment costs, improved manufacturing efficiencies, the reduced manufacturing plant footprint, or the improved reliability [Barth 2014].

The capital equipment costs for the equipment to fabricate the new architectures are also significantly reduced compared to the cap-ex required for lamination. A lamination tool capable of ~150-200 MW/yr. has a capital equipment cost of over $12 million [Hunter 2011]. Fully automated, semi-custom equipment to fabricate the new architectures at a similar throughput is under $2 million based on experience from Abound (see tooling in the right side of figure 5.9). The lamination equipment is over six times more capital intensive than the equipment needed for the new architectures. Additionally, the cost of the new equipment will likely drop significantly as it becomes standardized as more tools are fabricated. It is noted that there are additional cost savings associated with the significantly reduced manufacturing footprint that are not included in this analysis.

6 CONCLUSIONS AND FUTURE WORK

This research has shown that the DAE theory has a significant suitability in describing real design in complex environments, such as those in startup companies and where innovation and sustainability are integral to the efforts. Analyzing these heavily constrained design activities within the framework of the DAE theory has enabled an expanded understanding and extended applicability of the theory. Additionally, through the analysis with the expanded DAE method, insights into the design process methodology and opportunities to improve future design efforts were revealed.

6.1 Knowledge Generation within DAE

6.1.1 Knowledge Development to Enable Design: A consistent finding from this investigation is understanding the importance of knowledge generation in conjunction with real world design. For early stage companies and for innovative designs, the generation of new knowledge is needed before credible problem statements and requirements (Pi, Ri) could be developed. The first exploration iterations (Ex) are focused on broad based knowledge generation to the degree that the first iterations can be less a design exploration and more of a knowledge generation process. As shown, for design in these environments a much more general understanding is needed, primarily focused on building foundational domain knowledge, Kdm, before the specific attributes of the design (Dx) can be explored.

Interestingly, startup and innovative design circumstances were demonstrated to have strong similarities in the need to develop new knowledge. The knowledge deficiencies due to a startup company were biased to Kdm; innovative designs highlights deficiencies in both Kdn and Kdm early in the exploration process. This is somewhat counter-intuitive for the case of innovative design, where it would seem that the most emphasis would be focused on developing the design knowledge, Kdn, as that incorporates the novelty. Innovation in the design environment placed the designers in "uncharted waters" and required the development of the supporting domain knowledge that surrounded the innovation. Later, as the internal explorations progress and the required domain knowledge is obtained, knowledge generation shifts from Kdm to more Kdn.

The need to expand the DKR is the most important aspect of the early exploration iterations. As knowledge is accumulated, the exploration iterations focus more on defining requirements and problem descriptions (Rx, Px). Then late stage explorations are focused on the requirements, problem, and design (Rf, Pf and Df) attributes, drawing from the DKR. As the DKR expands, "innovation" becomes more understood and familiar, thus trending closer to "routine" design. In this manner the exploration process moves through phases where different aspects of the exploration are emphasized:

A. Knowledge generation (expanding Kdm, then later Kdn)

B. Design scope generation (continued expansion of Kdn, development of Rx and Px)

C. Solution development (utilization of the DKR to develop Dx and then the final DDD).

This result clearly demonstrates the inadequacy of design theories that do not robustly accommodate the broad generation of new knowledge. Only in the final stage, once the knowledge and scope are developed, can design perhaps be approximated by a mapping / searching method.

<u>6.1.2 Knowledge Levels</u>: The critical role that knowledge generation plays in constrained and innovative design environments requires effective categorization and documentation in order to maximize utility. The hierarchical expansion of the DKR into knowledge levels with multiple tiered Kdm and Kdns, presented here, facilitates this. Knowledge level categorization enables directed knowledge generation efforts within the design process (either R&D programs or targeted hiring of resources with key experience). Knowledge gaps are easier to identify expediting "learning focused" design explorations. The DAE theory, with an expansive, hierarchical accounting for knowledge, can easily accommodate high levels of innovation.

Within DAE, the understanding of these knowledge processes provides a backdrop to define the role of (and effectively utilize) prototypes and design centered R&D. These knowledge generating activates extend Kdm early in the exploration cycles, then extend Kdn as the exploration processes near completion. Early stage prototypes and R&D, particularly for an innovative design, are vehicles to extend higher, less specific knowledge levels in the DKR. They may be less about mocking up design details but instead are more focused on increasing understanding to facilitate the development of problem descriptions (Px). As the design matures, the utility of the prototypes and experimentation changes. They become tools to develop design details and fabrication methods (Df) as a prelude to manufacturing.

