Phase 1 Final Report

This STTR project was originally presented in the context of a response to a SBIR solicitation for BOS cost reducing innovations and concept development. It was redirected by NREL personnel at an early stage to focus specifically on the development of a glazed polymer solar collector for use in freeze prone climates. One of the goals of the proposed work is that the collector should wholesale at 50% of the cost of a conventional copper/glass collector. According to various manufacturers’ price list, the price for conventional 4’X10’ glazed collectors, for use with a drainback or glycol system, is in the $500 to $1,000 price range. It is this project’s goal to produce a glazed polymer solar collector to be used with closed loop, drainback systems. It will be suitable for use in freeze prone climates, having a wholesale price of $250 or less and providing a 40% mark up for the manufacturer above the direct cost of goods sold.

One such polymer collector, the Solarnor PPO collector, was identified on the market. It is manufactured in Norway and no distribution was identified for the US market and an email request for quotation on cost per panel was not responded to. In addition, while there are several unglazed pool collectors on the market, we considered using these absorbers and focusing on the task of minimizing stagnation however, the initial cost of the pool collectors was outside the target costs for the absorber necessary to achieve the goal.

There were four challenges which were identified and addressed in the process of determining the feasibility of producing a novel polymer solar collector with a first cost of goods sold at $178 or less.

System Design

The system design was critical because there were several freeze tolerant systems with widely differing physical and hydraulic characteristics. The candidate systems broadly fell into the following categories:

Draindown-While this style has the benefit of not requiring an additional thermal fluid tank and heat exchanger, the extensive history of drain-down valve failure resulting in catastrophic system failures caused this style to fall from consideration. Additionally, accommodation of the street water pressure would have required a level of development for the polymer absorber which would have been beyond the scope of this project to develop a prototype with available phase two funding.
Closed loop glycol—While this remains a popular option with many engineers for commercial installations it requires a more sophisticated level of technical skill than most installation contractors can demonstrate on a consistent basis. The challenges of system integrity, thermal fluid charging, air purging, double wall heat exchangers, thermal fluid degradation, and compatibility of glycol with candidate polymer materials all conspired to remove this design from consideration.

Thermo-siphon—These systems are manufactured under various patents and were not considered due to the complex production issues necessary to interface the collector and thermal transfer tank. Since some type of thermal transfer fluid which is able to withstand subzero temperatures must be used many of the same issues confronting closed loop glycol systems were considered too difficult to overcome and achieve the desired cost target.

Drainback—Previously identified by NREL as the most reliable design to achieve the cost reduction objective and maintain a high level of reliability for the owner over the life of the system. This is the system selected for this program.
Material selection

Materials Selection:
Selection Process - Step 1:
A polymer materials chart obtained from North Carolina Solar Center was used as a reference starting point in the selection of materials for the solar panel components.

In Step 2 of the materials selection process, the materials outlined in Table 2.1.3 1x were judged on their ability to meet the specific performance requirements of the individual solar cell components.

Glazing:
Selection Process - Step 2
The primary requirements for glazing considered in Step 2 of the material selection process were:

1. Resistance to embrittlement after prolonged exposure to sunlight and outdoor conditions of moisture and heat.
2. Resistance to softening at predicted operating and stagnation temperatures
3. Transmisivity to solar radiation after prolonged exposure to elevated temperature and outdoor conditions.
4. Availability in sheet, film, or profile form

The materials lightly highlighted in Table 2.1.3 1x represent those materials that met the glazing material requirements outlined above, namely acrylic (polymethylmethacrylate), and polycarbonate (with suitable UV absorbent coating or laminated top layer).

ABS, acetal, CPVC (chlorinated polyvinylchloride), FEP (fluorinated ethylene propylene), high temperature nylon, nylon 6/6 extruded, PEX (cross-linked polyethylene), polybutylene, polyphenylene ether, polyphenylene oxide, polyphenylene sulfide, polyphthalamide, polypropylene, polysulfone, polyurethane, PVDF (polyvinylidene fluoride), and UHMWPE (ultra high molecular weight polyethylene) were eliminated primarily on the basis of their inherent lack of transmisivity.

PET (polyethylene terephthalate) was eliminated on the basis of its poor weatherability.
Polystyrene was eliminated on the basis of its poor weatherability and lack of high temperature rigidity.

PVC (polyvinylchloride) also lacked elevated temperature rigidity.
Selection Process - Step 3
The primary evaluation criteria for the materials in Step 3 were:

1. Availability in the appropriate physical form
2. Cost
3. Durability

Both polycarbonate and acrylic are available in sheet form for use in glazing in applications such as greenhouses and skylights. Sheet forms of these materials are readily thermoformable. Polycarbonate is also available a twin wall sheet displaying improved rigidity as compared to conventional polycarbonate of the same weight per foot.

