U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Building Technologies Office

Market Assessment and Commercialization Strategy for the Radial Sandia Cooler

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NOTICE

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Market Assessment and Commercialization Strategy for the Radial Sandia Cooler

Prepared for:

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Prepared by:

Navigant Consulting, Inc.

77 South Bedford Street, Suite 400

Burlington, MA 01803

William Goetzler

Richard Shandross

Daniel Weintraub

Jim Young

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Executive Summary

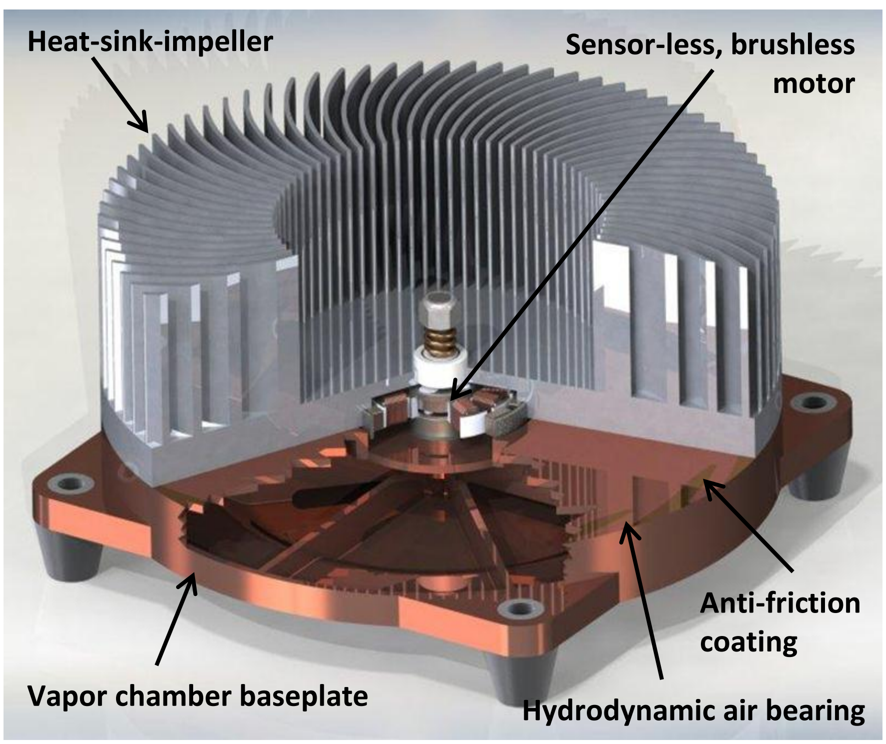
Background

The U.S. Department of Energy (DOE) Office of Energy Efficiency and Renewable Energy (EERE) Building Technologies Office (BTO) commissioned Navigant to conduct this market assessment and commercialization strategy for the rotating heat exchanger technology developed at Sandia National Laboratories (SNL) and known as the Radial Sandia Cooler (RSC). The market potential of the RSC was evaluated for the residential, commercial, industrial, and transportation markets.

Radial Sandia Cooler Overview

The RSC is a novel, motor-driven, rotating, finned heat exchanger developed by Dr. Jeff Koplow and his team at SNL. The RSC consists of three main components: an impeller (a rotating, finned heat sink), a baseplate, and an integrated brushless DC motor. The impeller is powered by the motor, allowing it to rotate on a thin hydrodynamic air bearing above the stationary baseplate.

In operation, the underside of the baseplate is mounted to a heat source. Heat flows through the baseplate, air bearing gap, impeller base, and impeller fins, and is ultimately transferred to surrounding airflow. Because the impeller fins are rotating at up to several thousand RPM, the air flow experiences a centrifugal force that decreases the thickness of the boundary layer, by as much as a factor of 10. This thinning of the boundary layer significantly improves the air-side heat transfer coefficient of the heat exchanger, as compared to traditional fan and fin devices.



Overview of RSC design
Source: Sandia National Laboratories

In 2010 and 2011, the SNL team developed a proof-of-concept prototype of the RSC, designed for electronics cooling applications. The prototype was 10 cm in diameter and was designed for a concentrated heat source such as a computer processor chip. As a part of a greater market assessment and commercialization analysis, this paper explores the feasibility and anticipated performance of derivative (i.e., scaled) models, both smaller and larger.

RSC Performance Characteristics

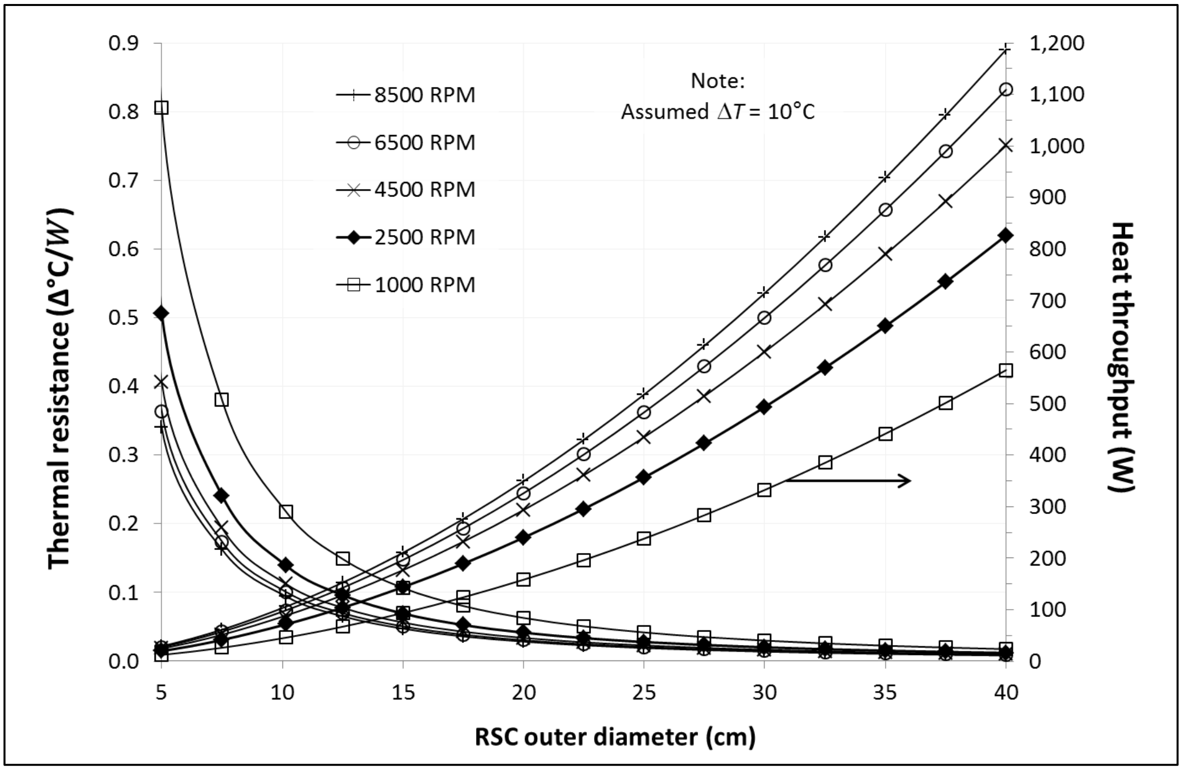
RSC performance was quantified for derivative models ranging from of 0.5 to 40 cm in diameter. Each model was evaluated at speeds from 1,000 to 9,000 RPM. The following performance parameters were estimated for all diameters and operating speeds:

- Heat transfer capability
  - Thermal resistance (Δ°C/W)
  - Total heat throughput—total heat transferred by the RSC (W)
  - Heat flux—heat transferred per unit area (W/cm^2)
- Fan performance
  - Pressure drop across the fan (inches H_2O)
  - Air flow (CFM)
- Motor power consumption (Watts)

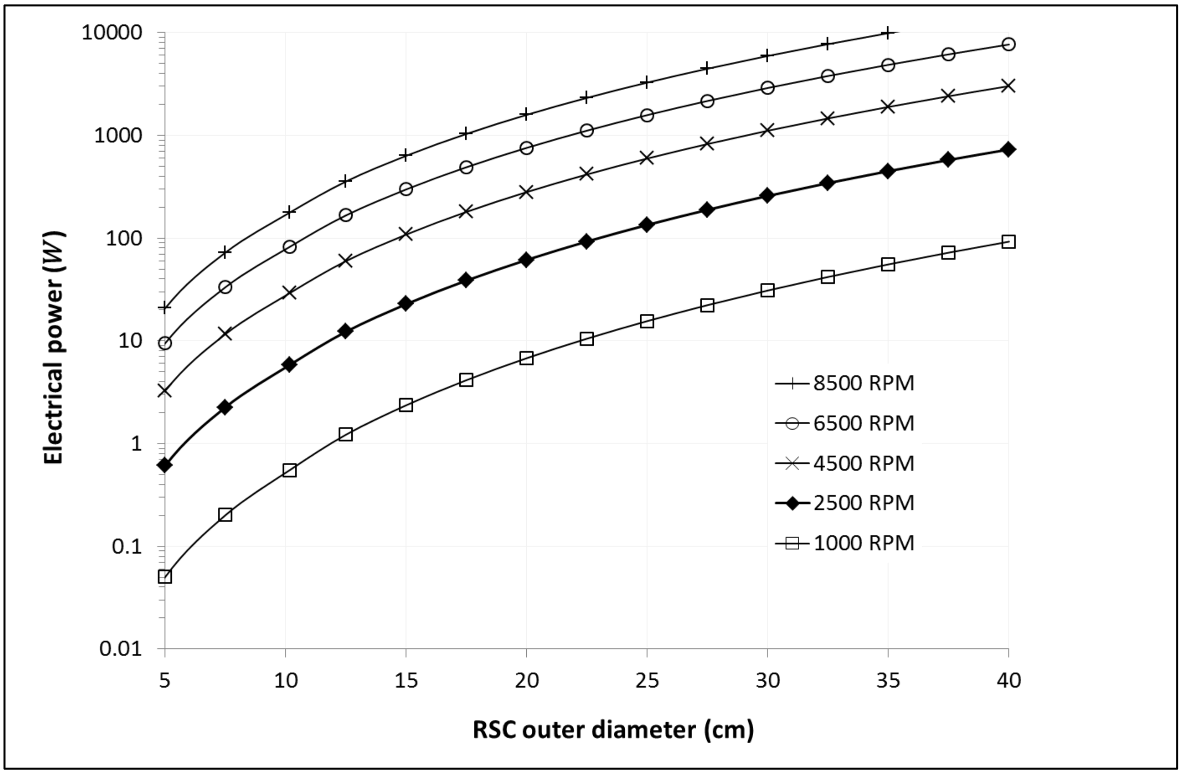
The RSC should do very well with most potential low-to-moderate heat flux applications. For the scaled models, heat transfer performance improves as both diameter and speed are increased. Within the bounds of the analysis, increasing diameter tends to provide a greater relative benefit than increasing speed. Thermal resistance decreases rapidly with increasing diameter in the size range from 5–15 cm, but realizes much less improvement above a diameter of 15 cm. Note that increasing speed above 2,500 RPM continues to improve thermal performance, but with diminishing returns for both thermal resistance and heat throughput.

Predicted RSC power consumption at the target speeds of 2,000–3,000 RPM compares well to that of existing fanned heat sinks of similar sizes. However, as with any motor driven device, power consumption grows quickly at higher RPM, at times to values greater than those seen at larger diameters.

Charts of RSC performance—thermal resistance, total heat throughput, and electrical power use, all at various rotational speeds and diameters—are shown below.



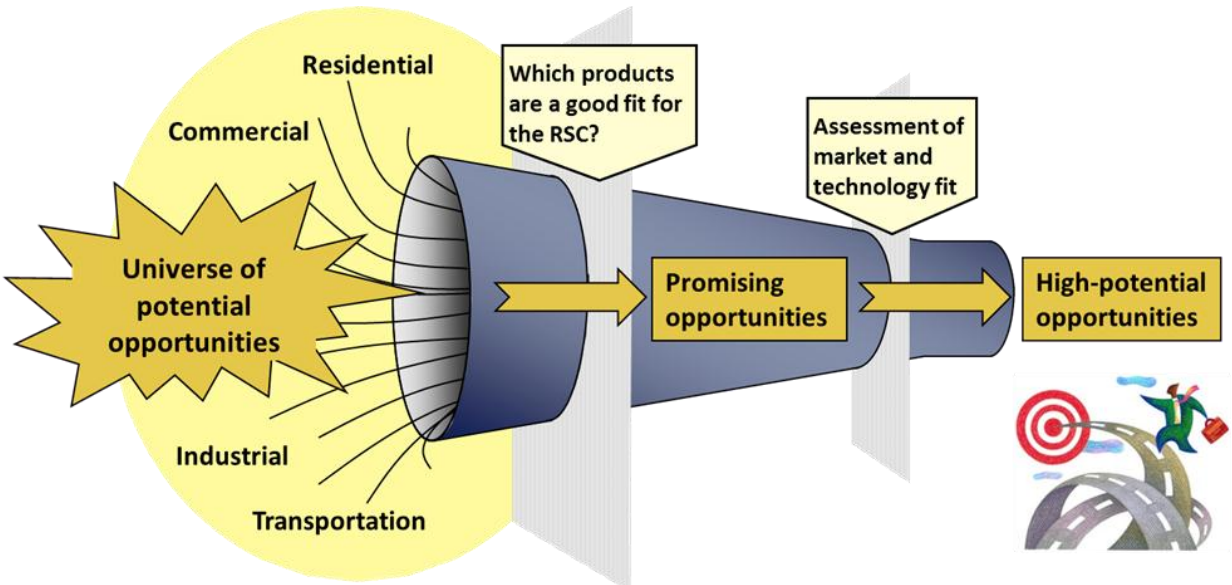
RSC thermal resistance and total heat throughput as a function of diameter and speed, for an assumed temperature difference of 10°C



Predicted electrical power required for an RSC at various diameters and speeds

High-Potential Opportunities for Initial Commercialization

Identifying high potential opportunities was a multi-stage process. The first stage involved the development of a list of all products for which the RSC might be suitable. The products on the initial list were subjected to two levels of screening: the first to eliminate products for which the RSC was not a good match, and the second to find the products most likely to meet DOE and SNL licensing goals. After the second filter, the remaining products were further evaluated to understand their relative strengths and weaknesses as an avenue for commercialization of the RSC. The figure below illustrates this process.



