Solid Thermal Storage as an Energy Storage Device in Insulated Solar Electric Cookers: Thermal Modeling and Experiment

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Abstract
The use of solid thermal storage (STS) as an energy storage device in insulated solar electric cookers (ISEC) was explored using a thermal simulation before retrofitting an existing cooker without energy storage and testing it under several conditions. STS sizing, material selection, and geometry were examined from both theoretical and practical perspectives and re-examined following experimental results. Characterization of the system’s thermal interfaces and methods to improve their thermal conductivities were investigated resulting in several performance enhancements to the system.

Executive Summary
An ambitious goal was set to simulate STS’s performance in a thermal model and use the model to inform the design of an optimized ISEC containing STS once validated. Modeling was performed in SolidWorks using its Flow Simulation tool and results were compared with existing experimental data. Accurately modeling the thermal interface between the cookpot and the thermal storage proved challenging and, despite continued work to converge predictions with reality, simulation results varied significantly from experimental findings.

Although the model did match existing experimental results, it did provide a wealth of knowledge on the operating characteristics of the system and illuminated key factors in performance such as the STS-pot interface. This information helped inform choices in retrofitting the experimental ISEC and, for instance, raised our attention to the importance of the thermal impedances of the STS-pot and STS-heater interfaces.

Testing showed that, while STS is a viable means of energy storage, care must be taken when selecting STS size, mass, and geometry based on the specific operating conditions present and characteristics desired. In the case of the unit tested, a mass of 8 kg was selected assuming minimal thermal loss to the environment. Results indicated that thermal losses were significant and that a lighter STS on the order of 4-5 kg was more appropriate with improvements to the STS heater’s design and ISEC’s insulation identified.

Finally, efforts to characterize the STS-pot interface showed that performance could be improved significantly using surface treatments such as sanding or through the use of an interface material such as a silicone thermal pad. Following treatment, power delivery increased greatly and scaled with interface surface area.

STS demonstrated the ability to store energy well into the evening with a thermal “half-life” of 9 hours while providing an expedient means for cooking with little additional complexity. As such, future work exploring the use of STS in the field is warranted following the integration of these findings into a new or existing ISEC.
Introduction

Insulated Solar Electric Cookers (ISEC) are low-cost sustainable alternatives to harmful bio-mass cooking commonly used in developing countries \[^1\]. ISECs leverage insulation to trap heat and allow food to be cooked using low-wattage solar panels, reducing cost, and making the technology accessible in communities where it is most needed.

Through an international group of collaborators known as the SuperGroup, ISEC systems have been successfully manufactured and deployed in communities around the world with significant focus on utilizing local techniques and materials to streamline community adoption and minimize cost.

While initial adoption and use of the technology has been successful, widespread use of the technology has been stifled by limitations of the current direct-cook implementation, illustrated in Figure 1, which consists of an electric heating element (directly connected to an electricity source) and an insulated cookpot.

Because remote communities often lack access to an electric grid, solar panels are required to power the ISEC, limiting cooking to daylight hours. In addition, the typically used 100-Watt solar panel configuration lends to a “low-and-slow”, crockpot-style cooking experience, which can make cooking local fare that relies on frying, charring, or searing difficult.

Several groups are exploring energy storage technologies such as batteries and thermal storage in phase change materials (PCM) to improve these shortcomings. For example, Erythritol has been used as a PCM to store energy as heat that can be transferred directly to the food when it is time to cook \[^1\]. Battery storage is being developed by several groups, each with a unique twist. AMPERES, for example, teaches communities to recycle used batteries and assemble them into battery packs for energy storage \[^2\]. These technologies, however, come with their own shortcomings. Batteries, for example, are expensive and, like Erythritol, suffer degradation with sustained use. As such, alternative methods of energy storage are worth investigating with consideration to local pricing and availability of materials.

Solid thermal storage (STS) is one such alternative and describes the use of a large thermal mass, often a chunk of metal, to store heat for later use. Solid thermal storage is appealing because it is safe, relatively inexpensive, and can be retrofitted into existing direct-cook ISECs without major modification as shown in Figure 2. Additionally, unlike many storage solutions, the STS does not degrade with continued use and will likely outlast the service life of the ISEC itself. STS, however, is not without its drawbacks. Solid thermal storage is heavy, and its cooking performance is sensitive to the thermal conductivity between the cookpot and the storage device. This paper explores the use of STS in an existing direct-cook ISEC and attempts to characterize its performance over a variety of conditions through real-world experimentation and computer simulation.
**ISEC Thermal Simulation**

Prior to retrofitting an existing direct-cook ISEC with STS and characterizing its performance experimentally, a thermal model was developed to understand the operating characteristics of the system and inform the design of the retrofit ISEC. Thermal modeling was conducted in SolidWorks using its Flow Simulation tool with the model mimicking a previous experimental setup. By validating the model’s predictions against existing experimental data, the model could be used to investigate various ISEC configurations without the need to physically construct the unit. Once an optimized design was selected based on model predictions, the unit could be constructed with high confidence that its performance would match expectations.

Figure 3, below, shows a cut view of the simulated ISEC containing STS. Well insulated, the outside of the ISEC remained near room temperature with heat conducting up from the STS into the water above. Initially only considering conduction, convection and radiation were added to the simulation with fluid flow lines illustrated. While simulation predictions more closely resembled experimental results as the sophistication of the model increased, model predictions did not match experimental data. As time was a limiting factor on this project, it was decided to cease additional improvements to the model and focus on retrofitting an existing ISEC with STS to characterize its performance experimentally. While the simulation could not be relied on to predict experimental results, the model did provide a wealth of knowledge and understanding about the system. In particular, the importance of adequate ISEC insulation was highlighted as well as the challenge of thermal conductivity across both the STS-pot and STS-heater interfaces. Additionally, interacting with the model and observing its behavior also instilled a level of intuition about the operating principles of the ISEC that proved valuable. A more detailed summary of the thermal modeling process and its findings is available in the Appendix of this report.