The price structure for acrylic and polycarbonate is similar. Refer to Table 2.1.3 - 2x. Unlike acrylic, polycarbonate sheet requires a UV resistant surface coating such as urethane, lamination with a UV resistant layer such as Corad™ (a form of acrylic) or copolymerization with siloxane to improve weatherability. This requirement drives its price to slightly higher than that of acrylic, but still economically viable for the application.

Despite a slightly lower transmissivity, polycarbonate was ultimately selected over acrylic for the glazing component because of its inherent toughness. Polycarbonate as the additional advantage of being available not only as a potentially thermoformable sheet stock material in varying thickness but also it is commercially available as an architectural twin sheet glazing under brands including THERMOCLEAR™ and Polygal®.

Absorber
Selection Process - Step 2
The primary requirements for the absorber considered in Step 2 of the material selection process were:

1. Resistance to degradation after prolonged exposure to elevated temperature water and dry stagnation conditions.
2. Resistance to softening at predicted operating and stagnation temperatures.

Materials that met the absorber requirements outlined above are darkly highlighted in Table 2.1.3 1x, namely CPVC (chlorinated polyvinylchloride), FEP (fluorinated ethylene propylene), PEX (cross-linked polyethylene), polybutylene, polyphenylene ether, polyphenylene oxide, polyethylene sulfide, polyphthalamide, polypropylene, polysulfone, PVDF (polyvinylidene fluoride), and UHMWPE (ultra high molecular weight polyethylene).

Polystyrene and PVC lacked the required elevated temperature stiffness.
ABS, acetal, acrylic (polymethylmethacrylate), high temperature nylon, nylon 6/6 extruded, PET (polyethylene terephthalate), polycarbonate, and polyurethane were eliminated on the basis of poor resistance to prolonged exposure in high temperature water.

Absorber:
Selection Process - Step 3
Key criteria:
1. Cost
2. Compatibility with the Twin-sheet thermoforming process
3. Thermal conductivity
4. Heat absorbance
5. Commercial availability in large sheet form
6. Fabrication adaptability

The estimated cost of the materials commercially available in sheet form is listed in Table 2.1.3 - 2x. The materials in Table 2.1.3 2x that remained in contention after cost and fabrication adaptability were taken into consideration are variants of polyphenylene ether, polyphenylene oxide and polypropylene. (Note: polyphenylene ether and polyphenylene oxide are essentially the same material. In practice, both are used as alloys with impact modified polystyrene for improvement of processing.)

The Twin Sheet thermoforming process was selected for forming the absorber component. This process requires a comparatively low initial investment in tooling, product modifications are easily accommodated, and the piece price is reasonable. Materials for this process must a) be available in large sheet form, b) be manageable by the process (i.e.: have good melt strength for control of the heat softened sheet, and reasonably broad softening range to accommodate the pressure welding process).

Polyphenylene ether/polyphenylene oxide: These materials are virtually identical chemically. They are typically alloyed with impact modified polystyrene to improve their melt process ability and are most commonly available under the trade name Noryl® from GE Plastics. The Noryl® family PPO/PPE alloys display good resistance to heat and elevated temperature water. There are grades available with reasonable weather resistance. At least one solar collector supplier is currently using a Noryl® collector in their product (Solarnor).

Polypropylene: Through alloying, copolymerizing with polyethylene, and the introduction of additives and reinforcements, a vast array of characteristics can be achieved in polypropylene based materials. With twin-sheet thermoforming in mind for the method of fabricating the collector, availability in sheet form was a necessary prerequisite in considering a polypropylene material. The thermal and UV stability of
polypropylene can be greatly enhanced through the addition of heat and light stabilizers. As evidence of its potential in solar collector applications, polypropylene is currently being used in at least two commercially available non-glazed collectors used in swimming pool applications with long advertised life expectancy (Fafco -30 years and EZHeat 20+ years).

The ultimately decision between Noryl PPE/PPO and polypropylene for the absorber came down to material cost. As shown in Figure Table 2.1.3 3x, the cost of polypropylene in approximately one quarter the price of Noryl at the same thickness of sheet. Assuming a predicted similar cost of twin sheet molding for the two materials, the lower cost of the polypropylene should translate to a significantly lower absorber fabrication cost. With reduced collector cost as a primary driving force, polypropylene was selected for the absorber material.