Overview of prioritization process

The screening process identified six products with a high potential for successful RSC introduction. These products are outlined below:

Standard PC processor (laptop-desktop)

- Description: Laptop and desktop computers require heat sinks, heat pipes, and fans to remove heat generated by the processor and other components
- Benefits from RSC: Noise and fouling reduction, potential size reduction for laptops

High-performance PC processor (gaming PC)

- Description: Gaming PCs use high-performance computing and graphics processors that typically require large, fanned heat sinks
- Benefits from RSC: Significant size advantage, ability to increase clock speeds, variable capacity, reduced noise and fouling

Peltier devices

- Description: Using the thermoelectric effect, Peltier devices remove heat from sealed enclosures at ambient conditions for remote telecommunications, military, and other mission-critical electronics applications
- Benefits from RSC: Opportunity for either size reduction or performance enhancement, reduced fouling

Data center processor (server)

- Description: Within data centers, server processors use heat sinks with either integral fans or those located within the rack to reject the significant amounts of heat generated in the server enclosure
- Benefit from RSC: Reduced size could allow either more components within a space or a smaller enclosure, variable capacity

A/V equipment

- Description: Audio-visual equipment (e.g., stereo receivers, set-top boxes, game consoles, projectors) and other enclosed electronic devices require proper thermal management to maintain operations
- Benefits from RSC: Reduced size, noise, and fouling

Residential refrigerator

- Description: Refrigerators use fans to supply airflow over condenser coils whose performance is limited by current fin-and-tube heat exchangers and dust accumulation over time
- Benefits from RSC: Improved coefficient-of-performance (COP), additional refrigerated space, variable capacity, noise and fouling reduction

Recommended Initiatives for Sandia Cooler Technology

Recommendations for commercialization were made based on assessments of the prototype RSC and the Sandia Cooler technology in general, as well as an in-depth analysis of the six most promising products for initial RSC commercialization. Because of the wide applicability of the technology, multiple cycles of development, demonstration, and subsequent commercialization are most appropriate for the Sandia Cooler technology.

We recommend the following priorities for commercialization activities:

- Focus the initial commercialization effort on high-performance PCs (e.g., gaming computers), as a readily attainable entry point into the broader electronics market. Within that broader market, the other identified high-potential products—standard PC processor, data center processor, and A/V equipment—should be pursued after efforts related to high-performance PCs are well underway.

- Pursue lighting and residential refrigeration applications as medium-term goals. These applications would involve later RSC generations that have benefitted from ongoing R&D activities and the information gained from experience in the electronics markets.
- Continue development of Sandia Coolers for HVAC and other higher-heat-flux applications, as longer-term prospects whose viability may be assessed through current and future R&D projects.

1 Introduction and Background

The U.S. Department of Energy (DOE) Office of Energy Efficiency and Renewable Energy (EERE) Building Technologies Office (BTO) commissioned Navigant to conduct this market assessment and address the commercialization strategy for the rotating heat exchanger technology developed at Sandia National Laboratories (SNL), which is known as the Radial Sandia Cooler (RSC). The market potential of the RSC was evaluated for the residential, commercial, industrial, and transportation markets.

1.1 Sandia Cooler Technology Overview

For a variety of mechanical and electrical systems, air-cooled heat exchangers are used to reject excess heat from a concentrated source to the surrounding atmosphere. Traditionally, air-side heat exchanger enhancement is accomplished by increasing surface area and/or the heat transfer coefficient (e.g., fin number and/or geometry), raising thermal conductivity (e.g., improved materials), or supplying more airflow (e.g., larger or higher-speed fan). Advancements in heat exchanger design have been very limited in recent years for most product applications.

Constraints on heat exchanger performance force designers of many products that require cooling to compromise on product size, capabilities, energy efficiency, or other characteristics. A significant improvement in the effectiveness of air-cooled heat exchangers would have a profound effect on the design, efficiency, and performance of such products. With support from BTO, Dr. Jeff Koplow and his team at SNL have developed a novel rotating heat exchange technology known as the Sandia Cooler, of which the RSC is one form (Koplow 2010). The Sandia Cooler technology improves heat exchanger effectiveness considerably.

The core of the Sandia Cooler technology is the rotation of a finned heat sink ("heat-sink-impeller" or, in this document, simply "impeller"). Rotation induces airflow over the curved fins, resulting in transfer of heat from a concentrated heat load, located under the impeller base, to the moving air. Because the impeller fins are rotating at up to several thousand RPM, the air flow experiences a centrifugal force that reduces the thickness of the boundary layer by as much as a factor of ten. This thinning of the boundary layer significantly improves the air-side heat transfer coefficient of the heat exchanger. Imparting motion directly to the impeller, as opposed to directing a flow of air from a fan at a stationary impeller, also makes it possible to achieve higher fin/air relative velocity at a given (electrical motor) power consumption. Depending on the specific application and design, this could result in reduced heat exchanger size, improved performance, and/or greater efficiency. Additionally, little dust accumulates on the moving heat transfer surfaces, allowing heat exchanger performance to be maintained over time without cleaning of the fins.

The Radial Sandia Cooler, or RSC, is a type of Sandia Cooler in which the air is accelerated radially from the center of the (flat) heat-sink-impeller, outward through the fins. In 2010 and 2011, the team at SNL developed a proof-of-concept prototype of the RSC, designed for electronics cooling applications, in which the impeller is located above a baseplate. The heat source, such as a computer processor chip, is attached to the RSC at the baseplate.

Rotation causes the impeller to lift off the baseplate, forming a hydrodynamic air bearing that is several microns thick. Heat flows from the heat source, through the baseplate, air bearing, impeller base ("platen"), and impeller fins, and is transferred to the airflow. Figure 1-1 provides an overview of the RSC design and operation; in this instance the baseplate contains a vapor chamber that functions as a heat pipe, significantly improving horizontal heat spreading.

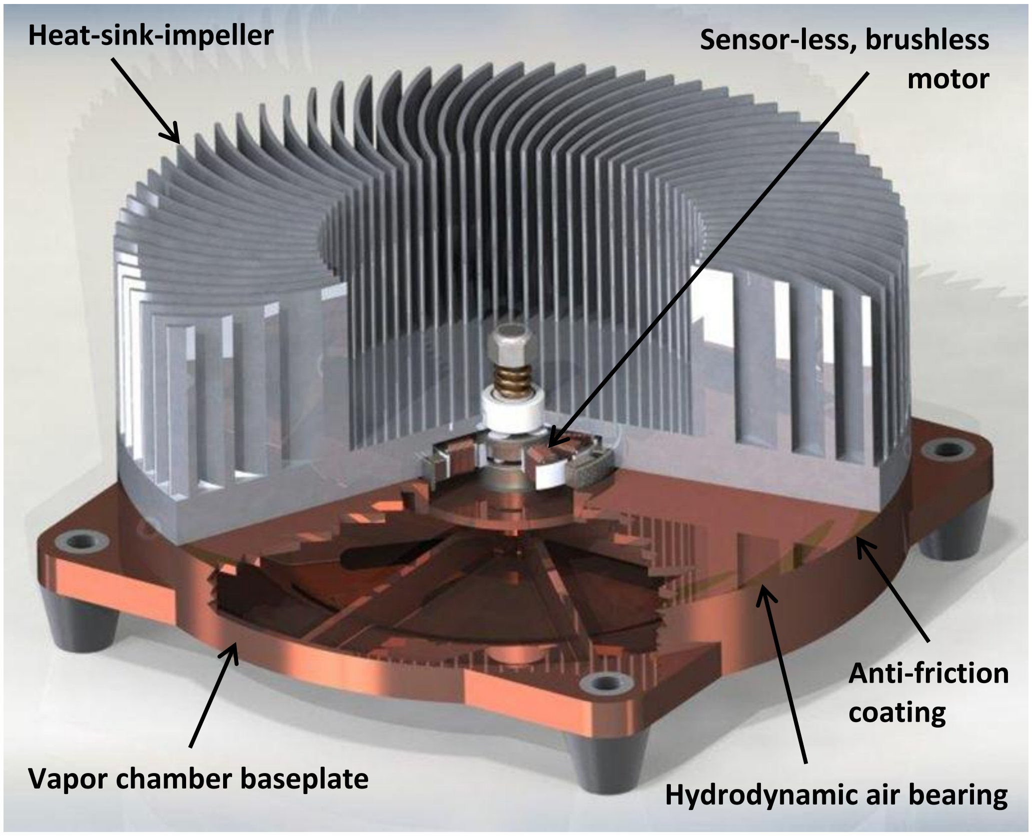


Figure 1-1. Overview of RSC design
Source: Sandia National Laboratories

Simultaneous with making improvements to the RSC design and producing additional prototypes, the SNL team has worked on other configurations that incorporate the fundamental Sandia Cooler technology. These alternative configurations, outlined in Table 1-1, address some of the challenges of the RSC design. Additional information about more-advanced Sandia Cooler designs, and their potential applications, is included in Section 4.

The RSC has many benefits for a number of applications, is the most developed architecture at this time, and will likely be the first Sandia Cooler concept to be commercialized.

Table 1-1. Advanced Sandia Cooler Designs

Design	Description
RSC without air bearing	Operating without an air bearing provides three main benefits: 1. Greatly simplifies RSC design, especially for multiple axis orientations 2. Improves heat transfer by removing the air bearing's thermal resistance 3. Decreases motor power by eliminating the shearing torque of the air bearing.
Baseplate integration with tubing	The current RSC baseplate is designed for contact with solid heat generating components. Integrating fluid tubing or coils into the baseplate would facilitate heat transfer for gaseous and liquid applications.
Axial air flow	To achieve greater RSC heat transfer area, the impeller diameter, and therefore the footprint, generally needs to be increased. Heat transfer area could be increased without a significant change in footprint with an axial configuration, in which rows of fins rotate around a central hub. The axial arrangement offers better performance for a given area (Koplow 2012a).

1.2 Project Overview

For context, in this study the term *commercialization* means the full process of developing a technology for introduction to the marketplace, while *deployment* refers to the process of acquiring specific avenues for introduction of the technology as a product.

The assessment involved the four tasks outlined in Table 1-2. Because RSC development continued throughout this assessment, we updated our findings as new information became available. At the conclusion of each task, we provided our results to SNL and BTO, gathered feedback, and discussed new developments. This report provides our assessment based on the information to date.

Table 1-2. Summary of Project Tasks

	Task description	Key steps
Task 1	**Market assessment**	For a large universe of products, determined feasibility of replacing current heat exchanger components with the RSC: • Assessed the feasibility and performance of the RSC at different sizes and rotational speeds • Analyzed current heat exchanger methods used in representative products • Compared RSC characteristics with product needs
Task 2	**Commercialization evaluation**	Identified the most promising products for initial RSC introduction: • Ranked potential applications, based on technology and market fit with the RSC • Characterized potential RSC configurations (i.e., size, speed, number) for the most promising markets • Identified key technical, market-acceptance, and manufacturing challenges.
Task 3	**Deployment strategy**	Developed deployment strategies for each of the most promising product applications: • Analyzed the dynamics of, and major players involved in, product development for each market • Identified potential public and private partners • Considered communication and demonstration activities to introduce the RSC to priority market segments
Task 4	**Conclusions & recommendations**	Prioritized deployment strategies according to the resources needed for implementation: • Identified the minimum deployment activities needed • Classified additional activities as near-term technology demonstration and longer-term development.

2 Identification of High-Potential Products for Initial Commercialization

This section corresponds to Tasks 1 and 2 of the project.