*Figure 3: SolidWorks thermal model of retrofit ISEC containing solid thermal storage.*
Existing Direct-Cook ISEC

A big advantage to using STS is that it can be readily added to an existing direct-cook ISEC. As discussed previously, a direct-cook ISEC consists of an electric heating element, a cookpot, and an insulated chamber that retains heat. The heating element is typically connected to a 100-Watt solar panel which provides the necessary power.

As a baseline for testing, a direct-cook ISEC was retrofitted with STS. The ISEC, photographed in Figure 4, was constructed from a mid-size aluminum trashcan and lined with a generous layer of rock wool insulation. A cavity measuring roughly 6.75 inches in diameter and one foot in depth was constructed in the center of the bin and lined with thin aluminum sheeting, constraining the insulation, and allowing the cook pot to be easily inserted and removed from the ISEC.

A “pancake” style heating element composed of a nichrome wire, refractory cement, and aluminum sheeting, illustrated in Figure 5, was placed at the bottom of the cavity before the leads of the heating element were fed through the side of the trashcan and terminated with a banana plug.

![Figure 4: Top-Down view of a direct-cook ISEC. The “pancake” heater is visible at the bottom of the cook-pot cavity. Rock wool insulation surrounds the cavity and is secured within the trashcan using aluminum sheeting and fire blanket.](image)

![Figure 5: Diagram of “Pancake” style heater. A nichrome heating element (green) is wound into a loop and set in refractory cement before being sandwiched by two sheets of aluminum.](image)
Selection of Solid Thermal Storage

Before adding STS, the material and size of the solid thermal storage was considered. Material selection and sizing play key roles in determining the operating characteristics of the STS and are sensitive to a variety of factors such as input power, insulation performance, and availability. As they depend on each other, material selection and sizing must be determined in unison. With accessibility being a primary goal, material selection was constrained to only locally available materials.

Material Selection

A variety of materials can be used for solid thermal storage but metals with a high specific heat and density are suited to the application as they have the highest volumetric heat capacity, maximizing energy storage. A high thermal conductivity is also critical to power delivery while cooking. Of the handful of common metals, provided in Table 1 below, aluminum and copper are clear standouts with high volumetric heat capacities and thermal conductivities.

<table>
<thead>
<tr>
<th>Material</th>
<th>Specific Heat ( \frac{\text{J}}{\text{gram} \cdot \text{K}} ) [3]</th>
<th>Density ( \frac{\text{gram}}{\text{cm}^3} ) [3]</th>
<th>Thermal Conductivity ( \frac{\text{Watt}}{\text{m} \cdot \text{K}} ) [3]</th>
<th>Volumetric Specific Heat ( \frac{\text{J}}{\text{cm}^3 \cdot \text{K}} )</th>
<th>Cost per Kilogram [6][5]\</th>
<th>Energy Capacity Per Dollar ( \frac{\text{J}}{$ \cdot \text{K}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steel</td>
<td>0.47</td>
<td>7.8</td>
<td>43</td>
<td>3.67</td>
<td>$12.81</td>
<td>36.68</td>
</tr>
<tr>
<td>Iron</td>
<td>0.44</td>
<td>7.8</td>
<td>80</td>
<td>3.43</td>
<td>$14.13</td>
<td>31.14</td>
</tr>
<tr>
<td>Aluminum</td>
<td>0.9</td>
<td>2.7</td>
<td>235</td>
<td>2.43</td>
<td>$25.17</td>
<td>35.75</td>
</tr>
<tr>
<td>Nickel</td>
<td>0.44</td>
<td>8.91</td>
<td>91</td>
<td>3.93</td>
<td>$233.19</td>
<td>1.89</td>
</tr>
<tr>
<td>Copper</td>
<td>0.38</td>
<td>8.92</td>
<td>400</td>
<td>3.39</td>
<td>$44.95</td>
<td>8.45</td>
</tr>
<tr>
<td>Lead</td>
<td>0.13</td>
<td>11.34</td>
<td>35</td>
<td>1.47</td>
<td>$12.27</td>
<td>10.59</td>
</tr>
</tbody>
</table>

Table 1: Material Properties of Common Metals

With a higher volumetric heat capacity and thermal conductivity, copper is the clear choice from a performance perspective. Copper, however, is highly sought after and would make STS extremely expensive. In addition, when exposed to the atmosphere, copper produces a thin layer of greenish blue corrosion product, known as patina, which could affect STS performance \[6\].

Aluminum, on the other hand, is relatively inexpensive and stands out for its high thermal conductivity and relatively high volumetric heat capacity. Equipped with a naturally forming, corrosion resistant, oxide layer, aluminum is suitable for long-term use in rural environments \[6\]. Conveniently, aluminum is also produced in reasonable quantities along the West Coast of Africa, particularly in Guinea, Ghana, and Cameroon \[7\]. Local accessibility to the raw materials not only drives down cost for end users, but also supports their communities at large. For these reasons, aluminum was selected as the STS material for this experiment.

Steel and iron are also attractive due to low cost and high volumetric heat capacity. Unfortunately, their thermal conductivity is relatively low compared to copper and aluminum.
Sizing

Sizing is the next step in the STS selection process and is divided into two steps. The first step is to determine the mass of the STS, which depends on its desired operating temperature, storage capacity, and cost. The second, while rather straightforward, is to determine the appropriate dimensions for the application given the mass and other constraints such as ISEC size and shape.

To inform the mass selection of the STS, it was assumed that an STS user would have access to a 100-Watt solar panel and would begin the day by cooking a breakfast, brunch, or lunch by direct-cook. With cooking complete, the rest of the day’s energy would be stored in the STS for cooking in the early evening or just after nightfall. This leaves roughly half of the days’ worth, around four hours, of sunlight to heat the STS to its final temperature before being ready to cook.

The total energy available for storage by the STS can be found via Equation 1 by multiplying the input power by the heating duration.

\[
E_{total} = P_{input} \times Duration
\]

\[
E_{total} = 100 \, W \times (4 \, hours) = 0.4 \, kWh
\]

For a given mass and starting temperature, the initial temperature of the STS after soaking up a day’s worth of energy, \(E_{total}\), can be estimated by Equation 2 where \(c\) is the specific heat of the material selected. In this case, 0.9 \(\frac{J}{gram \cdot K}\).

\[
T_{initial} = T_{start} + \frac{E_{total}}{mass \times c}
\]

Plotting Equation 2 over a range of STS masses yields Figure 6, below.