An expanded emphasis on documentation is needed to capture and effectively utilize the knowledge generated. Design documentation, particularly the exploration history, Hf, is critical to communicate to the next design cycle, or for startup companies to communicate the details of the early design decisions as the company expands. If the learning and design history are not captured, the overall design effort, including placing the product into manufacturing, product improvements, and developing end of use strategies (sustainability), are compromised. This result was seen at Abound.

6.2 Sustainability and Design Cycles: The requirements imposed by sustainable design and iterative product design cycles can be accommodated in the DAE theory by expanding the concept of a design exploration. Cradle-to-cradle sustainable design and product design cycles add a forward-looking, anticipatory component to the overall process. Thus, work on the future design or simultaneous work on multiple designs may be under way, concurrent with a more narrowly focused local design effort. Multiple simultaneous explorations can be visualized as being either in parallel with each other, each maturing at different rates. Or, a less expansive narrowly focused design cycle (a local exploration) can be visualized as being nested within a more expansive, broader (external) exploration. This is the case where ensuring cradle-to-cradle lifecycle management (anticipatory, external exploration) goes beyond specific functional requirements based design (local).

In these design environments, there is effectively a continuous series of explorations where one design cycle anticipates the next one in an ongoing process. In a broader context, new technological input / findings, business drivers, or external inputs are continually being generated. These are processed in external exploration cycles that harmonize with the previous explorations and anticipate the future efforts. New initial requirements and problem description inputs are developed which are digested in a local internal exploration process that produces a specific design. Multiple design cycles adds a future, forward-looking aspect to the DDD by anticipating the interaction with the parallel design explorations. This is an extension of the DDD role (and by extension, aspects of the DKR) beyond describing the results of a single design effort. The DDD and DKR audience is expanded beyond the design team to potentially include product end users (providing information on recycling), to company executives (enabling strategic decisions on managing the design cycles).

6.3 Expanded Design as Exploration: Figure 6.1 shows a graphical representation of the DAE theory that has been expanded to incorporate the findings from this research. Throughout the process, knowledge is utilized. Knowledge is denoted by maroon boxes and knowledge transfer is shown with maroon arrows. Knowledge generation is shown by green boxes and arrows. The design knowledge resources (DKR) incorporates knowledge levels. The highest, most general is general background knowledge not specific to any design. More detailed knowledge levels, specific for a give design for both the domain (Kdm) and design (Kdn) categories, are lower in the hierarchy.