2.1 Licensing Goals

As a publicly funded project, BTO and SNL have an obligation to advance the Sandia Cooler technology for the betterment of U.S. public, commercial, and national interests, with special consideration for national energy savings. An important avenue for disseminating technology from the National Laboratories is through licensing the patents to interested parties and providing support to develop the technology for specific product applications. BTO and SNL have near- and long-term commercialization goals for the RSC:

- The near-term goal for the RSC is to license the technology with a major original equipment manufacturer (OEM). This will demonstrate to other potential partners, and the market as a whole, that the technology is mature enough to consider for adoption into commercial products. Furthermore, the experience gained in working on real-world applications can only help SNL to continue improving the performance and capabilities of the RSC (and other Sandia Cooler variations) going forward. Licensing has already occurred in some product categories, but a goal of this work is to assist SNL in identifying additional products that are likely to succeed.
- For the longer term, a wider impact on reducing energy consumption in the United States and abroad is important, specifically by reaching high annual volume with major industry partners in several key sectors.

2.2 Methodology

An overview of the process used to identify high-potential products for initial RSC introduction is shown in Figure 2-1.

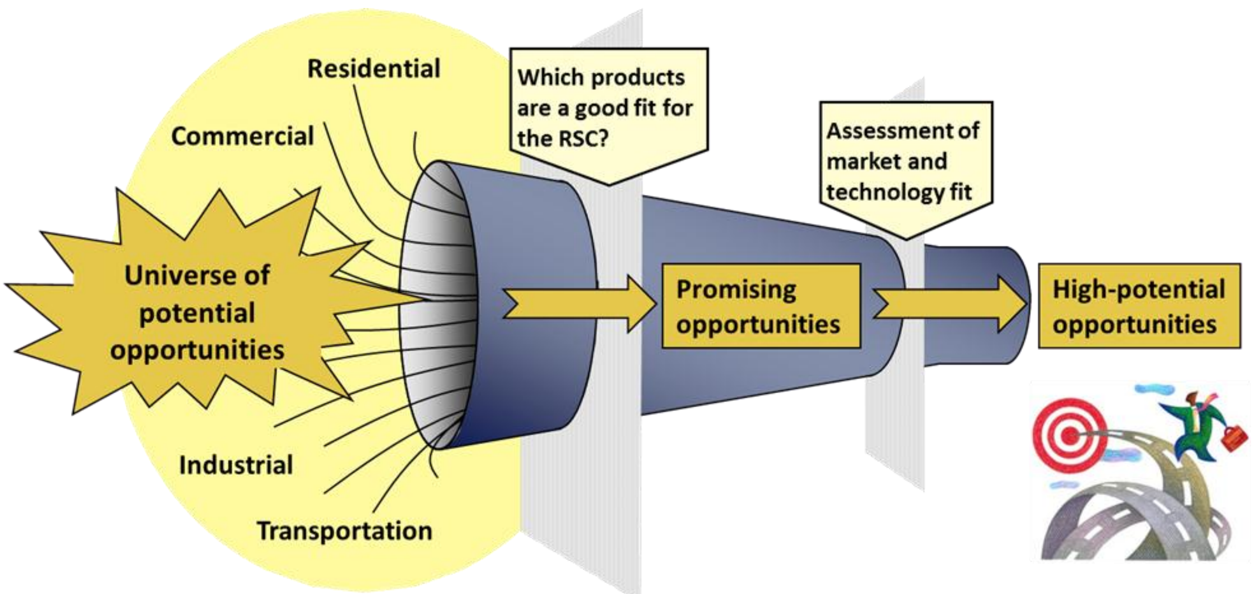


Figure 2-1. Overview of prioritization process

2.2.1 Universe of Products Considered

The first step in the multi-stage process shown in Figure 2-1 involved developing a list of products in the residential, commercial, industrial, and transportation sectors for which the RSC might be suitable. Table 2-1 summarizes the product types considered for the RSC.

Table 2-1. Products Initially Evaluated for Compatibility with the RSC

Sector	Application / product type	
Residential heating, ventilation, air conditioning, and refrigeration (HVAC&R)	• Split-system, central air conditioner (CAC) • Room air conditioner (RAC) • Ductless multi-split AC	• Standard refrigerator/freezer (RF) • Compact refrigerator • Heat pump clothes dryer
Commercial HVAC&R	• Rooftop CAC • Packaged terminal air conditioner (PTAC) • Beverage vending machine (BVM)	• Reach-in RF • Walk-in RF • Peltier devices
Industrial processes and transportation	• Fan-cooled motors • Radiators	• Electric vehicle (EV) battery pack
Solid-state lighting	• Residential light-emitting diode (LED) bulb • Commercial recessed LED fixture	• Industrial high-bay LED fixture
Residential and commercial electronics	• Standard personal computer (PC) processors (laptop-desktop) • High-performance PC processors (gaming PCs) • Mobile processors (cell phones, tablets, music players)	• Battery packs • Audio-visual (A/V) equipment (stereo receivers, gaming consoles, projectors, etc.) • Microwave • Television (TV)
Distributed energy systems	• Fuel cells (portable, residential, commercial)	• Battery chargers • PV inverters
Data center equipment	• Data center processor (servers) • Backup generator radiator	• Uninterruptable power supplies (UPS)

Because most of SNL's work to date had focused on hot-to-ambient heat transfer, this study only considered applications in which the RSC would dissipate heat from a concentrated source to cooler air (e.g., a residential CAC condenser). The RSC may be suitable for cold-to-ambient heat transfer (e.g., a residential CAC evaporator), but such applications require additional consideration for distribution airflow and condensate accumulation. We anticipate those applications to follow the successful RSC commercialization of hot-to-ambient products.

2.2.2 Screening and Evaluation Steps

The products on the initial list were subjected to two levels of screening, the first to eliminate products for which the RSC was not a good match, and the second to find the products most likely to meet the DOE and SNL licensing goals. After the second filter, the remaining products were further evaluated to understand their relative strengths and weaknesses as an avenue for commercialization of the RSC. The three-step screening and evaluation approach is illustrated in Figure 2-2.

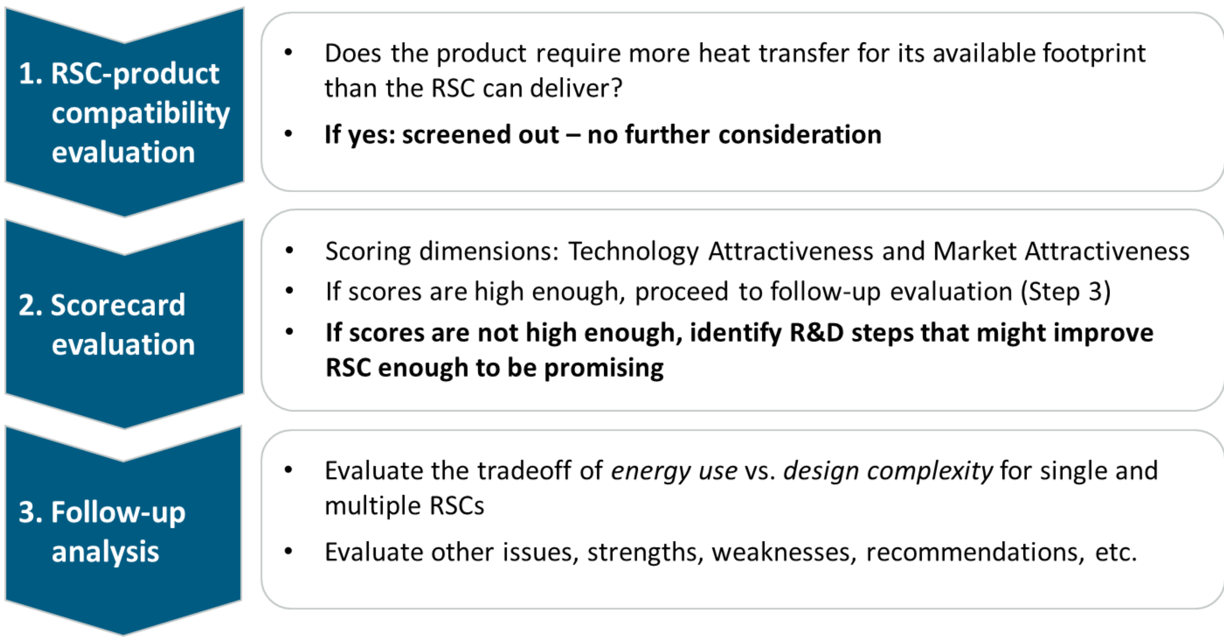


Figure 2-2. Overview of product evaluation process

2.3 RSC-Product Compatibility Evaluation (Step 1)

The key factor in determining the potential compatibility of the RSC with a given product is the ability of the RSC to remove the required amount of heat within the footprint (i.e., area and shape) allotted by the product for cooling equipment. To determine this, it is necessary to understand:

- The product's cooling requirements (heat to be rejected and temperature differential), as well as constraints on fan power and heat exchanger size and shape
- How the RSC performs at various sizes and speeds

These factors are discussed in subsections 2.3.1 and 2.3.2 below. Section 2.3.3 describes how the factors were analyzed to determine potential compatibility.

2.3.1 Product Requirements and Heat Exchanger Characteristics

Most of the product types listed in Table 2-1 are available in a wide range of sizes and characteristics. We chose a product with representative capacity, size, and heat transfer requirements (and other features as applicable), to evaluate technology fit with the RSC. In some cases, we analyzed multiple common configurations (e.g., solar photovoltaic (PV) inverters of 0.5, 20, and 100 kW capacity), to understand the relationship between capacity and available heat exchanger size. Details concerning the representative products analyzed in this work are found in Appendix A.

2.3.2 Estimating RSC Performance at Various Sizes and Speeds

For most forced-convection heat exchangers, increasing the size of the heat exchanger or the flow rate of the cooling fluid increases the amount of heat that can be removed. This relationship generally holds true for the RSC as well; i.e., the heat transfer ability of the RSC varies with impeller diameter and/or rotational speed. The RSC proof-of-concept prototype was originally designed with a 10 cm diameter (more precisely, 10.16 cm), operating at 2,000–3,000 RPM, to satisfy a relatively low heat load (75–100 W) that is typical for electronics cooling. To satisfy greater heat transfer requirements, the diameter of a single RSC can be increased so that the heat exchanger area increases, or several RSCs could be operated side-by-side.

In order to evaluate the compatibility of the RSC with the products listed in Table 2-1, we developed an understanding of how RSC performance scales with changes in size, speed, and number. The scaling analysis consisted of two key tasks:

1. Size feasibility analysis—quantification of factors leading to engineering uncertainty:
   - Understanding the relationships and tradeoffs between design parameters (e.g., weight, friction, torque, and motor selection)
   - Identifying engineering limitations at different RSC sizes, and how they could be mitigated
   - Determining the size and speed combinations for which tradeoffs and limitations outweigh heat transfer gains, therefore requiring multiple smaller RSCs, product redesign, or use of alternative architectures instead
2. Performance analysis—development of performance maps at various speeds and sizes:
   - Heat transfer capabilities (i.e., thermal resistance and heat removed)
   - RSC power consumption, comprising fan and air-bearing torque components

Heat load requirements ranging from 1 W to several hundred kW (or more) were considered.

2.3.2.1 Scaling Analysis: Size Feasibility

The feasibility analysis began with an investigation of the fundamental engineering viability of the RSC at diameters above 10 cm. Specifically, engineering viability was viewed as the ability of the RSC to *work*—to spin, create an air bearing, and function without failure or damage.

Scale-up was analyzed using general equations for fan performance, solid mechanics, and air bearings. Fin height and fan inlet diameter were kept constant during the analysis; RSC size was changed by varying the fan outlet diameter. The analysis relied on SNL data from testing of their 10–cm prototype, as well as motor manufacturer literature. No mechanical or flow simulation tools (e.g., finite element or finite difference modeling software) were used.

Scaling down from 10 cm was not included in the analysis, as it is not expected to pose a significant engineering risk; however, we expect that below about 5 cm the RSC would require additional redesign, such as reduced fin heights.

The key RSC characteristics considered in the scaling analysis were:

- Platen thickness (based on rotor bow[1])
- Weight
- Air bearing
- Mechanical stress
- Preload
- Friction
- Start-up torque
- Motor diameter, relative to platen diameter

Table 2-2 summarizes the assumptions and methods employed to calculate these characteristics. Overall feasibility of the RSC is influenced by these factors in various ways, as illustrated in Figure 2-3.