Because boiling water is critical, particularly in developing countries where access to clean water can be challenging, it is important that we consider the amount of water we can boil. Water boils at 100°C under standard conditions. Since STS relies on a temperature gradient to deliver heat, the STS must be above 100°C while boiling the water, making the energy stored below 100°C unavailable for use.
The amount of useable energy, $E_{\text{available}}$, in an STS device, can be estimated as the heat lost by going from its initial, post-heating, temperature to the desired temperature of the thermal load, food in most cases.

$$E_{\text{available}} = (T_{\text{initial}} - T_{\text{desired}}) \times \text{mass} \times c$$

Contours for desired food temperatures of 50°C, 75°C, and 100°C in Figure 7 illustrate that as the desired temperature of the food cooked with the STS increases, the amount of usable energy decreases. As the mass of the STS increases, more energy is “used up” keeping the STS at the heat transfer threshold, $T_{\text{desired}}$. Although heat has still been stored within the STS, the heat is unable to be utilized due to the lack of a temperature gradient between the STS and the heat sink.

Figure 6: Final STS temperature after 4 hours of heating at 100 W over a range of STS masses.
Figure 7: Useable energy stored in STS at various target temperatures for food (50, 75, and 100°C).

This points heavily towards using the lightest STS feasible, as the most energy would be available for use at a variety of threshold temperatures. While this is certainly the case under perfect conditions, real world conditions bring a variety of considerations to the table. As demonstrated in Figure 6, lowering the mass of the STS increases its peak operating temperature significantly. This puts additional strain on the ISEC’s internal components and increases the heat loss through the insulation meaning that more of the heat that is stored will be lost prior to cooking when compared to an STS at a lower operating temperature.

Striking a balance is difficult in this case and is up to the user to decide what is best for their application. As a baseline, an STS in the 4-to-6-kilogram range seems to be a reasonable tradeoff between operating temperature and free energy capacity. Keeping the STS lighter also reduces material cost, which is important for the success of STS ISECs in the field. In an interest to lower operating temperatures, we chose an 8 kg STS for the retrofitting. This decision would prove to be unwise, however, as will be discussed.

The ISEC’s pre-existing cavity was roughly 6.5 inches in diameter, leading to the selection of aluminum 6061 round stock 6.5 inches in diameter and 5.4 inches long. This maximized the STS-pot contact area while leaving room for the thermocouples to maneuver along the sides of the STS while inside the ISEC.


**STS Retrofitting**

As discussed earlier, a number of direct-cook ISECs have been distributed in communities around the world, making the addition of solid thermal storage appealing. Approaching STS from this point of view, an existing ISEC was retrofit with the selected 8kg STS.

Before retrofitting the ISEC, the STS was modified by adding two type-K thermocouples, photographed in Figure 8. During installation, holes, roughly 1 inch in depth, were drilled into the STS at each end perpendicular to the STS-pot interface. The holes were filled with boron nitride based thermal paste from Slice Engineering prior to inserting the type-K thermocouple. Structural JB Weld was used to secure the thermocouple and prevent thermal paste from escaping the cavity. The temperature difference across the STS, under an input power of 100 W can be calculated by eq 4:

\[
\Delta T = \frac{P_{input} \cdot H_{STS}}{A_{STS} \cdot K_{Al}} \quad (4)
\]

\[
\Delta T = \frac{(100 \text{ W}) \cdot (0.13 \text{ m})}{(0.214 \text{ m}^2) \cdot (235 \text{ W/m K})} = 0.22^\circ C
\]

where \(H_{STS}\) is the height of the STS in meters, \(A_{STS}\) is the surface area of the STS-heater thermal interface, and \(K_{Al}\) is the thermal conductivity of aluminum. This indicates that the STS should behave as an isotherm, although a larger temperature difference is expected during cooking due to the higher heat flux out of the STS.

After letting the epoxy cure, the STS was placed into the ISEC cavity directly on top of the pre-existing direct-cook pancake heater; allowing the STS to be removed if direct-cook was desired.

Figure 9 shows the final configuration of the ISEC after retrofitting. The STS fit securely in the pre-existing ISEC cavity while leaving ample room to maneuver the thermocouple leads.

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*Figure 8: Installation of type-K thermocouples into STS*

*Figure 9: Preparing retrofitted ISEC for testing.*
STS Thermal Cycling Test Results

The first test was to run the STS through a heating and cooling cycle. The pancake heater was connected to a benchtop power supply to provide a fixed power input of 79 W, which was the max output power of the supply before getting current limited. The temperature of the STS was monitored with a Gain Express 4-Channel Datalogger.

Heating and cooling curves are illustrated in Figure 10 below. The STS was heated to a target temperature of 200°C based on predictions made in Figure 6 about the final temperature of the STS after four hours of heating at 100-Watts. The process spanned approximately 24 hours with the first few hours of heating not being recorded due to operator error. Lost data was recollected under similar conditions and included on Figure 10 below as supplemental data to illustrate the full extent of the heating curve. Despite this loss of data, a number of key discoveries were made by analyzing each regime of operation.

Figure 10: Heating and cooling curve for aluminum STS in retrofit direct-cook ISEC (no load applied).
**STS Cooling**

For STS to be viable, the ISEC must insulate the STS well enough to enable cooking for several hours after sunset. After heating the STS to 200°C, power was removed from the pancake heater to simulate night-time conditions. With no input power, the temperature of the STS dropped as heat slowly leaked into the environment, cooling it over the course of the night. After two hours of cooling, illustrated in Figure 11 below, the STS was still quite hot at 180°C and would certainly be able to boil a liter of water or cook food. The next morning, the ISEC was still well above room temperature. This means that, after initial usage, subsequent uses of STS may require significantly less time to reach a suitable temperature for cooking.