Fabrication technique

Twin sheet thermoforming:

Heavy Gauge Twin Sheet Forming
(http://www.plasticsmag.com/features.asp?fIssue=May/Jun-04)

The twin sheet process is generally used to form structural, hollow thermoformed parts.

Twin sheet forming is a process of vacuum and compression forming two sheets of plastic simultaneously with a separate mold on the top platen and a separate mold on the bottom platen. Once the plastic sheets have been vacuum formed, they remain in their respective molds. While both sheets still remain at their forming temperature, the two molds are brought together under high platen pressures and the two sheets are bonded together wherever the mold-designed knit areas dictate. This will result in one single product with hollow areas and no secondary bonding required. The twin sheet process creates 3-dimensional parts with formed features on both sides. The parts are typically very strong, rigid and lightweight. Application specific to the material type, material gauge and machine configuration, foreign components or hardware may be inserted into the interior of the part during the forming process. Some of the hardware being inserted into twin sheet products today is wood, aluminum, steel, and foams. More advanced applications are now inserting tracking devises, measuring devices and mechanical sub-assemblies.
Typical twin sheet applications include: pallets, industrial dunnage, portable toilets, medical housings, surfboards, fuel tanks, air/ventilation ducts, electrical enclosures, recreational boats, cases, toys, marine products, doors, tables, spine boards and numerous transportation-related products.

The differences between twin sheet forming versus blow molding or rotational molding are typically cost-related. Twin sheet forming is very competitive with blow molding and much faster than rotational molding, especially with large, thick gauge products.

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Twin Sheet Thermoforming Challenges:
1. Weld Integrity: Both sheets must be maintained at sufficient temperature for proper bonding upon contact. This is more of a challenge with polypropylene due to its semi-crystalline nature than for amorphous thermoplastics. The same sharp melting point that provides resistance to softening during collector stagnation requires that the sheet be maintained at a temperature that approaches its complete loss of melt strength. Experienced twin sheet thermoformers are accustomed to holding temperatures at the discrete tolerances required. The recent trend toward twin sheet thermoformed fuel tanks composed of multi-layer polyethylene lend credibility to the use of this process in forming closed polyolefin vessels. (http://www.plasticstechnology.com/articles/200501fa5.html)

2. Attachment of Pipe Fittings: It is anticipated that it will be necessary to affix to the twin sheet thermoformed absorber, separately injection molded pipe fittings with sufficient strength for attachment of connected piping. There is much precedent concerning the successful use of reinforced polypropylene for pipe fittings. Injection molded fittings using this material would be melt compatible with the main body of the twin sheet thermoformed absorber. It is anticipated the injection molded plumbing adaptor fittings will be spin welded to the thermoformed twin-sheet headers.
**Stagnation tolerance**

Under certain conditions, a solar collector can reach what is called stagnation temperature, the temperature at which heat gain from solar radiation equals the heat loss to the surroundings. The condition of specific concern is dry stagnation when there is no fluid being pumped through a solar collector while it is exposed to high solar radiation on a hot day. Traditional metal-glass collectors are able to withstand high stagnation temperatures, but polymer collectors are more sensitive to this extreme heat condition.

The exact stagnation temperature for each collector varies because of the differences in the geometry, materials, and ultimately the overall heat loss coefficient. While a selective surface absorber is ideal for increasing the energy collected, it also increases the stagnation temperature of the absorber by decreasing the overall heat loss coefficient. A Kearney et al. (2004) developed a model of stagnation conditions and calculated the stagnation temperature for an ambient temperature equal to 43°C and solar radiation equal to 1100 W/m². For a non-selective polymer collector, it was predicted to be 149°C.

The stagnation temperature is the zero efficiency point on the linear efficiency curves that use the Hottel-Whillier-Bliss equation. Collector efficiency is reported in FR(τα), the maximum efficiency of the collector, and FRU_L, the collector heat loss factor (W/m²·C). The FRU_L and FR(τα) values for several collectors are shown in Table 1. The metal-glass selective collector is from the SRCC values obtained for the Radco Model 408C-HP and the non-selective is the Radco410P-HP (these collectors were referenced in Burch et al. (2004) as their base case). The SRCC values for the Sealed Air glazed pool collector were also used in this paper. The Solarnor collector is commercially available in Europe and these values come from their product literature. The efficiency curves for all four of these are shown in Figure 1. The Solarnor PPO collector has a heat loss coefficient between that of the non-selective metal glass and the Sealed Air pool collector.
The stagnation temperature was predicted of these commercially available collectors under the same conditions used by Kearney et al (2004) and is shown in Table 1.