Table 2-2. Summary of Key Scaling Parameters

Item	Definition	How determined
Platen thickness / rotor bow	Thickness of the base of the heat-sink-impeller	The minimum platen thickness required to maintain acceptable rotor bow; calculated using stress and strain equations[2]
Weight	Weight of the RSC (sum of fins and impeller platen)	Computed for various fan outlet diameters
Air bearing	Bearing that supports the heat-sink-platen solely on a thin layer of air	Online air bearing calculator[3]
Mechanical stress	Radial and hoop stresses in the impeller platen, caused by impeller rotation	Analyzed using impeller and fin weights at various diameters. (Stresses due to natural frequencies or stress concentrations were not considered in this analysis)
Preload	Downward force, applied by a spring, to maintain acceptable air-bearing height at the design rotational speed	Based on SNL information, assumed to be twice the impeller weight at all scales; i.e., the "preload ratio" is two
Friction	Static friction between the baseplate and the impeller platen at motor start-up	Extrapolated curve of static friction vs. load, based on available test data
Start-up torque	Torque that the motor must provide to start the RSC from rest	Calculated, based on friction, preload, and impeller weight
Motor diameter	Diameter of motor required to provide the necessary start-up torque	Estimated assuming off-the-shelf motors are used for the required start-up torque

[1] *Rotor bow* is axial deformation of the heat-sink-impeller platen due to rotational forces.
[2] "Roark's Formulas for Stress and Strain" (Young and Budynas 2002).
[3] Spiral groove thrust bearing calculator at: http://www.tribology-abc.com/sub22.htm

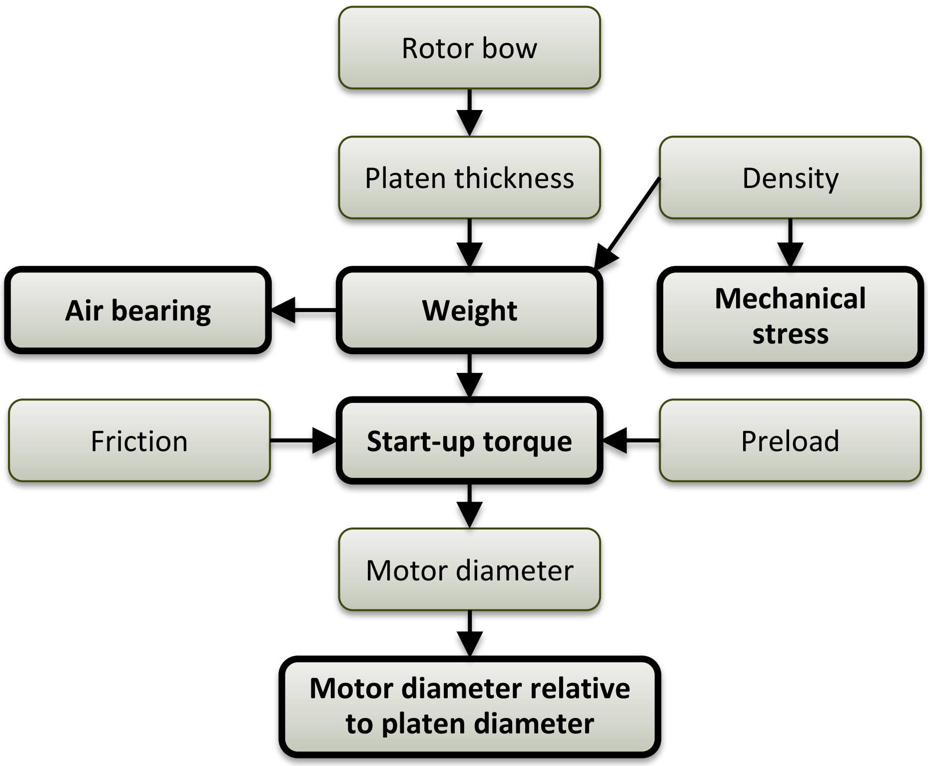


Figure 2-3. Overall size feasibility analysis. Emphasized boxes are factors critical to engineering feasibility.

Early in the analysis it was observed that the strong dependence of RSC weight on platen diameter results in the unit weight reaching impractical levels above a diameter of 40 cm (15¾ in.). At that diameter, the weight of an RSC with an aluminum impeller and a copper baseplate would be in the range of 50–115 lb., depending on the design of the baseplate. This, combined with consideration of the accuracy of scaling equations (described below) at multiples of the original diameter, led us to limit the analysis to the range of 10–40 cm.

Table 2-3 summarizes the results of the feasibility analysis for each key RSC characteristic. Our findings revealed that even under conservative assumptions there are no apparent fundamental engineering limitations to scaling-up the RSC to a 40-cm diameter.

We recommend more detailed analysis and/or design optimization for applications involving RSCs larger than 20 cm, due to the scaling accuracy question. A qualitative assessment of the uncertainty of the feasibility conclusion for different RSC sizes is:

- Minimal uncertainty for 5–20 cm
- Limited uncertainty for 0–5 cm and 20–40 cm
- Moderate uncertainty for ≥ 40 cm

Table 2-3. Summary of Feasibility Analysis Findings

<table>
<tr><th>Characteristic</th><th>Findings</th></tr>
<tr><td>Friction</td><td>• Static coefficient of friction for baseplate coating improves with total loading and therefore diameter
• Not anticipated to limit feasibility</td></tr>
<tr><td>Rotor bow</td><td>• Platen deflection grows to the 3rd power of diameter, and shrinks to the 3rd power of impeller platen thickness
• Deflection can be easily mitigated by minor RSC redesign</td></tr>
<tr><td>Weight</td><td>• RSC weight scales to the 3rd power of diameter
• Larger RSCs may be too heavy for some applications, but weight is not anticipated to be a major limiting factor</td></tr>
<tr><td>Start-up torque</td><td>• Torque scales to the 3rd power of diameter
• Start-up torque can be accommodated by off-the-shelf brushless direct-current motors (BLDC) running 12 or 24 V</td></tr>
<tr><td>Motor diameter</td><td rowspan="2">• Off-the-shelf motors fit within the available RSC platen area, but begin to reduce the available platen heat transfer area at larger RSC diameters (above 20 to 25 cm)
• RSC or motor redesign can mitigate these impacts</td></tr>
<tr><td>Platen heat transfer area</td></tr>
<tr><td>Mechanical stress</td><td>• Radial and hoop stresses were found to be acceptable
• Additional investigation is necessary to evaluate the effect of natural frequencies on the RSC system</td></tr>
</table>

2.3.2.2 Scaling Analysis: Performance vs. Size and Speed

With the feasibility of scaling the RSC to larger sizes established, the next step in our analysis was to understand how the RSC performs at scaled sizes and speeds. The goal of this analysis was to map the performance of the RSC for diameters of 0.5 to 40 cm and speeds of 1,000 to 9,000 RPM, and to evaluate the results. Performance was quantified using the measures listed below and described immediately afterward.

- Heat transfer capability:
  - Thermal resistance (Δ°C/W)
  - Total heat throughput—total heat transferred by the RSC (W)
  - Heat flux—heat transferred per unit area (W/cm^2)
- Fan performance:
  - Pressure drop across the fan (inches H_2O)
  - Air flow (CFM)
- Motor power consumption (Watts)

2.3.2.2.1 Thermal Resistance

Thermal resistance is an important figure of merit for heat sink thermal performance. It represents the effective resistance of an object to heat flow, and is characterized by the temperature difference across the object per unit of heat throughput. The lower the thermal resistance, the smaller the temperature drop across it when 1 W of heat energy flows through it.

To estimate the RSC's thermal resistance, the unit can be divided into four sub-components, each with its own thermal resistance: impeller fins, impeller platen, air gap, and baseplate. Because the components are in series, their thermal resistances may be summed to yield the total thermal resistance for the RSC system [Lienhard and Lienhard, 2008].

Thermal resistances for the air gap and impeller platen were calculated using standard heat transfer methods. Baseplate and fin thermal resistances were calculated using a fin efficiency analysis [Mills, 1995] and an empirically derived equation for heat transfer coefficient from SNL. The equations used are provided in Appendix B.

Two baseplate configurations exist, one of solid copper and the other consisting of a vapor chamber heat pipe within a copper shell. Future scaled versions of the RSC may use either of these configurations, depending on specific design requirements.

Figure 2-4 provides a schematic of the RSC and the underlying thermal resistance equations. Here, *R* = thermal resistance, *t* = thickness, *k* = thermal conductivity, and *A* = area.

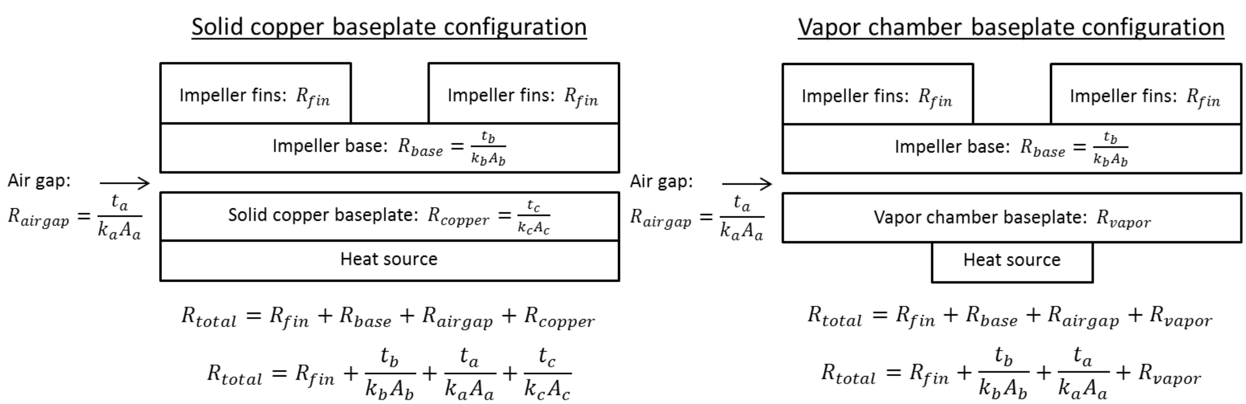


Figure 2-4. Basic RSC configurations (solid copper and vapor chamber heat pipe) and their thermal resistances.

The effective thermal conductivity of a well-designed heat pipe is much higher than that of copper. Therefore, baseplates of RSCs with vapor chambers have lower thermal resistance than solid copper baseplates.

2.3.2.2.2 Total Heat Throughput and Heat Flux

Total heat throughput is defined as the heat removed and rejected by the RSC, <u>for a given temperature difference (ΔT)</u>, thus reflecting the cooling capability of the unit. It is calculated by:

$$Heat\ throughput\ (W) = \frac{\Delta T\ (°C)}{R_{thermal}\left(\frac{°C}{W}\right)}$$

Heat flux is the total heat transferred per unit of heat exchange area. This quantity, which also requires an assumed ΔT, provides insight into how well a device transfers heat for a given footprint area. Heat flux is simply the heat throughput divided by the base area of the cooler or, equivalently:

$$Heat\ flux\left(\frac{W}{cm^2}\right) = \frac{\Delta T\ (°C)}{R_{thermal}\left(\frac{°C}{W}\right) \cdot A_{base}\ (cm^2)}$$

2.3.2.2.3 Fan Performance

For the purposes of cooling in concert with a heat sink, basic fan performance can be characterized by a pressure-versus-flow curve. This curve, which is generally constructed from empirical test data, defines the relationship between pressure and flow at a given rotational speed.

Given a baseline mechanical design and its fan curve, a set of equations known as the *fan affinity laws* can be used to estimate the pressure-flow relationship over a range of speeds and diameters. The fan affinity laws are summarized below.

Fixed speed, variable size:

$$Q_2 = Q_1 \cdot \left(\frac{D_2}{D_1}\right)$$

$$P_2 = P_1 \cdot \left(\frac{D_2}{D_1}\right)^2$$

Variable speed, fixed size:

$$Q_2 = Q_1 \cdot \left(\frac{\omega_2}{\omega_1}\right)$$

$$P_2 = P_1 \cdot \left(\frac{\omega_2}{\omega_1}\right)^2$$

Here, Q = volumetric flow rate, D = diameter, P = pressure, and ω = motor rotational speed. The subscript “1” refers to the property at the initial condition, and “2” refers to the property at the scaled condition.

SNL provided a pressure-flow curve for the baseline 10-cm diameter RSC. Pressures and flows for all other speeds and diameters under investigation were estimated using the fan affinity laws.

2.3.2.2.4 Power Consumption

In terms of its power consumption, the RSC is essentially a centrifugal fan driven by an electric motor. In a basic fan-motor system the electric power consumption for any operating condition can be calculated from four basic quantities: airflow, pressure drop (head), fan efficiency, and motor efficiency. Additionally, because the RSC rides on an air bearing, the drag caused by the bearing must also be considered. The values needed to estimate power consumption were determined as follows:

- Pressure and flow: The development of pressure-flow curves for various speeds and diameters is discussed above.
- Fan efficiency: Although fan efficiency was not directly determined by SNL's fan test, electrical power input to the slave motor was measured. This input power data, paired with the slave motor's rated efficiency profile, allowed an estimated fan efficiency curve to be calculated. For analytical purposes the efficiency profile is assumed to remain constant over the range of diameters and speeds investigated. This is consistent with standard usage of fan affinity laws. While not strictly true, it is a reasonable approximation within the bounds of the present analysis.[4]
- Motor efficiency: Sandia is designing a BLDC motor for the RSC, but that design is not yet complete. SNL provided an estimated motor efficiency for analysis purposes.
- Air bearing drag: The drag caused by the air bearing was estimated using air gap shearing torque equations.

Specifics of the power consumption computation are given in Appendix C.

2.3.2.3 Scaling Analysis: Results and Conclusions

Calculations and tabulated results for weight, startup torque, fan performance, thermal resistance, and power consumption across all diameters and speeds, are included in Appendices B and C. Thermal resistances are provided for copper baseplates only: vapor chamber baseplate resistance is dependent on many design factors that have not been settled, so no estimates of $R_{thermal}$ are reported for that baseplate type.