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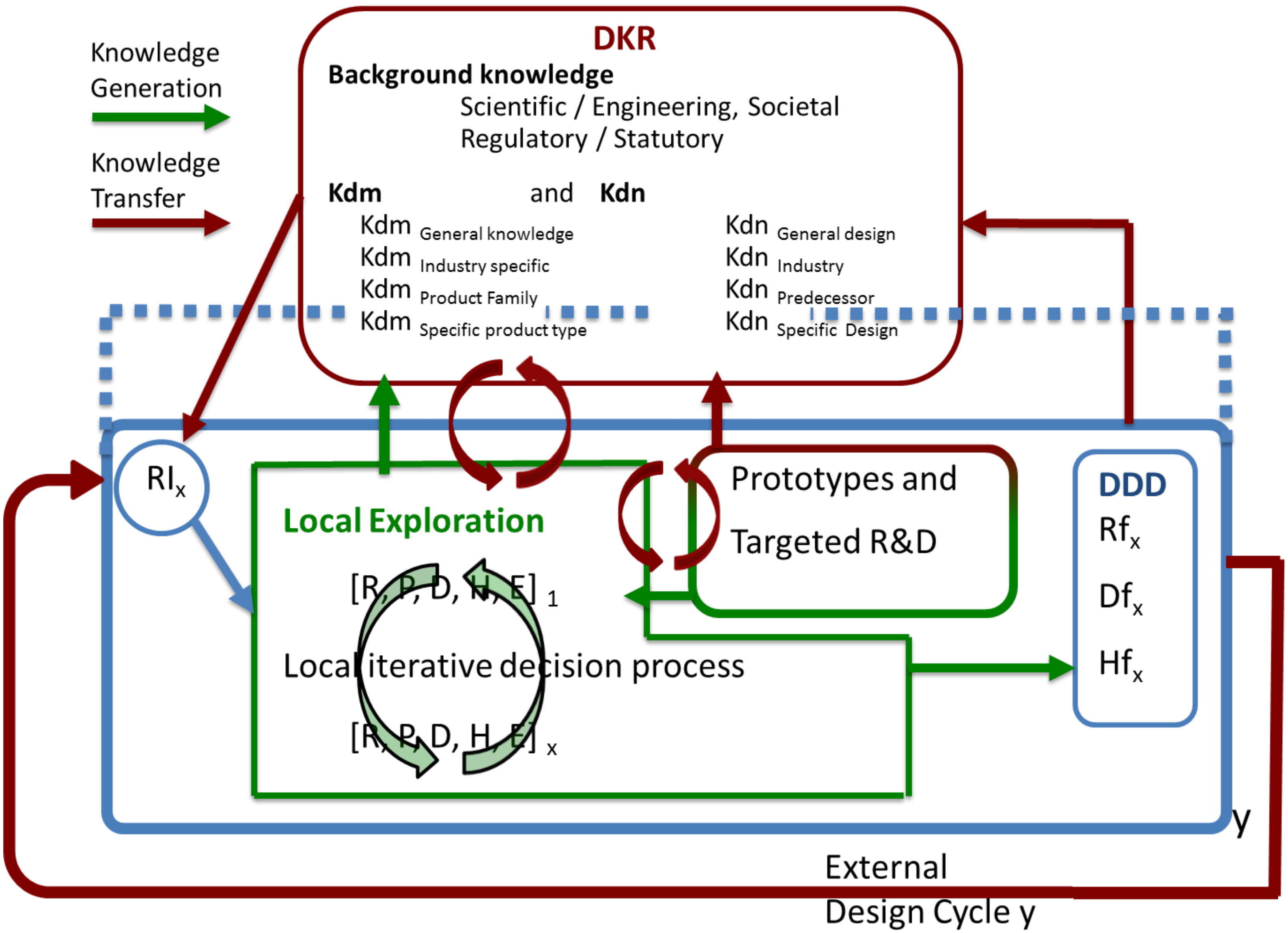

Figure 6.1: Expanded Design as Exploration

The process initiates a general identification of a “need," which generates very poorly defined initial requirements (Ri) which draw upon some limited knowledge from the DKR. This Ri information is then transferred to and seeds the internal exploration process. The local exploration process involves iteration (E1 .... Ex) of requirements (Rx), the problem statement (Px), the design description (Dx), and the design history / chronology (Hx). During the exploration, knowledge is both used and generated. Knowledge is generated in the exploration process, shown by the green cyclic iterative process arrows. This is the dominant generation process in DAE.

Knowledge is transferred both ways between the DKR to the exploration. As demonstrated here, a key outcome of the explorations is the generation and transfer of knowledge back to the DKR. This bidirectional flow may happen simultaneously, where some new knowledge is being generated in one aspect of the design ($Kdn_{product}$) while domain knowledge is being used. This flow of knowledge from the exploration to the DKR is a critical aspect of DAE and is represented by the maroon cyclic arrows.

Research and development that is specific to the exploration process[5] and prototype development are closely related. These efforts are undertaken to generate knowledge about the design effort that is then utilized by the exploration. The prototyping and R&D are closely coupled with the design effort and are shown as carving out a section of the exploration process box. However, they are not directly part of the exploration process, and thus are shown as separate. These tasks do not advance the requirements, problem statement, or design iterations directly. They are not part of the exploration decision process but generate knowledge which enables / facilitates the effective iteration on Rx, Px, and Dx. The specific questions asked of the prototype / R&D activity, along with the engineering details needed to conduct a meaningful experiment,

[5] This is in contrast to basic scientific R&D which is conducted solely to build knowledge without a specific product or design objective. Within DAE, this research would transfer knowledge to the "background knowledge" of the DKR.

represent the transfer of the knowledge *from* the exploration process. The findings of the experiments are new knowledge which is transferred *to* exploration processes. This bidirectional knowledge flow is shown with maroon cyclic arrows. The knowledge generated during R&D is transferred to expand the DKR. When the local exploration process is completed, a local final design is developed. This is denoted by the green knowledge generation arrow between the exploration process and the design document description, DDD. The knowledge represented by the DDD is transferred to the DKR.