![STS Cooling (Input Power = 0 Watts)](image)

*Figure 11: Temperature and heat loss of STS within ISEC when STS is not being heated.*

Heat flux to the environment was calculated by taking the derivative of the STS temperature. STS heat lost to the environment was proportional to the temperature gradient between the STS and ambient as predicted by Equation 4. During this trial, the STS exhibited environmental heat losses of approximately 0.15 Watts per degree Celsius difference in temperature between the STS and its surroundings. This aligns with previous testing done on a different, better insulated, ISEC which was measured at approximately 0.1 Watts per degree Celsius.\(^1\)
STS Heating

Zooming into the heating portion of the curve in Figure 10, a temperature plateau is visible, indicating increased heat loss as the STS got hotter. For comparison, an ideal STS temperature was calculated using Equation 2 assuming that all the heat output by the pancake heater was absorbed by the STS (79 Watts). While not realistic, this line represents the absolute best performance of the system and serves as a benchmark for comparison, illustrated in Figure 12.

Comparing the ideal and measured temperatures, significant losses were clearly occurring somewhere in the ISEC. To better understand the discrepancy, a polynomial fit was applied to both curves before taking the derivative, resulting in the Heater Output Power and Net Heat Flux into STS, plotted in Figure 13, below. Utilizing STS behavior captured during cooling between 200°C and 70°C in Figure 10, the Heat Flux from STS to Environment was estimated, allowing the Heat Flux to STS from Heater to be determined via Equation 5, below.

\[
P_{\text{Heater to STS}} = P_{\text{Net STS}} - P_{\text{STS to Environment}}
\] (5)
As the STS increased in temperature, more heat was lost to the environment, as predicted by Equation 4, since the temperature gradient between the STS and the environment increased. This resulted in a decrease in the net heat flux into the STS as it approached 200°C. At 100°C, approximately 60% of the heater’s output power was stored as heat in the STS, decreasing to 30% at 200°C.

Throughout the entire trial, the heat flux to the STS from the heater (~ 60 Watts) deviated from the heater output (~80 Watts) by approximately 20 Watts. Although difficult to determine the source of the discrepancy without additional testing, heat flux calculations producing Figure 13 neglected the thermal mass of the ISEC’s insulation and internal aluminum sleeve. Weighing the two components after the eventual deconstruction of the ISEC showed that they contributed roughly 500 grams of additional aluminum and 75 grams of refractory cement which is a non-negligible yet small thermal mass relative to the thermal mass of the STS.
STS-Heater Interface

To investigate the heat loss encountered during heating, an additional thermocouple was adhered to the bottom of the pancake heater, opposite the solid thermal storage, using structural JB weld as photographed in Figure 14. After curing overnight, the STS was reinstalled in the ISEC, and data collection began.

Since the STS had been tested successfully several times, the device was left unattended for several hours to reach a target temperature of 200°C. Upon returning, the ISEC was releasing fumes and, as such, power was removed.

Reviewing data captured by the datalogger, the pancake heater rapidly reached temperatures in excess of 350°C and continued to rise before leveling off around 400°C, illustrated in Figure 15. The STS, on the other hand, maintained a relatively steady increase in temperature throughout the duration and only reached 160°C in over 5 hours of heating.

Figure 14: Installation of type-K thermocouple on bottom of pancake heater. The heater was flipped over after the JB Weld cured.

Figure 15: Temperature of STS and pancake heater after installation of additional type-K thermocouple.
Due to the unexpected magnitude of the temperature gradient between the pancake heater and the STS, the thermocouple bonding agent that had been selected for the application, structural JB weld, had vaporized during heating, coating the inside of the ISEC in a powdery residue and filling the area with a foul, potentially toxic, odor.

Figure 16, right, captures the intense temperature experienced by the thermocouple. The formerly gray epoxy was reduced to a brittle brown material. Because the thermocouple was no longer adhered to the heater after the epoxy melted, gravity likely caused the thermocouple’s position relative to the heater to change. As such, the temperature reported by the thermocouple throughout the trial should be taken with a grain of salt.

While the ISEC itself did not fare well, this test resulted in a lot of learning. Specifically, that there is a large STS-heater temperature gradient, and that the STS-heater interface needs to be improved for maximum power delivery.

Using data captured during the trial, an experimental thermal contact conductance for the STS-heater interface was calculated.

Thermal contact conductance describes the heat flow across a thermal interface, in this case the mechanical contact of the pancake heater and STS, as a function of the difference in temperature between both sides of the interface. Equation 6 describes this relationship where \( P_{\text{STS-heater}} \) is the heat flux into the STS from the pancake heater as measured by the rate of STS temperature increase, \( T_{\text{heater}} \) is the temperature of the pancake heater, and \( T_{\text{STS}} \) is the temperature of the STS.

Because the net heat flux into the STS is a combination of heat flux from the pancake heater and heat flux to the environment, the power delivered to the STS from the heater could not be measured directly. The net heat flux into the STS, \( P_{\text{measured}} \), had to be corrected by the heat flux to the environment, \( P_{\text{ambient}} \) (heat lost to the environment being negative) to calculate \( P_{\text{STS-heater}} \). Because the STS was allowed to cool with no thermal inputs during the trial in Figure 10, the heat loss could be attributed solely to the environment. Fitting a curve to the heat loss as a function of temperature, \( P_{\text{ambient}} \) was estimated for the heating trial.

\[
C_{\text{contact}} = \frac{P_{\text{STS-heater}}}{(T_{\text{heater}} - T_{\text{STS}})} \tag{6}
\]

\[
P_{\text{STS-heater}} = P_{\text{measured}} - P_{\text{ambient}} \tag{7}
\]

Figure 17, below, represents this analysis. Note that the domain of was constrained such that the temperature of the STS was within the domain of the curve fit predicting \( P_{\text{ambient}} \).
As suggested by the large STS-heater temperature gradient, the thermal contact conductance was quite low, around 0.1 Watts per Kelvin, indicating that the mechanical connection between the two surfaces was limited. Because heat transfer to the STS was stifled, heat continued to accumulate within the heater, causing its temperature to skyrocket.