From a practical perspective, a vapor chamber is more complex than a solid baseplate, and the resulting RSC product will be costlier (assuming that the price of copper does not offset the vapor chamber fabrication and assembly cost). Thus, in a given application there will be a cost-benefit tradeoff. Some products will require removal of a large amount of heat from an area smaller than the baseplate (e.g., a high-speed CPU); a vapor chamber baseplate could prove necessary in such instances, despite the higher cost, to improve horizontal heat spreading.

The net result of better vertical heat transfer combined with uneven heat distribution on the bottom of the vapor chamber shell will depend on the specifics of the application and the RSC design used as a solution. For present purposes, we assumed that the two heat transfer factors balance enough that, when heat spreading is involved, the net thermal performance of a vapor chamber baseplate is at least as good as that of solid copper. On that assumption, analysis of the

[4] It also reflects the fact that there is much design flexibility remaining. For a given size-speed configuration, minor design changes could likely be made to "make up" the difference in performance due to non-ideal fan efficiency.

solid-baseplate RSC design for all applications is the most conservative approach. For this reason, we assumed a solid baseplate for all calculations used to predict thermal performance of the RSC.

Figure 2-5 shows the thermal resistance and total heat throughput of the RSC for Δ*T* = 10 °C.

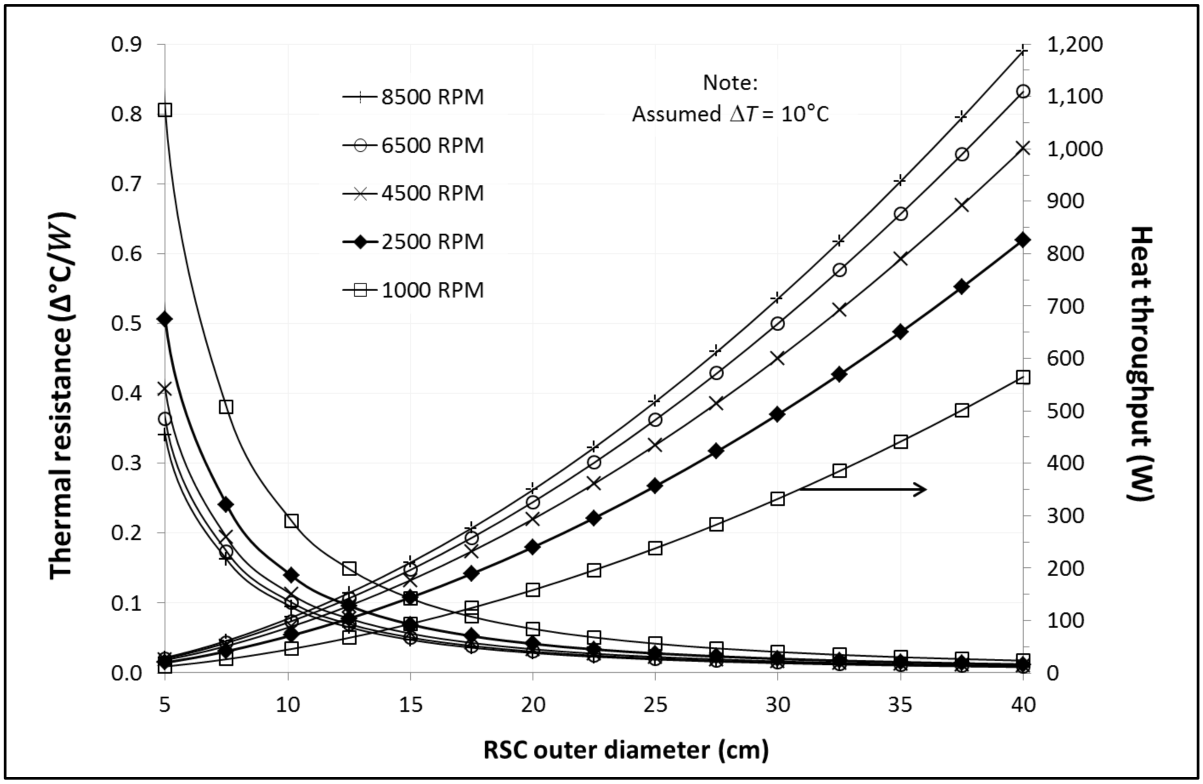


Figure 2-5. RSC thermal resistance and total heat throughput as a function of diameter and speed, for an assumed temperature difference of 10°C

Heat transfer performance improves at larger diameters and greater speeds. Increasing diameter tends to provide a greater relative benefit than increasing speed. Thermal resistance decreases rapidly with increasing diameter in the size range from 5–15 cm, but realizes much less improvement above a diameter of 15 cm. Note that increasing speed above 2,500 RPM continues to improve thermal performance, but with diminishing returns for both thermal resistance and heat throughput.

Heat flux is shown in Figure 2-6. Compared to the heat flux of an RSC with a speed of 2,500 RPM (a likely value for many applications), increasing speed to 8,500 RPM achieves an improvement of about 50% for all diameters.

However, scaling up in diameter from 10 to 20 cm results in a decrease in heat flux of about 15% for all speeds; in going from 10 to 40 cm, the heat flux drops by about 25%. Heat flux, which is $\Delta T/(R_{thermal} \cdot A_{base})$, decreases because as diameter increases the base area increases faster than the thermal resistance. Thermal resistance, which governs heat throughput, follows an asymptotic curve that is relatively flat by a diameter of 20 cm.

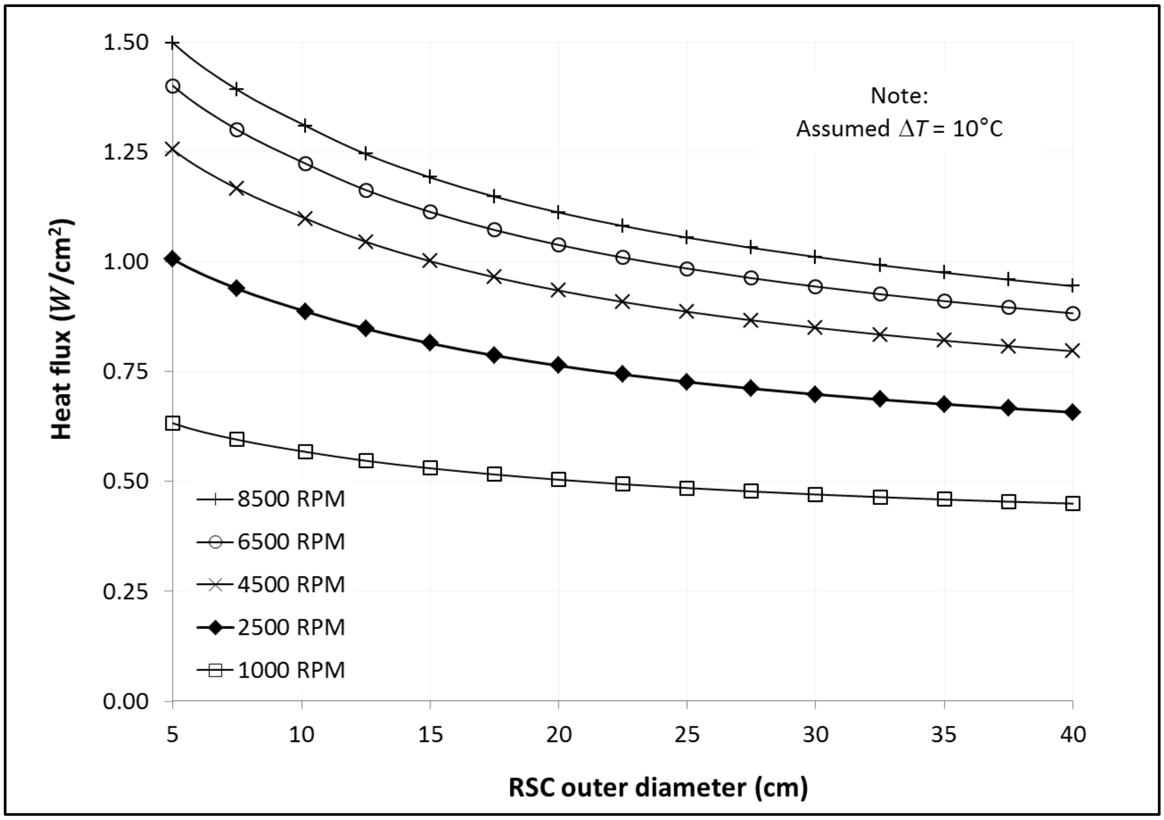


Figure 2-6. RSC heat flux versus diameter and speed, for an assumed ΔT of 10°C

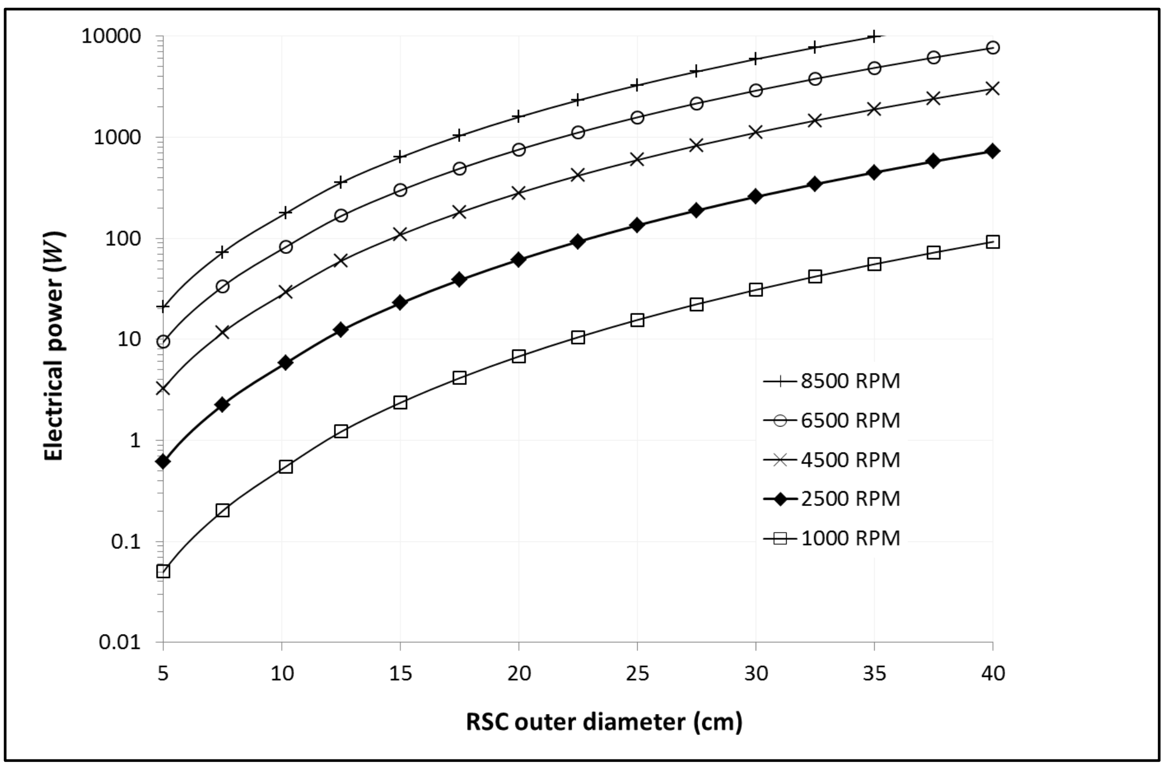


Figure 2-7. Predicted electrical power required for an RSC, versus diameter and speed

Figure 2-7 illustrates the relationship between diameter and power consumption for various speeds. Predicted RSC power consumption at the target speeds of 2,000–3,000 RPM compares well to that of existing fanned heat sinks of similar sizes. However, as with any motor-driven device, power consumption grows quickly at higher RPM, at times to values greater than those seen at larger diameters.

Due to high power consumption and diminishing improvement in thermal performance, we expect that most end-users will find that the costs of using high-speed RSCs outweigh the benefits, especially when combinations of lower-speed RSCs are suitable for the application. In any case, power-performance tradeoffs are generally application-specific, and end-users are encouraged to use the figures above, as well as Appendices B and C, to evaluate the potential performance of the RSC for their specific design goals and constraints. The optimization of size, speed, and number is discussed further in Section 2.5.1.

When designing a cooling system it is also important to evaluate the maximum possible pressure difference (ΔP_{max}) across the fan. Air flow will only occur if the actual ΔP is less than ΔP_{max} (and, in practice, will follow the pressure-flow, or "P-Q" curve of the fan). Thus, ΔP_{max} is an indicator of the compatibility of an active heat sink with a given product to be cooled, including its enclosure (if applicable) and any auxiliary fans. The estimated values of ΔP_{max} for the range of diameters and speeds studied are shown in Figure 2-8.