Other than the expression of "needs," there is additional initiation opportunity into the local design process. This is denoted by the knowledge transfer arrow coming from the DDD back around to the Ri. This demonstrates the design cycle concept, where a specific local exploration anticipates a subsequent effort. As described above, there may be multiple iterations. These could be a series of product design introductions, sustainable product “births," or "rebirths", or multiple design efforts happening simultaneously. In the expanded DAE understanding, these are accounted through the external design cycles, designated by the subscripts "1 ... y” in figure 6.1. Different design cycles can use much of the same DKR, perhaps with variations at the lowest, most specific of the knowledge levels. An example would be the design of the next incremental version of a product. Alternately, new design cycles may require significant additions / alterations for the DKR. To accommodate different possible requirements placed on the DKR with subsequent design cycles, the blue box of the exploration design cycle has a dashed line through the DKR indicating that different knowledge level requirements can be accommodated.

6.4 Next Steps

6.4.1 Future Work for DAE Theory Development: This work extends the understanding within the DAE method of how knowledge is used, expanded, and managed. This was developed by investigating DAE in a startup company environment and through the introduction of an innovative product. This work began investigating how these insights are relevant in different design environments, suggesting that there was broad applicability. This effort needs to continue. Different design circumstances need to be explored to test the applicability and further refine the role of knowledge in DAE.

In sophisticated design environments there is a clear need to account for ongoing parallel design efforts and to drive the sustainable aspects of the designs. The ability to model ongoing iterations in the DAE theory utilizing the design cycle concept was developed here. A further investigation of the design cycle is needed to fully extend the method for adoption. Then the DAE method needs to be explored with real world scenarios. Smithers identified the lack of accounting for design cycle scenarios as a limitation of DAE, so additional research must be taken to ensure that a truly appropriate method is developed.

6.4.2 Future Work Module for Architecture Development: Improving module reliability, reducing degradation, reducing encapsulation materials costs and encapsulation cap-ex costs are needed to achieve broadly economic solar energy in the US [Jones-Albertus 2015]. The module architecture presented here addresses these key deficiencies with the current industry standard encapsulation. This technology development presents the opportunity to drive down PV energy costs and expand the use of solar generated electricity. Although one million modules utilizing the Abound technology were produced and shipped across the US, Asia, and Europe, more technology development is needed with the next generation architecture to realize these outcomes.

This fall the US government's DOE SunShot office announced a strategic thrust to improve solar reliability. The author has assembled a consortium that includes NREL, SEMATECH, and First Solar, and has developed a $1.2 million research program to respond to the DOE opportunity and to drive the new architecture to implementation. A concept paper outlining this effort (see appendices) has been reviewed by DOE and received a formal response encouraging a full application. The research efforts outlined in the concept paper are the next steps needed to advance the technology and develop an architecture suitable for 50 year field life. The four key objectives targeted for under this program are listed:

A. Optimization of polymer materials formulations to fulfill 50 year life with improved cost and manufacturability. The specific formulation of the acrylate internal structure will be optimized for performance, adhesion, and polymer application.

1. Investigate nozzle for polymer dispensing
2. Ensure integrity of internal pattern geometry and that polymer bridges both substrates
3. Determine optimal process conditions for dispensing 9 mm edge seal

B. Development of prototype processes and fabrication tools for module encapsulation with the new architecture. Perform computational fluid dynamic simulation for tool nozzle development and model the edge seal configurations and desiccant requirements.

1. Viscosity with temperature and impact of reheating (stop and start)
2. Impact of desiccation additives in viscosity and flow characteristics
3. Optimize nozzle design

C. Coupon fabrication, moisture, UV, adhesion, and other durability testing.

1. Design and construct small scale experimental tool
2. Evaluate nozzle configurations and confirm computational fluid dynamics (CFD) models
3. Numerically simulate moisture ingress and adhesion performance for 50 year life
4. Fabricate samples and subject to accelerated tests, moisture ingress studies, and heavily accelerated UV exposure

D. Fabricate modules, subject to accelerated durability tests, demonstrate industrial suitability.

1. Fabricate full 120 x 60 cm modules

2. Pass IEC encapsulation tests, including 4x damp heat. Demonstrate adhesion and performance with 50 year equivalent UV dose and combined UV / damp heat tests.