Table 1: Estimated stagnation temperature for solar radiation equal to 1100 W/m² and ambient temperature of 43°C (109.4°F)

<table>
<thead>
<tr>
<th>Collector Type</th>
<th>Metal Glass Selective</th>
<th>Metal Glass Non-Selective</th>
<th>Solanor Collector</th>
<th>Sealed Air</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fr(10)</td>
<td>0.770</td>
<td>0.768</td>
<td>0.770</td>
<td>0.739</td>
</tr>
<tr>
<td>FrUf</td>
<td>4.770</td>
<td>7.245</td>
<td>5.800</td>
<td>8.216</td>
</tr>
<tr>
<td>Stagnation Temperature (°C)</td>
<td>221</td>
<td>160</td>
<td>189</td>
<td>142</td>
</tr>
</tbody>
</table>

The Solanor collector is a commercially available PPO collector and has a predicted stagnation temperature of 189°C. While this analysis only applies to one extreme ambient condition, these collectors were also examined under typical meteorological conditions for several representative climates over a year to determine how many hours in a
year the collector would reach a range of temperatures if left to dry stagnate all the time.

Using the collector curves, the stagnation temperature under typical meteorological conditions can be estimated under certain assumptions. First, only steady state is considered, meaning that the thermal capacitance of the collector is not included. Also, the collector plate is at a constant temperature.

For this analysis, Typical Meteorological Year (TMY2) data from NREL was used. The TMY2 data provides hourly values for typical weather conditions for a one-year period for 239 stations in the United States. Four cities were chosen based on their differing climate zones (including non-freezing climates): Phoenix, AR; Raleigh, NC; Miami, FL, and Madison, WI. These data files provided the ambient outdoor temperature and the global horizontal solar radiation. TRNSYS, a transient system simulation program was used to determine the solar radiation for each location at the typical tilt for a solar collector. In all cases, the collector tilt was set equal to latitude.

The stagnation point temperature was calculated for each collector under the given ambient conditions. Again, this is only steady state estimation, and may not well represent actual fluctuations in ambient conditions on a given day. The number of hours at a given stagnation temperature range is shown for each city in Figures 2-5 (Note that the scale for number of hours is different for figure 2). These temperatures represent those associated with a non-operational system all year long, the worst case scenario. Under typical operation of a solar domestic hot water system, there will be hot water drawn from the storage tank which is replaced with cooler water. This water is pumped up to the collector and prevents the collector from reaching stagnation temperatures.
Figure 2: Predicted number of hours per year that collector in continuous stagnation would attain temperature range for Phoenix, AR.
Figure 3: Predicted number of hours per year that collector in continuous stagnation could attain given temperature range for Raleigh, NC.

Figure 4: Predicted number of hours per year that collector in continuous stagnation could attain given temperature range for Miami, FL.
Figure 5: Predicted number of hours per year that collector in continuous stagnation could attain temperature range for Madison, WI.

By examining the worst case circumstance of continuous stagnation, the team was able to get a reasonable idea of the number of hours that the polymer must be able to withstand the high temperature. For example, a Solarnor collector placed in Raleigh, NC under continuous stagnation could experience about 220 hours between 140°C-150°C, 120 hours between 150°C-160°C, and 10 hours above 160°C. This analysis needs to be extended to look at normal operation in a residential application and predict the absorber temperature.

Maximum Working Temperature Determination

The team considered two independent sets of polymer industry data to establish a maximum working temperature which provides adequate protection for the polymers used in the collector during stagnation. This analysis builds on the cumulative stagnation time data from the preceding charts.

Our dry stagnation exposure at SRCC is limited to 30 days above a specified insolation level. For purposes of setting the maximum working temperature for our collector, the team assumed a stagnation period of 90 days. We further assumed a maximum daily exposure time of 8 hours per day. The resulting specification for the period of stagnation thermal stress is thus 720 exposure hours.

Basell Inc, a polypropylene resin manufacturer with over 30 years lineage in polypropylene and 7 million metric ton polypropylene capacity has been providing polypropylene grades for various solar collector production applications for over 20 years. They responded to a request for elevated temperature exposure test results by providing data on one of their solar industry products as shown in the following tables.