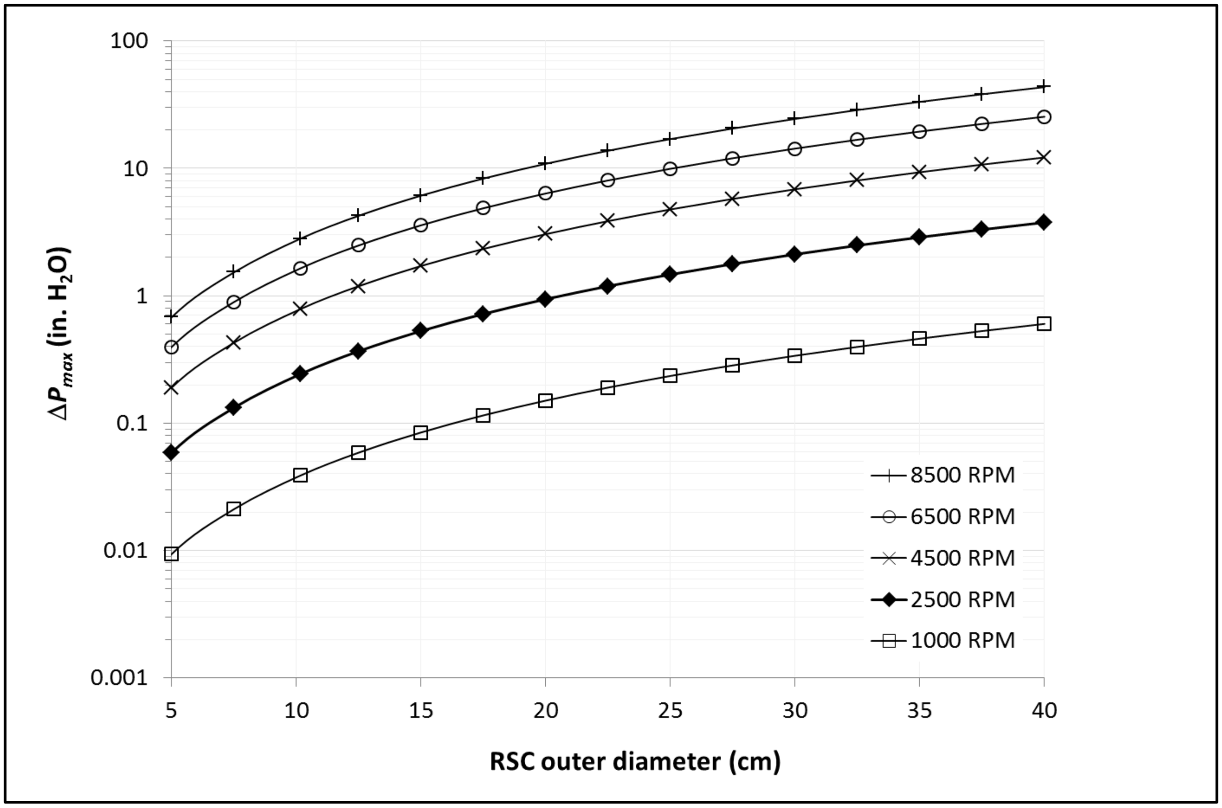


Figure 2-8. RSC maximum pressure drop for various diameters and speeds

Because of the radial nature of the air outflow from an unducted RSC, care should be used in comparing its ΔP_{max} to the usual active heat sink pressure requirement. For example, a straight-finned active heat sink is effectively a semi-ducted fan, having a large resistance to outlet flow due to flow bending and channel effects. The RSC does bend airflow, but the outlet of the impeller (i.e., fan) does not encounter any intrinsic channeling effects. There are likely other important differences between an RSC and a typical active heat sink that make comparison of numbers, as opposed to empirical test results, difficult to interpret.

Finally, since many applications may be concerned with, or even limited by, weight, it is also important to evaluate system weight. This is shown in Figure 2-9, in this case for both solid copper and vapor chamber baseplates since the latter has a significant advantage at larger sizes.

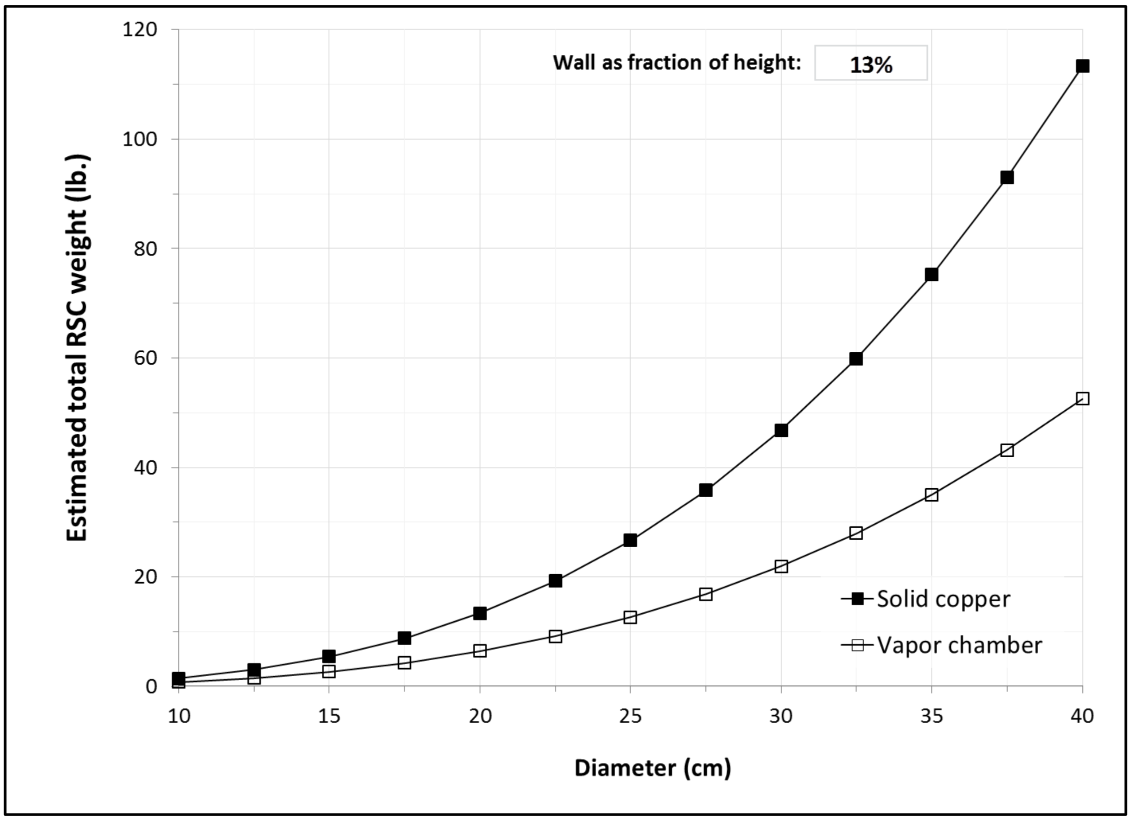


Figure 2-9. Estimated total RSC weight for various diameters, for solid copper and vapor chamber (wall thickness = 1/8th of baseplate height) baseplates

2.3.3 Compatibility Analysis

Because the RSC is not yet a commercial product and many design and optimization choices remain available, the essence of the compatibility analysis was to screen out products for which the current RSC would be highly impractical.

2.3.3.1 Compatibility Analysis Method

Two critical technical product requirements were considered in determining compatibility at this stage:

- Heat transfer, using thermal resistance as a measure
- Area, based on the smallest dimension and the shape (cm x cm) of the heat exchanger space.

Factors such as noise, weight, and reliability were addressed in later evaluation steps. Figure 2-10 illustrates the key questions considered to address the product heat transfer and area requirements.

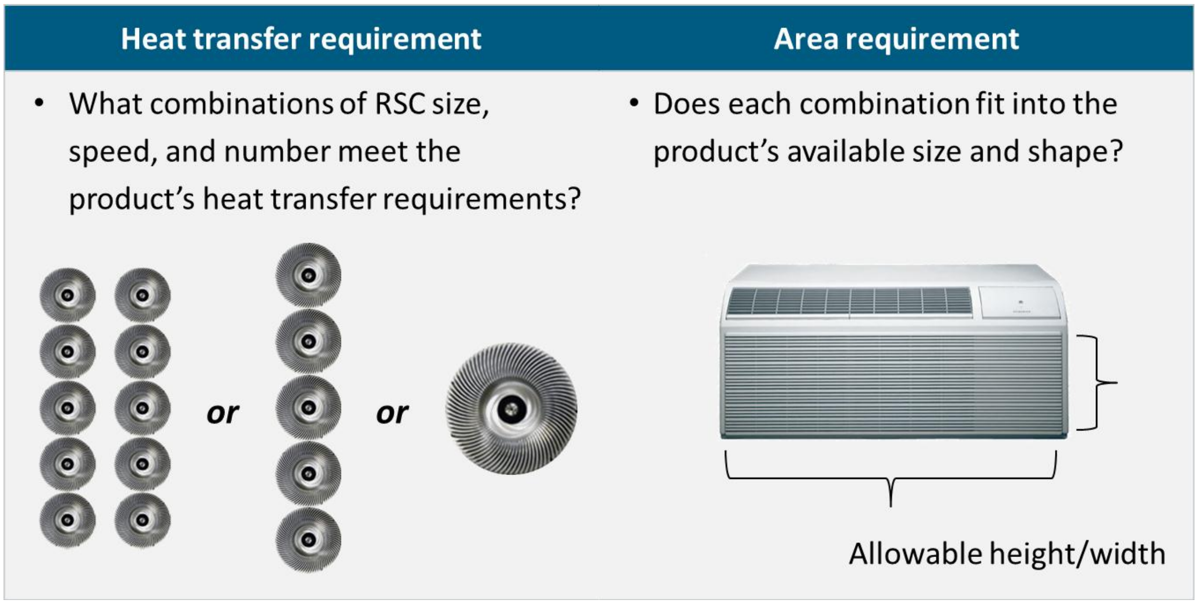


Figure 2-10. Overview of RSC selection process for each product
Sources: Sandia National Laboratories, Friedrich

In determining the answer to these questions for all of the products listed in Table 2-1, all RSC configurations that met the heat transfer requirement and physical constraints were identified. Products that met the following criteria were then screened out:

- The product requires heat exchangers with significantly higher heat flux than offered by any available RSC configuration
- The product requires many RSCs larger than 40 cm to meet the heat transfer requirement.

Screened-out products could be attractive after further RSC enhancement, but they are not practical near-term targets for RSC introduction.

2.3.3.2 Compatibility Analysis Results

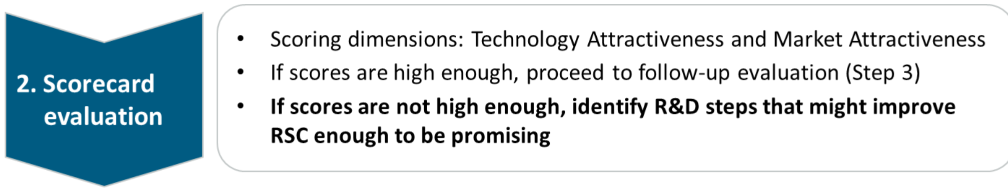
The following products passed the compatibility analysis and moved on to Step 2, the scorecard screening:

- Fan-cooled motors (5, 30, and 75 HP)
- A/V equipment
- Beverage vending machine
- Commercial LED bulb
- Compact refrigerator
- Data center processor
- High-performance PC processor
- Ice maker
- Industrial LED bulb
- Microwave
- Mobile processor
- Peltier devices
- Portable fuel cell (500 W)
- PTAC
- Reach-in RF condenser
- Res. CAC condenser
- Res. fuel cell (5 kW)
- Residential LED bulb
- Residential PV inverter (500 W)
- Residential PV inverter (20 kW)
- Residential RF condenser
- Room air conditioner
- Small battery
- Standard PC processor
- TVs
- Uninterruptible power supply

These products were filtered out by the initial screen:

- Backup generators
- Commercial fuel cell
- Commercial rooftop CAC
- EV battery packs
- Heat pump clothes washers
- Transportation radiators
- Walk-in refrigerators and freezers

2.4 Scorecard Evaluation (Step 2)



2.4.1 Methodology

For each of the products passing the screen described in Section 2.3.3, we assembled information on heat exchanger performance, operating attributes, and market characteristics to assist in understanding how the RSC needed to perform to meet overall product requirements. The following are the characteristics considered for each potential application:

- Heat to be rejected
- Need to have variable heat transfer rate
- Temperature differential (air-side and source-to-sink)
- Airflow requirements (distribution and heat dissipation of nearby components)
- Current heat transfer limitations
- Noise
- Size (limiting length and allowable area)
- Power consumption
- Weight
- Reliability requirements
- Market size
- Potential cost premium
- Heat exchanger integration factors
- Market acceptance of new technology
- International market opportunities

This information was compiled from a variety of sources, including:

- Manufacturer literature and thermal management guidelines
- DOE Energy Efficiency rulemaking technical support documents (TSDs)
- Parts supplier catalogs
- Technology and market research reports
- Discussion with subject matter experts
- Hobbyist forums
- Other online literature

This information provided a basis to evaluate the value of an RSC, or set of RSCs, for each product application. When quantitative values were unavailable (e.g., allowable cost premium) we consulted with internal Navigant subject-matter experts and utilized best judgment.