3. Demonstrate tool / process capabilities for industrial usage

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8 APPENDICES

Appendix I: Statements of Support for Next Generation Module Development performed by Direct Solar

The following are quotes taken from letters of support for Direct Solar's module architecture development:

"We believe that Direct Solar's technology development holds potential to improve reliability, streamline manufacturing and lower costs."

Scott Mills, Director Process Development, First Solar Inc.

"PPG is familiar with Direct Solar's experience in the area of module construction and believe your approach is relevant and may play a critical role in the reduction of the LCOE for thin film photovoltaics. The new module construction is an advancement of the technology and could improve reliability, manufacturing, lower costs and is less sensitive to temper distorted glass."

Mehran Arbab, Director, Glass Science and Technology, PPG Industries

"Stion is always interested in ways to improve module performance and durability, and to reduce costs. The innovative module configuration developed by Direct Solar....holds promise to accomplish these goals."

Robert Wieting, Sr. Vice President Research and Development, Stion Corp.

"This is an innovative module architecture that has significant potential to improve PV field reliability, significantly streamline manufacturing and reduce manufacturing costs."

Kennety Kormanyos, President Calyxo USA

Appendix II DOE PVRD Project Concept paper

This concept paper received a "encouraged to apply" review the highest possible. As of this writing the full application has undergone the initial review. The expert reviewers stated that the project to further advance the encapsulation technology was, "...*of great relevance and importance to the PV industry."* It is noted that First Solar, the world's leading thin film PV company is a participant in this project.

Project Title: **Advanced industry viable thin film module architecture suitable for fifty Year life with reduced costs and significantly improved manufacturability**

Specific FOA Topic Area	Topic 3, Improving module reliability and manufacturability
Lead Organization	Colorado State University (CSU), Next Generation PV Center (NGPV), CSU Site
Technical Point of Contact	Kurt L. Barth Associate Site Director, NGPV Kurt.barth@colostate.edu O: 970-491-8314, M: 970-217-9434
Business Point of Contact:	Jennifer Strange Senior Research Administrator jennifer.strange@colostate.edu O: 970-491-2083

Project Team

Lead Organization

CSU Next Generation PV Center	Principal Investigator:	Kurt L. Barth
	Co-Principal Investigator	W. S. Sampath

Team members Organizations

NREL/ Reliability & Systems Engineering Group

US Photovoltaic Manufacturing Consortium (PVMC)

First Solar Inc.

I. Project Description

1.1 Project Overview: The outcome of this program will be a thin film module architecture capable of providing 50 year field life. A prototype manufacturing process to fabricate this new module architecture will be demonstrated that reduces process cycle time from 13.5 minutes (currently in industry) to 30 seconds. Associated hardware for manufacturing will be demonstrated which will enable fabrication and strenuous accelerated stress testing of 120 x 60 cm modules to demonstrate the 50 year life capability of the package. This low cost manufacturing method will increase throughput and materials efficiency while significantly decreasing capital costs, factory footprint and materials costs. The new architecture and associated manufacturing technology will enable lower cost thin film modules with higher reliability and durability needed to achieve the SunShot goals of 3 cents/kWh.

1.2 Requirements for achieving SunShot goals: A recent detailed analysis was performed by DOE and NREL [1] that identified technologies needed to achieve the SunShot goals. Two key reductions are identified: reduce module costs and improve module reliably and lifetime. Module reliability improvements are needed to reduce degradation to 0.2%/yr and an increase in module lifetime to 50 years is mandatory to achieve the long term goal of 3 cents / kWh[1] For thin film CdTe, the materials costs for the "back end" (post semiconductor processing) are the highest single cost category for CdTe fabrication. These exceed by over 2x the cost of materials for the semiconductor device absorber. The materials costs for the module lamination dominate this high category. The capital equipment costs for the back end (of which the expensive slow lamination equipment is a significant contributor) are exceeded only by the specialized semiconductor fabrication hardware.

1.3 Need for improved module architecture: The current thin film technologies are generally warranted for lifetime and reliability for only 25 years. A typical warranty is 97% rated power in the first year, and 0.7%/year degradation through 25 years.[2] Two NREL studies have reported the degradation rates of fielded thin film installations at ~1%/year for thin film modules. The CdTe results were between ~0.5%/yr to ~1.8%/year.[3,4] Recent CIGS and a-Si rates were higher. Although the industry has made significant strides to improve reliability and warranted lifetime, these results are far short of the 0.2%/yr and 50 year life needed to achieve the SunShot goals.