<table>
<thead>
<tr>
<th>Physical Property Evaluation of SB572C Black after 150°C Heat Aging</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Table 1</strong></td>
</tr>
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</table>

<table>
<thead>
<tr>
<th>Hours</th>
<th>As Molded</th>
<th>Heat Aged</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0</td>
<td>400</td>
</tr>
<tr>
<td>Elongation at Yield (%)</td>
<td>13</td>
<td>12.16</td>
</tr>
<tr>
<td>Elongation at Break (%)</td>
<td>443</td>
<td>500</td>
</tr>
<tr>
<td>Tensile at Break (MPa) 22.1</td>
<td>21.73</td>
<td>22.14</td>
</tr>
</tbody>
</table>
Table 2

<table>
<thead>
<tr>
<th>TOTAL HOURS OF EXPOSURE</th>
<th>INDICATION OF CRACKING</th>
<th>INDICATION OF CRAZING</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hours</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>400</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>600</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>800</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>1000</td>
<td>No</td>
<td>No</td>
</tr>
</tbody>
</table>

Table 3

<table>
<thead>
<tr>
<th>SB572C Black: Notched Izod Impact (kJ/m²)</th>
<th>0</th>
<th>500</th>
<th>1000</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>62</td>
<td>40</td>
<td>35.48</td>
</tr>
</tbody>
</table>

*ISO 180

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Table 1 depicts the change in properties over time “as molded” and after exposure to 150°C (~300 °F) in a circulating air oven designed for accelerated aging. For the aged specimens, Tensile Strength (at Yield and Break) plateaued at 600 hours through the balance of the 1000 hours indicating retention of integrity. The pronounced reduction in Elongation accompanied by the drop in Notched Izod Impact Strength (Table 3) is thought to be due to a temperature induced increase in the crystallinity (annealing), and not thermal degradation. This is supported by the significant increase in Modulus and no apparent visual signs of cracking or crazing after 1000 hrs. (Table 2). The observed changes in mechanical characteristics will be compensated for through appropriate product design.

A second check of the durability of the material is the RTI (Relative Temperature Index) measure of a polymer. This fundamental quantification of material integrity under continuous thermal stress is
normally the result of UL testing which costs in excess of $40,000 to perform. The RTI is the temperature at which a polymer is projected to retain 50% of its various ASTM structural properties after 100,000 hours (the equivalent of 10 years continuous exposure) of exposure.

The RTI was also identified by Davidson (2004) while developing the ventilation affect on stagnation temperature model as a quantifiable maximum exposure temperature for material durability.

A RTI of 110 °C is readily achievable in polypropylene. Using the generalization that a material’s durability curve timeline is shortened approximately 50% for each 10 °C increase in temperature above the RTI point, it can be seen that the reduction of time to maintain material integrity at 150 °C is approximately 6000 hours; which is also in excess of our design threshold of 720 hours of dry stagnation.

Thus both the RTI and the Basell tests confirm the polypropylene material compatibility with a maximum design stagnation temperature of 150 °C for the defined period of 3 months continuous exposure. This temperature will now be the target for the development of the protective ventilation design.

While some polymers may be able to withstand the predicted temperatures, the polymer that was identified as meeting the cost requirements of a low-cost collector, namely polypropylene, looses much of its stiffness and dimensional stability above 140°C. Therefore, it is believed that some cooling of the collector would be necessary under stagnation conditions.

Two options have been identified as feasible ways to overcome stagnation: 1) Ventilation and 2) Transitional translucent glazing. Kearney et al (2004) examined the effectiveness of passive ventilation. For the theoretical collector examined in their work, ventilation between the absorber and the glazing will cool the non-selective collector to 123°C under the 1100 W/m² and 43°C. Again, a thermal simulation in a program like TRNSYS would beneficial to quantify the temperatures the collector would reach with an effective ventilation strategy and how many hours the absorber would reach the critical temperature range under normal operating conditions.
The transitional translucent glazing will be the subject of developmental work to be done using the thermocromatic gel under development at Sandia National Laboratories. The issues to be examined include the application method to stabilize the highly viscous liquid state material, the long term stability of the gel under varying conditions of humidity and temperature associated with the application and the correlation of the transmissivity transition point to the stagnation temperature of the absorber. Finally, the feasibility from a cost stand point of producing commercial quantities of the gel and process it into an applicable form for permanent positional stability under the influence of gravity on a glazing surface set at an angle normally associated with residential roof pitch will be examined.

It is not envisioned that the development work for the Sandia gel will result in a commercially viable alternative for insolation reduction on a collector during stagnation; however it will move the technology into a position where continued evaluation could result in such an application achieving that status.

Conclusion

In the opinion of the team performing the due diligence related to this phase one feasibility study, it appears that the development of a glazed solar collector fabricated from polymer materials which is able to withstand the thermal stress of stagnation and meet the cost of goods sold price point set forth as a goal; is feasible and realistic utilizing the protective mechanisms, materials and design features outlined above.