At such a high temperature, much of the heat contained within the heater is radiated to the environment, partially explaining the 20 Watt discrepancy found during STS heating. By increasing the thermal conductivity of the interface, heat buildup in the heater can be mitigated and STS heating efficiency increased. Figure 18, right, illustrates a straightforward method for increasing the interfaces thermal conductivity whereby the STS and pancake heater assembly are enveloped by aluminum foil. The aluminum foil, increasing mechanical contact, acts as a pathway for heat to flow from the bottom of the heater, where it is being trapped and lost through the bottom, into the STS above. Increasing ISEC insulation under the pancake heater is also likely to improve heating efficiency as less heat will be lost to the environment.
Choosing an 8kg STS, while suitable for controlled testing, is likely too heavy for day-to-day use considering ISEC heating inefficiencies. Reproducing Figure 6 and Figure 7 while accounting for ISEC inefficiencies, Figure 19 and Figure 20 demonstrate the effect of ISEC insulation to the STS mass selection process. As ISEC insulation decreases, STS performance decreases with the largest effects seen in STS weighing less than 4kg. In the case of an ISEC with losses on the order of 0.15 W/k, Figure 20 predicts comparable energy availability for STS in the range of 5kg to 10kg. Because two key factors, cost and power delivery, are optimized with decreased STS mass, an STS in the 5kg range would have likely outperformed the 8kg STS selected for these trials.

Figure 19: Temperature of STS after 4 hours of heating at 100 W including heat loss to the environment.

Figure 20: Useable energy for boiling water captured by STS after 4 hours at 100 W. Curves for multiple ISEC insulation levels are presented.
STS-Pot Interface

The second thermal interface in the retrofitted ISEC is the STS-pot interface. The STS-pot interface determines food power delivery and, thus, cook time. Because the ISEC is not perfectly insulated, increasing cook time effects STS efficiency. The longer cooking takes, the more heat will be lost to the environment. More critically, people want to cook food rapidly, at high power, making this interface extremely important.

Stainless Steel Cook Pot

Accompanying the direct-cook ISEC was a thin, stainless-steel cookpot form-fit to the ISEC’s insulated cavity. This pot served as a baseline for testing STS power delivery. The pot, pictured in Figure 21, was 20 cm tall, 15 cm in diameter, 1mm thick, and weighed 455 grams. The bottom of the pot was extremely smooth but featured a slight concavity, approximately 1mm deep at its apex.

To measure power delivery to the cookpot, the STS was heated to 200°C before placing the stainless-steel cookpot, containing 1 liter of water at room temperature, in contact with the STS. The STS and water temperature were recorded with a datalogger and monitored until the water boiled. Simulating night-time conditions, the STS heater was disabled once the STS reached 200°C. Both the STS and cookpot remained in the ISEC’s insulated cavity for the duration of the test.

Figure 21: Stainless-steel ISEC cook-pot.
**Direct-Contact**

The first approach was to place the stainless-steel cookpot directly in contact with the STS. In this configuration, 80 minutes were required to boil 1L of water. By taking the derivative of the water temperature, power delivery to the water and pot were estimated as *Heat Flux to Cookpot* assuming the water-filled cookpot behaved as an isotherm. The heat leaving the STS, *Heat Flux from STS* was calculated similarly by taking the derivative of the STS temperature. Due the pot’s material and mass, very little energy was required to heat the pot. This is reflected in the near immediate power delivery to the water, peaking at ~200 Watts, shown in Figure 22 below.

![Stainless-Steel Pot Containing 1L of Water in 3SEC with STS (Direct Contact)](image)

*Figure 22: Heat flow from STS to stainless-steel cookpot filled with 1L of water when cookpot is placed in direct contact with STS.*

Because the heat flux to the cookpot was calculated based on changes in the temperature measured by a type K thermocouple submersed in the water-filled cookpot, the heat flux calculated should approach zero as the temperature of the cookpot approaches water’s phase transition at 100°C. This behavior can be seen in Figure 22, above. The actual heat flux to the cookpot, responsible for facilitating the completion of the phase transition, is better described by the heat flux calculated from the STS during this period.

Although clearly demonstrating the feasibility of cooking at night with STS, peak power and boiling time fell short of expectations based on simulations performed in SolidWorks, available in the Appendix. As mechanical contact plays a key role in conduction, STS and cookpot surface flatness were assumed to be a key factor in power delivery. Because the pot had a slightly concave bottom, mechanical contact between the pot and the STS were likely limited during the trial, resulting in reduced power delivery.
Compensating for the cookpot’s known concavity and any irregularities in the surface of the STS, the test was repeated with a silicone thermal pad manufactured by Aiyunn, 1 mm in thickness, placed between the two surfaces. Visible in Figure 23, peak power increased significantly, to 650 Watts, with a corresponding decrease in boiling time, to 35 minutes. The use of a thermal pad, however, is not practical outside of a laboratory setting as it must be carefully applied to the STS-pot interface and would be disturbed routinely as the cookpot was removed from the ISEC for cleaning. Being a silicone membrane, the thermal pad is also susceptible to a buildup of dirt and other particulates in the environment, degrading performance significantly.

A keen eye may notice that despite bringing water to a boil significantly faster than the direct-contact method, the final temperature of the STS in both trials is relatively close to 125°C. This is because the pancake heater was accidentally left powered for approximately 40 minutes of the direct-cook trial, offsetting additional environmental loses that accrued during the prolonged trial. Because the direct-contact method was underwhelming even with the additional heat flux afforded by the heater the trial was not repeated.
**Aluminum Cook Pot**

To reproduce the results of the previous trial without the use of a thermal pad, a flatter cookpot was procured. The pot, made of aluminum and pictured in Figure 24, was 14 cm tall, 17 cm in diameter at its base, 5 mm thick, and weighed 1167 grams. Prior to testing, the surfaces of the cookpot and STS were smoothed using 400 grit sandpaper to improve mechanical contact between the two surfaces. The STS surface before and after sanding are pictured in Figure 25, below.

Because the aluminum pot was significantly wider than its stainless-steel counterpart, it did not fit within the ISEC’s insulated cavity. After attempts to modify the cavity to accommodate the larger pot were unsuccessful, a conventional kitchen oven was chosen as a testbed for additional STS testing. Although there are likely differences between the two testbeds, the oven provides both an insulated cavity and a heat source: the essence of an ISEC.