The leading thin film producer in the world, the US based First Solar Inc., has had reliability issues and has over $200 million in warranty expenses in late 2011 and 2012[5,6] It is noted that First Solar is the most advanced and successful of the thin film PV manufacturers in the world, further highlighting the significant issues that module reliability has for all producers. Since thin film PV technologies are the cost leaders and are demonstrating module reliability issues, without significantly improved module reliability, the DOE cost goals will not be achieved. New module designs are critically needed for thin film PV.

1.4 Metrics: Moisture performance and UV radiation and edge seals: The main factor determining PV operational life is the encapsulation material.[7] Most PV technologies are sensitive to moisture and thin film materials are especially sensitive to corrosion from water vapor.[8] Thin film modules deployed in hot, humid, and maritime climates show greater field degradation than in other areas due to fill factor decrease attributed to moisture ingress.[3] The ability for the module architecture to withstand UV radiation without degrading the encapsulation is a key requirement for 50 year life. UV degrades the commonly available hydrocarbon based encapsulations materials used in PV modules.[9] UV radiation has sufficient energy to cleave C–C bond[10] which causes embrittlement and delamination. Encapsulation embrittlement can result in module mechanical failures, while delamination will result in moisture ingress and subsequent failure in the module.

It is noted that silicones, which do not have the C-C bond structure, are not susceptible to UV degradation.[11]

The most common thin film package designs are glass / glass laminates with edge seals. The glass is effectively impenetrable to moisture and not impacted by UV radiation. The lamination materials have fairly high moisture vapor transmission rates [8]. To overcome the moisture ingress along the edge, thin film modules typically use a polyisobutylene (PIB) edge seal [8] which has a significantly lower moisture vapor transmission rate than the lamination materials. The PIB provides moisture control as long as good adhesion is maintained with the glass. However, delamination was seen for specific edge seals subjected to thermal/humidity tests; mechanical and UV debonding present an additional failure mechanism. [8]. The PIB materials have C-C bonds and are susceptible to UV degradation. NREL experts have seen compromised edge seals in fielded modules [8]. So, a key aim of this study is to demonstrate moisture ingress and UV resistance in the package suitable for 50 year life.

1.5 Manufacturing Limitations: In addition to the moisture performance deficiencies with the current thin film module architectures, there are significant manufacturing limitations. All common commercially available (thin film and c-Si) modules are laminated and cross-linked, many using EVA for the lamination film. Lamination and cross-linking is a time consuming, batch type manufacturing process with a cycle time of greater than 13 minutes for advanced films. In order to maintain production throughput, large vacuum laminators are required. Additionally, batching and queuing of modules in the factory is needed to maintain production flow. Laminators for high volume production have high capital costs and very large factory footprints.

1.6 New Architecture to address limitations: In partnership with SunShot and after significant industrial experience, a pathway for high reliability module architecture was developed [12] which holds promise for 50 year life with improved cap-ex and materials costs. However, significant research is needed to advance this concept to an industrially relevant technology that can enter the market within 5 years. This novel module architecture and encapsulation technology addresses the critical needs of the PV industry. The technology has significant benefits including:

Extreme robustness to moisture degradation (approx. 4x better than current methods)
Excellent adhesion even with UV light exposure
Process cycle time for each manufacturing step is less than 30 seconds
Small manufacturing tool footprint (approx. 20x smaller than current methods)
Increased mechanical strength (~2x)
Increased tolerance to glass temper distortion
Reduced manufacturing cost
Reduced capital costs

This new architecture is extremely robust to moisture ingress and utilizes a specialized two part edge seal incorporating high strength, UV tolerant silicone and low moisture vapor transmission polymers in conjunction with a separate desiccant material as shown in Figure 1. The modules are fabricated without lamination, vacuum pressing or module heating. The encapsulation sealants are dispensed through hot melt injection. Each of the components is applied in under 30 sec cycle time using tooling derived from production processes used in other industries. This significantly streamlines the manufacturing process, enabling small foot print tools to be located in-line with other module finishing steps avoiding the batching of traditional lamination.