For each candidate product, we used two scorecards to perform an evaluation, based on the characteristics listed earlier in this section. These characteristics were organized into Market Attractiveness and Technology Attractiveness dimensions, with the goal of prioritizing products that show the best technology and market fit with the current RSC. Details on each scorecard will be presented later in this section. Figure 2-11 maps combinations of scores to RSC market introduction potential.

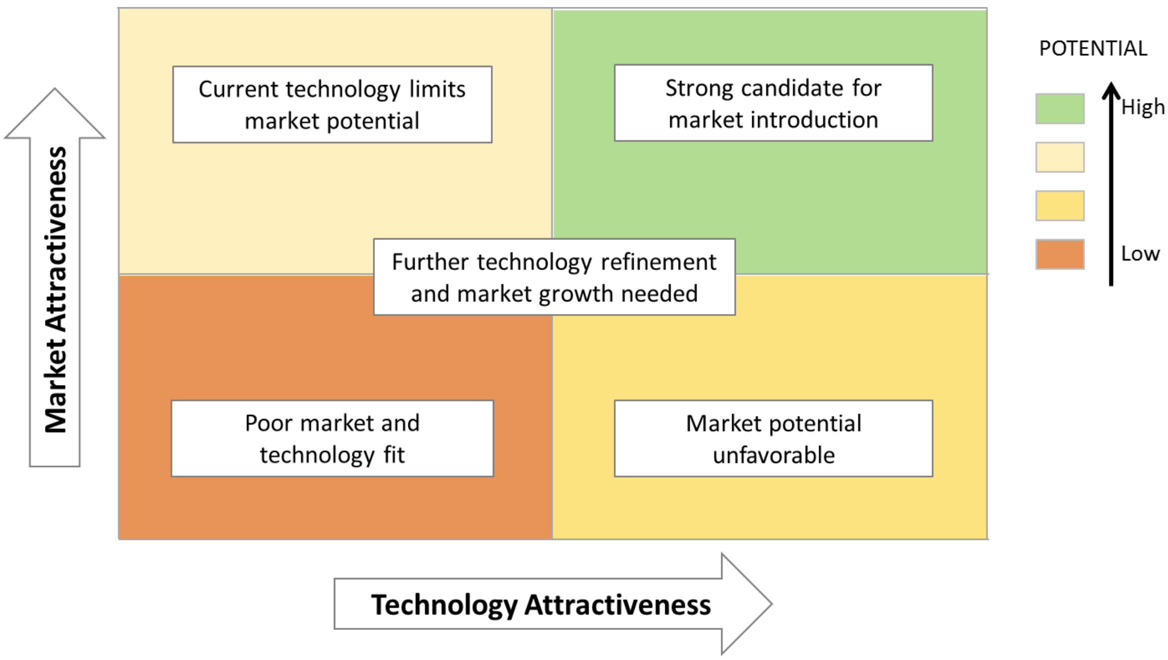


Figure 2-11. Map of RSC market introduction potential relative to Market and Technology Attractiveness scores

For visualization and evaluation purposes, the scorecard map was divided into four quadrants. The dividing lines between quadrants are defined by the average of the highest and lowest scores on the relevant axis.

The most promising products for RSC introduction landed in the top half of both scorecards, thus reside in the upper right quadrant of map. That quadrant contains products for which the RSC is nearly ready to meet the needs of the particular market, and the market is worthy of pursuing to commercialize the technology.

Conversely, products in lower left quadrant are considered least promising. That quadrant contains products for which the RSC would require significant R&D to meet product needs, and the market is unreceptive to new technologies carrying a cost premium.

For each of the scorecards we assigned a weight to each rating factor to reflects its approximate overall importance. Using a three-point scale, we scored each product against each rating factor, then calculated an overall score by multiplying the rating factor scores by their weights and summing them.

2.4.1.1 Technology Attractiveness

The Technology Attractiveness scorecard evaluates how well the current RSC design fits a market, from the OEM or licensee perspective. The scorecard consisted of four rating factors:

1. Design complexity: A quantitative assessment of the size and number of RSCs needed to meet the heat transfer requirements of the product. Also, as applicable, the level of risk and/or uncertainty involved in scaling the current 10-cm RSC to that combination of size, speed, and number of units.
2. Product integration: A qualitative evaluation of the level of RSC refinement, starting with the current design, required to integrate it into the product. Levels included:
    - The current RSC design generally meets the current product configuration with minimal RSC or product refinement (e.g., a drop-in replacement)
    - Moderate RSC refinement is required to meet the current product configuration (e.g., it needs to operate within a ducted system), or the product needs moderate refinement to enable an RSC to be used
    - Substantial RSC refinement is required to meet the current product configuration, or the product needs substantial refinement to enable an RSC to be used. This may pose an barrier to RSC introduction.
3. Market advantages: A qualitative evaluation of whether the RSC would provide significant improvements of certain critical factors for that product, over conventional heat transfer methods. Includes size, weight, noise, fouling, etc.
4. Potential for breakthrough: A qualitative assessment of whether the RSC can break through any current market barriers, or enable the product to offer breakthrough capabilities.

Figure 2-12 below shows the scoring matrix and weight for each rating factor in the Technology Attractiveness scorecard.

2.4.1.2 Market Attractiveness

The Market Attractiveness scorecard evaluates how promising the market looks, from SNL's standpoint, for initial RSC introduction and widespread adoption (i.e., how difficult will it be to gain market success). The Market Attractiveness scorecard consisted of three rating factors:

1. U.S. market size: Based on the estimated number of units sold in the United States annually
2. Market adoption of new technologies: A qualitative estimate for the readiness of a given product category or market to integrate and adopt new technology, specifically related to heat transfer.
3. Allowable cost premium: A qualitative estimate of the willingness of a given market to accept a cost premium for a new heat exchanger technology in its products.

Rating factors / Key questions	Wt. (%)	Score		
		1 (Low)	2	3 (High)
Design complexity Does the RSC meet the requirements for the product with minimal complexity?	**40**	Requires multiple RSCs, either above 20 cm or in the 0–5 cm range	Requires multiple RSC in 5–20 cm range, or one RSC in either the 0–5 cm or 20–40 cm ranges	Requires one RSC in the 5–20 cm range
Product integration Is the current RSC ready for immediate integration in products?	**25**	Significant RSC refinement required, potential issues to introduction	Moderate RSC refinement required for product introduction	Minimal RSC refinement required for product introduction
Market advantages Does the RSC provide significant advantages over current technology in this product?	**25**	None expected	Limited potential to address concerns	Moderate potential to address concerns
Potential for breakthrough Does the RSC break through any known product barriers?	**10**	None expected	Limited, incremental improvement, or product differentiation	Significant improvement, or market disruption

Figure 2-12. Technology Attractiveness scorecard

Rating factors / Key questions	Wt. (%)	Score		
		1 (Low)	2	3 (High)
U.S. market size What is the potential market size for the RSC for this product?	**50**	< 500 k/year	From 500 k/year to < 5 M/year	> 5 M/year
Market adoption of new technologies How readily does this market accept new technology, historically?	**35**	Slow adoption of new technology (5–10 years), few innovative products	Moderate adoption of new technology (3–5 years), several innovative products in niche areas	Rapid adoption of new technology (< 3 years), numerous innovative products
Allowable cost premium How willing is the market to bear a more expensive heat exchanger for this product?	**15**	Low to moderate, especially if product solves key issue	Moderate to high, especially if product solves key issue	Typically high

Figure 2-13. Market Attractiveness scorecard

Figure 2-13 above shows the Market Attractiveness scorecard. Appendix F contains scoring results for each product for both the Technology Attractiveness and Market Attractiveness scorecards.

2.4.2 Results of the Scorecard Evaluation

After the Technology and Market Attractiveness scores were determined for each product, these scores were plotted on the scorecard map introduced in Figure 2-11. The resulting graphic (Figure 2-14) helps in identifying the most promising products for initial RSC commercialization. To provide a broader view of how product categories fared, similar products were assembled into the *product groups* displayed in the figure. These groups help to show general trends, though it should be noted that the grouping was made based mostly on proximity on the map rather than product category; some circles do contain unrelated technologies (e.g., batteries are found in the LED Lighting group).

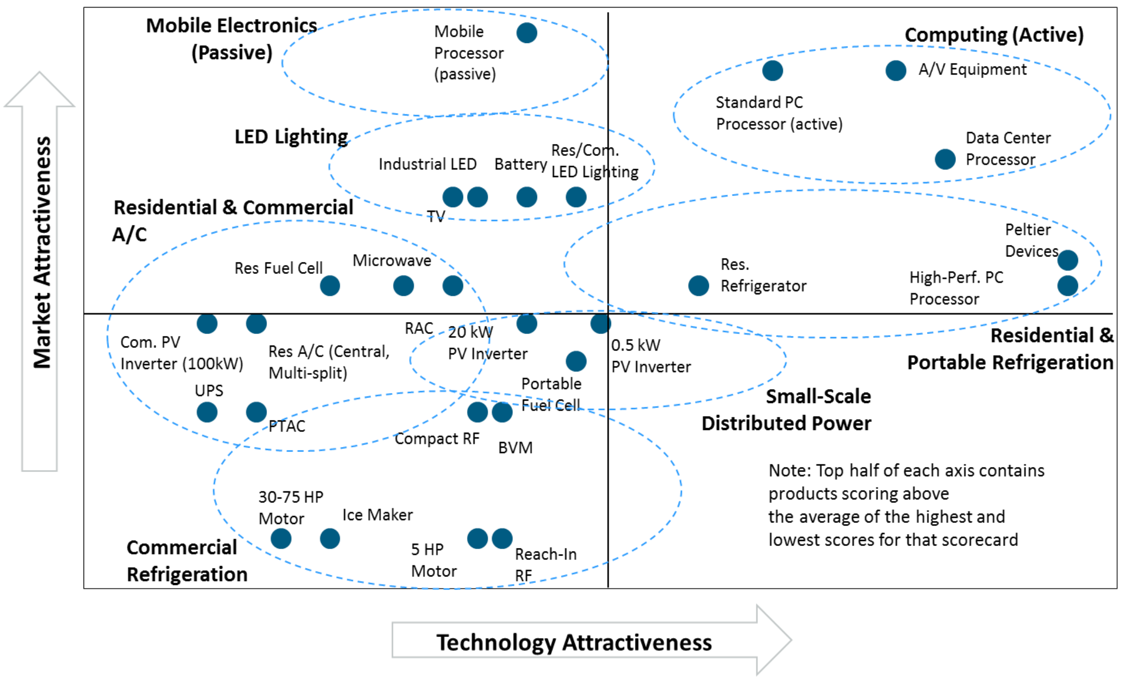


Figure 2-14. Scoring map, by product category

Six products with a high potential for successful RSC introduction are found within the Computing and the Residential & Portable Refrigeration groups. These products are described at a high level in Table 2-4 and are discussed further in Section 2.5.

The products not listed in Table 2-4 were screened out of the remainder of the analysis under this project.

Table 2-4. Summary of Most Promising Products for Initial RSC Commercialization

Product	Description
Standard PC processor (laptop-desktop)	Laptop and desktop computers require heat sinks, heat pipes, and fans to remove heat generated by the processor and other components Benefits from RSC: Noise and fouling reduction, potential size reduction for laptops
High-performance PC processor (gaming PC)	Gaming PCs use high-performance computing and graphics processors that typically require large, fanned heat sinks Benefits from RSC: Significant size advantage, ability to increase clock speeds, variable capacity, reduced noise and fouling
Peltier devices	Using the thermoelectric effect, Peltier devices remove heat from sealed enclosures at ambient conditions for remote telecommunications, military, and other mission-critical electronics applications Benefits from RSC: Opportunity for either size reduction or performance enhancement, reduced fouling
Data center processor (server)	Within data centers, server processors utilize heat sinks with either integral fans or those located within the rack to reject the significant amounts of heat generated in the server enclosure Benefits from RSC: Reduced size could allow either more components within a space or a smaller enclosure, variable capacity
A/V equipment	Audio-visual equipment (e.g., stereo receivers, set-top boxes, game consoles, projectors) and other enclosed electronic devices require proper thermal management to maintain operations Benefits from RSC: Reduced size, noise, and fouling
Residential refrigerator	Refrigerators use fans to supply airflow over condenser coils whose performance is limited by current fin-and-tube heat exchangers and dust accumulation over time Benefits from RSC: Improved coefficient-of-performance (COP), additional refrigerated space, variable capacity, noise and fouling reduction

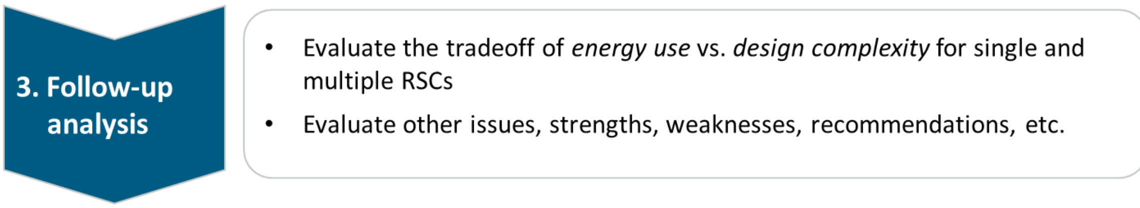
Although the following products did not rank as highly attractive for *initial* RSC introduction, they are still promising and may become more appropriate for RSC introduction as the technology matures:

- Mobile electronics
- LED lighting
- Small-scale distributed power

- Residential & commercial
- HVAC and commercial refrigeration

Appendix G provides further detail on these screened-out products and categories.