Setting the oven to 395°F (201.7°C), the STS was heated until it reached 200°C after which the oven was turned off. Once the STS began dropping in temperature, indicating that it was in equilibrium with the surrounding oven, the cookpot, containing 1 liter of water at room temperature, was placed in contact with the STS. The temperature of the STS and water were monitored from outside the oven using thermocouples, routed through the closed oven door, until the water reached a boil.

![Figure 24: Flat-bottomed aluminum pot.](image)

![Figure 25: STS surface before sanding (left) and after sanding (right).](image)
Because the test environment changed significantly, testing was conducted to account for any heat introduced the cookpot by its surroundings in the oven. After preheating the oven to 395°F (201.7°C), the oven was left to bake for 15 minutes. After turning off the oven, the aluminum pot, containing 1 liter of water at room temperature, was placed on a small ceramic tile, and left until reaching equilibrium with its surroundings. After 50 minutes, the water reached a maximum temperature of 50°C, illustrated in Figure 26, below. Shortly after being placed in the oven, 140 Watts of peak power was delivered to the water-filled cookpot indicating that the oven’s contributions in subsequent trials must be considered.

The rate of change of the temperature, measured via a thermocouple submerged in the cookpot, was utilized to estimate the Heat Flux to Water and Heat Flux to Metal assuming an isothermal cookpot. The two values were added together to produce the total heat flux, Heat Flux to Cookpot.

![Figure 26: Heat flow from oven to aluminum pot containing 1L of water while reaching equilibrium with the oven. The oven was powered off with the door closed during this trial.](image)

That is, given a peak power measured in a subsequent trial, up to 150 Watts can be attributed to contributions from the oven’s latent thermal mass. It is important to keep in mind that while 150 Watts is delivered to the water-filled cookpot by the oven, it is only during a brief period where the temperature of the water-filled cookpot is well below 50°C. Once the water-filled cookpot eclipses 50°C, the heat flux from the oven to the cookpot is negligible.

A key point illustrated in Figure 26, above, is that the heat is distributed between both the cookpot and the cookpot’s contents. In this case, the aluminum pot’s mass is significant relative to the mass of the water. As such, a significant amount of heat is used to warm the cookpot that could otherwise be used to heat its contents. For this reason, a light cookpot is advantageous.
**Direct Contact**

Placing the flat aluminum pot in direct contact with the now smooth STS, 700 Watts of peak power was delivered as measured at the cookpot; improving on results using the stainless-steel cookpot in combination with a thermal pad. Boiling time was also reduced to ~14 minutes, significantly increasing the appeal of STS. Interestingly, a small hump is visible at the start of both heat flux curves at around the two-minute mark that is not expected based on the temperature profiles of either the cookpot or the STS, as depicted in Figure 27, below. This seems to be an artifact of the numerical analysis performed on the dataset to extract the rate of change of temperature. The behavior is likely constrained to the edges of the domain as the function attempts to meet boundary conditions on either side of the dataset. Because this analysis is interested in the general shape and trend of the curve, such artifacts, while not ideal, can be tolerated.

![Figure 27: Heat flow from STS to aluminum cookpot filled with 1L of water when cookpot is placed in direct contact with STS.](image)

As the water comes to a boil, the heat flux as measured by the cookpot approaches zero due to the approaching phase change that stifles temperature change. Of course, energy is still being transferred, and is better characterized by the STS behavior as it does not experience a phase transition during this period. The cookpot is supplied with roughly 200 Watts during this phase transition based on Figure 27.

An interesting observation is that the offset between the heat flux predicted by the STS temperatures and that predicted by the cookpot temperatures. Although once can only speculate, the bottom of the STS (near the STS thermocouple location) was in contact with the wire rack of the oven which may have supplied heat to the STS as heat was wicked up and into the cookpot. This would result in less net heat loss for the STS and would display itself in a manner similar to that displayed in Figure 27.

Regardless, these results are significant as they show that without the use of an interface material, such as a thermal pad, significant power can be delivered to a cookpot by STS. In addition to reducing the cost of STS it, more importantly, allows users to remove and replace their cookpots from the ISEC without having to worry about damaging the thermal interface. The experience of serving food from, cleaning, and switching between cookpots are all improved significantly.
Despite the success of the direct-cook method using the flat-bottomed aluminum cookpot, an additional trial utilizing the previously mentioned thermal pad was conducted. Because significant power delivery had been achieved without the use of a thermal pad, additional increases were not expected. Surprisingly, however, the thermal pad had a noticeable impact on power delivery and delivered nearly 900 Watts of peak power to the water-filled cookpot, reducing the boiling time to ~12 minutes. While sanding had a significant impact on power delivery, the thermal pad’s supple, compressible nature, allowed it to mold itself to the surface of the STS and cookpot and improve mechanical contact in a way that a rigid interface (metal on metal for example) cannot.

![Figure 28: Heat flow from STS to aluminum cookpot containing 1L of water. A thermal pad was placed between the STS and the cookpot to improve heat transfer between the two surfaces.](image)

Because the use of the thermal pad resulted in the addition of approximately 200 grams of silicone which was not accounted for in the analysis the two figures are not apples-to-apples, however, Figure 28 shows improved correlation between the STS and cookpot predictions for system heat flux relative to Figure 27. Power delivery during the water’s phase transition also improves significantly to around 375 Watts.
Comparison of Trials

Table 2, below, summarizes the results from the four trials conducted. Trials using the stainless-steel pot showed increased power delivery to the water relative to power delivered to the cookpot itself due to reduced cookpot mass and specific heat. The stainless-steel pot’s concave bottom and rough STS surface significantly reduced power delivery in the direct-cook trial. Surface imperfections were compensated by the installation of a thermal pad in a subsequent trial, greatly improving power delivery.