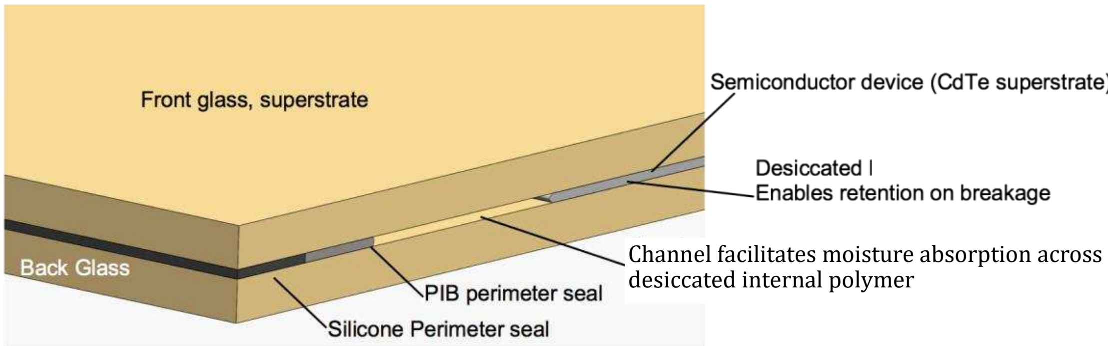

Figure 1: Schematic of the new module architecture with channels for moisture absorption

1.7 Proposed effort and Barriers: Four key objectives will be accomplished under this program:
A. Optimization of polymer materials formulations to fulfill 50 year life with improved cost and manufacturability. The specific formulation of the acrylate internal structure will need to be optimized for performance, adhesion and polymer application.

1. Investigate nozzle for polymer dispensing
2. Ensure integrity of internal pattern geometry and that polymer bridges both substrates
3. Determine optimal process conditions for dispensing 9 mm edge seal

B. Development of prototype processes and fabrication tools for module encapsulation with the new architecture. Perform computational fluid dynamic simulation for tool nozzle development and model the edge seal configurations and desiccant requirements

1. Viscosity with temperature and impact of reheating (stop and start)
2. Impact of desiccation additives in viscosity and flow characteristics
3. Optimize nozzle design

C. Coupon fabrication, moisture, UV, adhesion and other durability testing

1. Design and construct small scale experimental tool
2. Evaluate nozzle configurations and confirm CFD models
3. Numerically simulate moisture ingress and adhesion performance for 50 year life
4. Fabricate samples and subject to accelerated tests, moisture ingress studies and heavily accelerated UV exposure.

D. Fabricate modules, subject to accelerated durability tests, demonstrate industrial suitability

1. Fabricate full 120x60 cm modules
2. Pass IEC encapsulation tests including 4x damp heat. Demonstrate adhesion and performance with 50 year equivalent UV dose and combined UV / damp heat tests.
3. Demonstrate tool / process capabilities for industrial usage

1.8 Comment on funding: The PVRD program is ideally suited for this development. This technology is sufficiently advanced that it is not suitable for basic research, NSF type funding. However, the key objectives described above need to be completed and the key reliability and cost metrics demonstrated before a company such as First Solar would be comfortable commercializing a product based on this new architecture. The PI has discussed with companies (First Solar, Stion, Calyxo US, and PPG) and they have all expressed interest in the technology but require the proposed research to evaluate the suitability prior to industrial implementation.

2. Team Description

2.1 Current status: A prototype version of module architecture has been developed and tested. The initial version of this design has passed IEC 61646 and UL 1703 certification tests on 120 x 60 cm modules. Modules have passed 4500+ hrs. of the rigorous 85 C / 85% relative humidity "damp heat test". This is 4.5 times the duration required by the certification standards. The prototype development resulted in the filing of two US patents [13], both pending, and was placed into production by Abound Solar. Over 1 million modules were produced. Subsequent development to advance the design beyond the Abound configuration was completed under DOE SunShot support. The program proposed here will demonstrate the suitability of this improved architecture for industrial application and 50 year module life. An initial materials cost model was developed for both a laminate module (with traditional edge seal) and the new module design. Materials cost numbers were provided from the materials vendors for ~100-200 MW/year production volume. These are what a sophisticated manufacturer could be expected to negotiate. The current estimates show an approximately $0.02/Wp reduction in overall module materials costs [12]. It is noted that this is only the materials cost savings, and does not take into account the significant reduction in capital equipment costs, improved manufacturing efficiencies reduced manufacturing plant footprint, and, most significantly, the increased reliability.