<table>
<thead>
<tr>
<th>Trial</th>
<th>Boiling Time (Minutes)</th>
<th>Peak Power (Watts)</th>
<th>Thermal Conductance (Watts Per Square Centimeter)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stainless-Steel Direct-Contact</td>
<td>80</td>
<td>200</td>
<td>1.21</td>
</tr>
<tr>
<td>Stainless-Steel Thermal Pad</td>
<td>35</td>
<td>650</td>
<td>3.67</td>
</tr>
<tr>
<td>Aluminum Direct-Contact</td>
<td>14</td>
<td>700</td>
<td>3.08</td>
</tr>
<tr>
<td>Aluminum Thermal Pad</td>
<td>12</td>
<td>850</td>
<td>3.75</td>
</tr>
</tbody>
</table>

Table 2: Summary of results from STS-Pot interface trials.

Aluminum pot trials demonstrated that proper surfacing of the STS and cookpot resulted in significant direct-cook power delivery but showed that increased pot mass and specific heat decrease power delivery to the contents of the cookpot. Power delivery can, however, be improved with the use of a thermal pad but may not be warranted based on increases in cost and complexity.

While care was taken to account for differences in the testing configurations between the stainless-steel and aluminum pots, it is important to remember the influence of the test environment on the results. As discussed previously, the oven contributed a non-negligible amount of heat to the water-filled cookpot in isolation. Additionally, the cookpots had slightly different footprints, with the aluminum pot having 28% more surface area, increasing mechanical contact area and, thus, interface heat transfer. Accounting for these differences, the thermal conductance of the thermal pad trials is strikingly similar at $3.67 \frac{W}{cm^2}$ and $3.75 \frac{W}{cm^2}$ respectively. This indicates that pot footprint was the largest factor in cookpot peak power delivery following the improved mechanical contact afforded by the thermal pad. In trials without the thermal pad, the bottom of the pot’s profile and surface roughness affected power delivery significantly with a more than two-fold increase in thermal conductance from $1.21 \frac{W}{cm^2}$ to $3.08 \frac{W}{cm^2}$ following optimized pot selection and surface treatment.
Conclusion and Outlook

Storing cooking heat in an aluminum puck is a reliable, non-degradable, energy storage solution enabling night-time use of insulated solar electric cookers (ISECs) without the need for additional complexity. Solid Thermal Storage, STS, can be readily integrated with existing direct-cook systems (without thermal storage) requiring little to no modification, facilitating distribution and adoption. In addition, raw materials are accessible in areas where ISECs have already been deployed, supporting local communities and minimizing costs.

The 8kg aluminum STS selected was too large for a 100 W solar panel over a 4-hour day, as it didn’t allow for the temperature of the STS to rise high enough to provide a large amount of heat above 100°C and we instead suggest an STS of about 4 to 5 kg. Optimization will depend on the insulative properties of the ISEC being retrofit and the desired operational characteristics of the STS.

Because the STS-heater interface dictates the “charging” efficiency of the STS, poor interface performance significantly reduces the amount of food the system can cook after a day’s worth of charging. Insufficient mechanical contact at the STS-heater interface was shown to cause the heater to get extremely hot. Insufficient ISEC insulation coupled with the increased temperature gradient between the heater and the outside world resulted in significant thermal loss and, thus, decreased charging efficiency. The steady state operating temperature of the heater can be reduced by increasing the mechanical contact between the heater and the STS. This can be achieved by wrapping the STS and heater in aluminum foil, although other methods exist. Insulation can be improved by using more rockwool or other insulating material between the heater and the bottom of the ISEC container.

Of equal importance, the STS-pot interface is responsible for delivering the power required for rapid-cooking. Increased mechanical contact and power delivery can be achieved by smoothing and flattening the interface surfaces. Further improvements can be made by selecting STS and cookpots with larger footprints, as well as using a silicone thermal conductivity pad. In addition, selecting a light cookpot, can maximize heat utilized to do meaningful work (like heating food).

Although this study showed that STS can be used successfully to store cooking heat for nighttime use, it did not consider the end user and their approach to cooking. Moving forward, STS performance should be tested in the field, incorporating changes identified in this report with specific consideration to the STS-heater and STS-pot interfaces. Such tests will be pivotal in identifying day-to-day challenges, which can inform future prototype iterations.

Acknowledgements

Thank you to the ISEC team at Cal Poly and abroad for their support and feedback throughout this project. Above all, I’d like to thank Dr. Pete Schwartz for his patience and guidance. I’d also like to thank Andrew Shepherd for building and providing an ISEC for retrofitting.
References


Appendix
SolidWorks Thermal Modeling

The following is a summary of the thermal modeling work performed on STS usage in ISEC using SolidWork’s built-in thermal modeling and simulation capabilities. While much was learned building and testing the model, completion of the model and correlating simulation results to the experimental results presented above was not feasible due to time constraints. This summary is presented as a record of the work conducted in hopes that it may be useful to individuals researching this topic in the future.

Initial Model

I began the thermal simulation in SolidWorks by creating a very simple model of a cylindrical aluminum thermal storage positioned beneath a cylinder of water. The specific configuration was chosen to mimic a real-world test that was being conducted to characterize STS performance boiling water. Figure 29, below, illustrates the configuration.

![Initial SolidWorks thermal model configuration.](image)

Using the basic model, I ran my first thermal simulation, with the following initial conditions:

- 1 Liter Water at 20°C
- 5kg Thermal Storage at 300°C

The model assumed the following:

- Perfectly insulated (no losses)
- Bonded Interface (no gaps)
- No Convection (water does not circulate)
- No State Transition (water can be heated higher than 100°C)
The simulation predicted a boiling time for the water of approximately 11 minutes. Although this was not too far off the 20 minutes that we had witnessed during our real-world test in the laboratory, it was clear that the model was not high enough fidelity, as much of the water was much hotter than 100°C (SolidWorks allowed water to heat above its phase transition). The hot water remained at the bottom of the vessel, stifling conduction to the cooler water at the top. Figure 30, below, illustrates the temperature distribution of the STS after all the water had reached at least 100°C.

![Figure 30: Temperature distribution of initial thermal simulation (no convection, perfectly insulated)](image)

**Internal Convection**

The initial trial made it clear that convection was required if the model was going to be anything like the real world. Using the same, 5 kg, thermal storage, the solid model of water was replaced with an aluminum pot with walls 3mm thick, and a similarly gauged lid as shown in Figure 31 below.