2.2 Team Qualifications: This program will be conducted by CSU's Next Generation PV Center. The NGPV is a NSF supported Industry/University Cooperative Research consortium performing cutting edge research in partnership with the PV industry, including First Solar. Now in its sixth year, the Center was founded by CSU and includes Texas A&M and Univ. of Texas at Austin: photovoltaics.colostate.edu. The NGPV's focus is the increased use of solar and reducing PV LCOE. For 15 years, this team has been at the forefront of CdTe reliability research.

The PI, Barth, is the Assoc. Director of CSU's NGPV site and has over 20 years of experience in thin film PV reliability, materials science and R&D. Barth brings significant strategic leadership experience. As founder/Board member and VP of Product Devel. of Abound Solar, a CdTe PV manufacturer, he drove the module product from conceptualization through deployment and achieved IEC and UL certifications in one of the shortest times in the industry. Barth is a member of Task Group 8, Int. PV Module QA Task Force.

Prof. W. S. Sampath is co-PI. In the past two decades, Dr. Sampath and his colleagues have persistently investigated and eliminated obstacles to the mass production of CdTe PV. His research has resulted in a continuous, inline, scalable manufacturing process significantly lowering manufacturing costs. Prof Sampath initiated and directs the NSF NGPV at CSU. He brings over 30 years of materials science expertise which will directly aid this research.

The CSU team is joined by NREL's Reliability Group, the world's leading resource on PV reliability. The group is headed by Dr Sarah Kurtz and is working to facilitate the growth of the PV industry through improved understanding of the performance and reliability. She has been recognized with a jointly received Dan David Prize in 2007 and the Cherry Award in 2012. Dr. John Wohlgemuth is responsible for establishing and conducting research programs to improve the reliability and safety of PV modules at NREL. He worked at Solarex/BP Solar for more than 30 years. He has been an active member of working group 2 (WG2), within TC-82, the IEC Technical Committee since 1986 and convenor of the group for more than 15 years. Wohlgemuth is a member of the Steering Committee for the PV Module QA Task Force (PVQAT) and he chairs Task Group 3 on Humidity, Temperature, and Voltage. Dr. Michael Kempe is a Senior Scientist in NREL's PV Module Reliability Group, where he studies the factors affecting the longevity of photovoltaic cells and modules with an emphasis on moisture ingress. Kempe has a Ph.D. in Chem.

Engineering from CA Institute of Tech and been conducting photovoltaic research for decades at NREL.

First Solar is a key participant in this project. First Solar is a leading PV manufacturer and the dominant producer of thin film PV, and a member of the NGPV and an ongoing collaborator. They provide leadership for ensuring industrial relevance and a pathway for utilization / commercialization. They have expressed interest in the technology in writing.

SEMATECH PVMC is an industry-led consortium for cooperative R&D among industry, university, and government partners to accelerate the development, commercialization, manufacturing, field testing, and deployment of next-generation PV. PVMC brings a broad industry perspective with testing capabilities. Scott McWilliams will head the PVMC effort. He worked for both First Solar and Heliovolt (CIGS PV). As Director of Technology for SEMATECH-PVMC, his broad based knowledge of the PV industry's reliability requirements and his experience with the major stakeholders in the thin film PV value chain are key for developing a cost effective encapsulation technology that is will be adopted for the industry.

2.3. This research will be conducted primarily at the NGPV at CSU, which has significant infrastructure, resources, and personnel to drive these activities. The NGPV at CSU has 8,000 sq. ft. of lab space plus offices, and houses a research license for ANSYS Fluent which runs on two enterprise level server computers of NGPV. This combination enables simulations that can have more than 100 million elements even in radiation heat transfer. The NGPV has considerable experience in large scale involving complex physics. Thus, it is possible to accurately simulate the polymer application and the moisture ingress processes. In addition, CSU has access to advanced materials selection software (CES Selector) that would allow the selection of the best possible material for the proposed design and also provide accurate data for the simulation. CSU also has facilities for fabricating 3.5x3 inch CdTe PV devices for testing.

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Appendix III Pictures of the Abound Solar Modules and Manufacturing Systems

Figure AIII.1 Photograph of the front side of an Abound Solar production module

Figure AIII.2: Photograph of the back side of an Abound Solar production module. The internal desiccated polymer strips and edge seal are seen.

Figure AIII.3: Photograph of the high throughput encapsulation fabrication tools at Abound Solar's Longmont Colorado facility. These automated manufacturing systems could process one module in under 30 seconds.

Figure AIII.4: Photograph at the end of the manufacturing line showing crated modules awaiting shipment.