![Figure 31: Convective thermal model configuration (internal)](image)
Utilizing SolidWorks’ Flow Simulation tool, the cavity was filled with water and a convective simulation with the following initial conditions was run:

- 1L Water at 20°C
- 5kg Thermal Storage at 300°C

The model assumed the following:

- Perfectly insulated (no losses)
- Bonded Interface (no gaps)
- Convection (circulating)
- No State Transition (water can be heated higher than 100°C)

This simulation was extremely interesting to watch and decreased the boiling time of the water from 640 seconds, in the basic simulation, to just over 70 seconds. The large difference in boiling time was due to a combination of factors. For starters, adding convection allowed the fluid to maintain a uniform temperature which maximized the temperature difference and, in turn, the heat flux between the water and the thermal storage. In addition, this model added both the aluminum pot and lid which increase the surface of conduction significantly. Figures 32 and 33 illustrate the fluid’s velocity flow lines demonstrating convection occurring.

![Fluid velocity flow lines (cut view).](image)
Internal and External Convection

Although internal convection was a significant improvement over the basic model presented earlier in this report, to fully simulate the ISEC, external losses needed to be included. To facilitate this, insulation and an external housing were added to the model, presented in Figure 34 and 35. The measurements used for the insulated ISEC were based on rough measurements taken of ISECs being built at Cal Poly.
Once modeled, simulations began with Flow Simulation’s External Flow option, which allows for convective losses to be modeled in a non-enclosed area. The simulation’s computational domain was defined to be a volume of air significantly larger than the ISEC to simulate an ideal heat sink. The ISEC in its simulation domain is illustrated in Figure 36 below.
With the computational domain defined, I ran the simulation with the following parameters:

- 2L Water at 20°C (Volume of cavity was increased)
- 5kg Thermal Storage at 300°C

The model assumed the following:

- Convective Losses (Air at STP)
- Bonded Interface (no gaps)
- Generic Glass Fiber Insulation
- Convection (water circulating)
- No State Transition (water can be heated higher than 100°C)

In this configuration, the ISEC was able to boil 2 liters of water in just under 6 minutes. Figure 37 below illustrates the fluid flow lines as the water and thermal storage reached equilibrium. Air surrounding the ISEC can be seen heating up slightly before rising due to convection. The insulation surrounding the thermal storage is also visibly warm, however, quickly cools before reaching the aluminum enclosure.

Figure 37: Insulated ISEC fluid velocities (internal and external convection) [Copy of Figure 3]
Air Gap Simulation

At this point, the simulation was performing quite well except for the interface between the thermal storage and the water filled vessel. As such, an investigation began into how adding an air gap between the vessel and the thermal storage effected the time required to boil water.

Using the same configuration as the one presented in Figure 37 and varying the size of the air gap described above, the results in Figure 38, below, were collected.

![Time to Boil Water (2 litres) vs Air Gap](image)

*Figure 38: Effect of air gap at thermal interface on boiling time of 2L of water.*

With both faces bonded (no air gap) 2 liters of water boiled in just under 6 minutes. Adding the smallest of air gaps to the model, the boiling time nearly doubled to over 10 minutes. Further increases in the size of the air gap increased the boiling time, however, to much less of an effect. While this was to be expected, the discontinuity in the data gave me pause. After discussing this result, it was clear that there was a better path forward for describing imperfections in the thermal interface within the simulation environment.
Contact Resistance

The air gap simulation led to the investigation of a parameter known as the contact resistance. SolidWorks defines the contact resistance with units of (kelvin*meter^2)/watt giving a ground aluminum surface with a roughness of 2.5 micron a contact resistance of 8.8 e-5K*m^2/W; inverting the parameter to make it a bit more transparent, 11 kW/m^2*K. That is, for a square meter of surface area, the heat flux across the surface increases by 11 kW for every degree of temperature difference across the gap.

The real-world experiment, mentioned previously, involved quantifying the time required to boil two liters of water with a 3.2 kg aluminum thermal storage heated to 350°C. In the experiment, shown in Figure 39 below, one liter of water was boiled in around 20 minutes. After the first liter boils, it is removed before placing a second liter at room temperature in the cookpot to boil.

Out of curiosity, the experimental setup in SolidWorks using similar puck and pot geometry. Using the contact resistance preset described above, 1 litre of water boiled in 3 minutes; significantly faster than the experiment that was ran. This indicated that the contact resistance of the actual junction was significantly different than the Solidworks preset I used in the simulation.

Using the experimental data from real-world test, the contact resistance was estimated for use in the simulation. Figure 40, below, shows a 10 second running average of the instantaneous contact resistance for the interface using experimental data from Figure 39.
Based on the results above, a conservative value of 270 W/Km^2 (0.00369 Km^2/W) was chosen for the next SolidWorks simulation. The simulation ran for much longer, taking over 15 minutes for the water to reach 100°C, much closer to the 20 minutes it took in the experiment, indicating that the SolidWorks simulation was converging to the real-world solution. The results from the simulation are presented below in Figure 41.

**Figure 40: Instantaneous Contact Resistance of Thermal Storage - Pot Interface (Experimental)**

**Figure 41: Simulated Boiling Time for 2L of Water (Resistance of 270 W/m^2 *K)**
Thermal Simulation Conclusion

With help from real-world experimentation and analysis, the fidelity of the ISEC simulation increased significantly. The largest challenge facing the simulation is obtaining an accurate characterization of the STS-pot interface so that the heat flow between the STS and the pot can be modeled appropriately.

Moving forward, the model could be further improved by comparing trials presented in prior sections of this paper with simulation predictions. By increasing the number of real-world to simulation comparisons, the model can be refined to the point where model predictions can be relied upon in the ISEC design phase, improving overall ISEC performance by reducing the complexity and cycle time of testing new ideas.

On a personal note, the development of the ISEC simulation significantly improved my understanding of the complex mechanisms and processes at play in a seemingly simple device. I am very thankful to have been able to work on this analysis and bring it to the point where it stands despite having more that I would have liked to have accomplished.