2.5 Follow-Up Evaluation (Step 3)



2.5.1 Determining the Best-Fit Compatible Configuration

The follow-up evaluation provided an opportunity to dig deeper into the six most-promising products. For those products, tradeoffs between energy use and design complexity were explored to select the RSC configuration, among those identified in the compatibility analysis, with the best fit in terms of size, speed, and number of units.

Assessing energy use was straightforward, but design complexity was more complicated. That characteristic consists of two factors, the number of RSCs required and their size.

It is clear that, at this stage in the development of the RSC, solutions requiring a single RSC close to 10 cm in diameter could be defined as minimally complex. When forced to compare more-complex combinations of multiple scaled RSC, the idea of design complexity becomes less clear and more subjective. Several units operating at lower speed could be preferred over a single unit at higher speed because the configuration is “simple enough” and requires less energy. On the other hand, operating multiple RSCs in close proximity may introduce risk and uncertainty. For example, a configuration with three RSCs with lower energy consumption might be less attractive than a single RSC that requires greater energy use. Best judgment was used for this study; in practice, the product designer will balance this tradeoff for their specific application.

Of the six products evaluated, five had a best-fit solution consisting of a single RSC. Those were the four electronics and computing applications, plus Peltier devices. Residential refrigerators could require one RSC, but might also need multiple units, depending on the method of integration with the condenser’s refrigerant tubes. Table 2-5 below outlines the heat transfer requirements and anticipated size ranges, for the case of a single RSC, for all six most-promising products.

2.5.2 Additional Evaluations: Energy Savings

After the best-fit compatible configurations were determined, strengths, weaknesses, and any other remaining issues were explored in depth. In this report we will focus on exploring energy savings opportunities in the specified products

Table 2-5. Best Size Range for a Single-RSC Configuration for the Most-Promising Products

	Heat throughput (W)	Size range for single RSC (cm)
Standard PC processor	77	5–10
High-performance PC processor	95	7.5–10
Peltier devices	120–240	10–17.5
Data center processor	130	7.5–12.5
A/V equipment	200	10–20
Residential refrigerator	285	12.5–17.5

For the electronics cooling applications, a single RSC has the potential to be a drop-in replacement for the current active heat sink. A best-fit RSC configuration, as defined in the previous section, could offer an estimated energy savings of about 40–80% for these products. While the fan consumption is a small portion of the overall product energy use, any power savings achieved would increase battery life and offer other secondary benefits. As discussed later in this section, these “secondary” benefits are often of primary importance for electronics applications.

Table 2-6 shows the potential fan energy savings of a best-fit RSC design for each product, and how that could affect overall product energy consumption.

Table 2-6. Potential Fan Energy Savings for Most-Promising Products

	Potential fan energy savings (%)	Optimizes RSC design			Current product	
		Size (cm)	RPM	RSC power (W)	Current fan power (W)	Est. total product power (W)
Standard PC processor	70%	7.5	1,500	0.6	2	20–60 (laptop) 75–200 (desktop)
High-performance PC processor	80%	7.5	2,000	1.2	6	300–600
Data center processor	83%	10	1,500	1.5	9	200–450
Peltier devices	31%	3 x 7.5	2,500	6.9	10	240
A/V equipment	40%	2 x 10	1,500	3.0	5	175–350

For residential refrigerators, modest fan energy savings are available but the main savings in that product category are associated with heat exchanger thermal resistance and reduction of fouling. For a refrigeration cycle, a lower heat exchanger air-side thermal resistance has a direct effect on the overall system coefficient-of-performance (COP).

With a lower thermal resistance, the required temperature difference between the refrigerant and air can be decreased for a given heat load. In the case of a condenser, lowering the required condensing temperature improves compressor efficiency, which reduces power consumption. Preliminary simulations by SNL and a major industry partner indicate that lowering the air-side thermal resistance by 50% will result in an overall COP improvement of approximately 10%. Our performance evaluation indicates that this thermal resistance improvement is possible, but the actual results will depend on refrigerant tube integration with the RSC baseplate.

Additional COP-related benefits may also be gained from the fouling resistance of the RSC. Current condenser heat exchanger designs are susceptible to dust accumulation, which increases thermal resistance and negatively affects COP over the lifetime of the product. The rotating character of the RSC heat exchange surface significantly reduces dust accumulation, which maintains efficient operation throughout the product life.

2.5.3 Other RSC Benefits

Beyond energy savings, the RSC offers a number of performance benefits that are often more important than fan energy savings alone. In certain instances, these non-energy benefits are what will most interest OEMs, potential licensees, and consumers, in that the RSC will enable new product form factors, improved customer experience, or other product-related improvements. Non-energy benefits include:

- Performance enhancement: By allowing greater heat transfer from a given footprint, product manufacturers can install more capable components with greater heat dissipation. Also, RSC speed can be modulated to provide extra heat transfer when needed (at the cost of energy efficiency), which would be valuable for variable-speed operations, maintaining small size, increasing processor clock speeds, etc.
- Size and form factor: The RSC generally has smaller footprint and height than conventional fan-plus-heat-exchanger assemblies, which allows for more innovative and slimmer product designs.
- Noise: By maintaining quiet operation, the RSC permits higher-speed operation and better product performance without diminishing user experience.
- Fouling: The RSC design reduces dust build-up that is a major cause of electronics overheating and long-term loss of heat exchanger performance.

3 Product Deployment Strategies

This section corresponds to Task 3 of the project.

3.1 Deployment Process Overview

As previously discussed, we are using *commercialization* to mean the full process of developing a technology for introduction in the marketplace. *Deployment* is a key part of commercialization, defined here as the process of developing specific avenues for the introduction of a technology as a market-ready product.

In the previous section we identified markets that we recommend for initial introduction of the RSC technology in a product. In order to successfully commercialize the RSC in a product, deployment activities must be pursued, specifically those involving finding avenues for introduction. For the most part, initial avenues should be strategic institutional and industry partnerships.

Such partnerships can help bridge the gap between this new technology and a market-ready product. In many cases, the current development status of the RSC technology does not yet fully align with the expectations of an OEM, licensee, or consumer. Strategic partners can provide the insight, guidance, and development necessary to advance the technology to a market-ready status.

The goal of the deployment strategy task was to develop detailed and prioritized strategies that are best able to acquire these partnerships for each of the most-promising products.

3.1.1 Deployment Roadmaps

For each high priority product, the deployment strategy, along with the product and market assessments performed earlier, were synthesized to form a comprehensive roadmap for engaging desired partners. Table 3-1 provides an overview of the types of information contained in the deployment roadmaps. The remainder of this section will focus on the details of the deployment strategies contained within these roadmaps.

Table 3-1. Overview of Deployment Roadmaps

		Description
Product and Market Assessment	**Product overview**	• Topology of current heat transfer solutions • How the RSC would integrate into products • Value of additional RSC benefits
	Scorecard evaluation	Scoring details from Technology Attractiveness and Market Attractiveness scorecards
	“SWOC” analysis	Summary of RSC Strengths, Weaknesses (and risks), Opportunities, and Customers for the product
	Market analysis	• Product development dynamics • Target audience categories and potential partner names

		Description
		• Development tasks to answer key partner questions
Deployment Strategy	**Proposed strategy**	Step-by-step description of the proposed strategy for target audiences; key suggestions; and activity prioritization flowchart
	Recommended activities	Specific communication, demonstration, and development activities, prioritized for each product, including: • Key print/online media outlets, conferences, and trade shows • High-level timeline of deployment strategy

3.2 Deployment Strategy Activities

Each proposed strategy consisted of activities aimed at attracting partner interest and demonstrating the RSC's capabilities for their product. We prioritized these activities based on their relative cost, benefit, action risk (i.e., the risk of doing the activity), inaction risk (i.e., the risk of not doing the activity), and deployment time frame.

While many of the activities could provide long-term benefits for wider RSC commercialization, we prioritized for initial deployment those that had the greatest near-term benefit. After achieving initial market introduction in one or more key areas, many of the other deployment activities might become important to accelerating the growth of success from one product area to other potential applications.

Deployment activities could generally be categorized into three subsets:

- *Development activities* continue and/or extend SNL's research activities, focusing on answering a number of common questions that partners may have about RSC operation, performance, and reliability.
- *Communication activities* attract the attention of potential industry partners and convey the advantages and benefits of the RSC.
- *Demonstration activities* show the RSC's capabilities and help to prove its ability to solve a product's current heat transfer and operational issues.

Details for each communication and demonstration activity are found in Appendix H.

3.2.1 Development Activities

During our evaluation of how best to engage potential partners and convince them of the RSC's benefits, we identified a number of common questions about the RSC's operations that partners could have. While these questions may not preclude partner licensing or outreach, they may delay the process by raising doubt about the RSC's readiness and causing potential partners to take a "wait-and-see" approach. We recommend SNL investigate, at least qualitatively, these high- and medium-priority activities before widespread partner outreach and engagement. The recommended near-term development tasks include:

High priority

- Operating map: Provide pressure vs. airflow curve for 10-cm RSC at different RPM and performance map of shaft power and thermal resistance for scaled RSCs at different RPM

Medium priority

- Duct, enclosure, multiple RSCs: Conduct testing in ducted or enclosed environment to determine operational issues with nearby walls, other objects, and multiple RSCs
- Reliability: Perform accelerated life testing to determine RSC lifetime, points of failure, and identify ways to increase reliability
- Fouling: Conduct testing on the current RSC design to quantify the relationship between fouling (minor as it may be) and long-term performance
- Noise: Perform noise testing for various speeds with the most current RSC design

Low priority

- Rotation (transient): Analyze the transient performance of the air bearing when the RSC is rotated from its primary axis to understand operational limitations of the current design
- Rotation (steady): Quantify heat transfer performance losses due to the air bearing operating outside of the design orientation and investigate ways to adjust pre-load ratio to different operating orientations.
- Safety: Demonstrate safety screen or other mechanism to protect users and other components and ensure performance

3.2.2 Communication Activities

Communication activities work to attract the attention of industry partners and convey the advantages and benefits of the RSC. These activities include:

High priority

- Print/online publicity update: Update media publications, periodicals, websites, etc. on RSC development
- Public/private webinar: Present introduction and update to RSC technology through online webinar
- Industry or developers conference presentation: Update RSC white paper and present to technical audience in target sectors

Medium priority

- Federal Computing Group outreach: Present to federal researchers and industry groups working on more efficient data center cooling
- ARPA-e Technology Showcase: Participate in the trade show portion of the Innovation Summit

Low priority

- DOE / ENERGY STAR Product Team outreach: Lead discussions among appliance project teams to raise awareness for future efficiency rulemakings and specifications

- Innovation conference presentation: Discuss importance of heat exchanger breakthroughs including RSC

3.2.3 Demonstration Activities

Demonstration activities act to prove the RSC's capability to solve a product's current heat transfer and operational issues. These activities include:

High priority

- Provide prototype to interested OEMs/suppliers: Invite interested industry partners to evaluate an RSC prototype

Medium priority

- Conduct testing at federal computing facilities: Work with federal data center staff to integrate RSCs into current or retired systems

Low priority

- Develop/distribute tools and computational fluid dynamics (CFD) modules: Create a CFD module that simulates RSC operations in different environments, and/or work with major CFD software vendors to incorporate RSC in design suite.
- Test RSC in actual products at SNL: Integrate prototype RSCs in computer, server, and A/V electronics at SNL
- RFP/FOA for demonstration: Offer funding or cost share to demonstrate the technology in actual product applications or separate concepts
- Invitation for press to benchmark: Provide interested media members the opportunity to conduct performance testing on an RSC prototype.
- Co-sponsor development or business plan competition: Partner with industry organization or university to create competition or project focused around RSC technology
- Pre-order and direct manufacture: Offer public to pre-order a prototype version of RSC

4 Recommendations

4.1 Recommended Initiatives for Sandia Cooler Technology

The initiatives outlined in this section are based on our assessments of the prototype RSC and the Sandia Cooler technology in general, plus an in-depth analysis of the six most promising products for initial RSC commercialization. Because of the wide applicability of the technology, we anticipate that multiple cycles of development, demonstration, and subsequent commercialization are appropriate for the Sandia Cooler technology.

Prioritizing resources to achieve initial success in one market sector can have a significant impact on the market acceptance of the new technology throughout industry. Therefore, we recommend the following:

- Focus the initial commercialization effort on high-performance PCs (e.g., gaming computers), as a readily attainable entry point into the broader electronics market
- Pursue lighting and residential refrigeration applications as medium-term goals. These applications would involve later RSC generations that have benefitted from ongoing R&D activities, and the information gained from experience in the electronics markets
- Continue development of Sandia Coolers for HVAC and other higher-heat-flux applications as longer-term prospects, whose viability may be assessed through current and future R&D projects.

Figure 4-1 illustrates our recommended roadmap for commercializing the Sandia Cooler technology, which is subsequently discussed in detail.

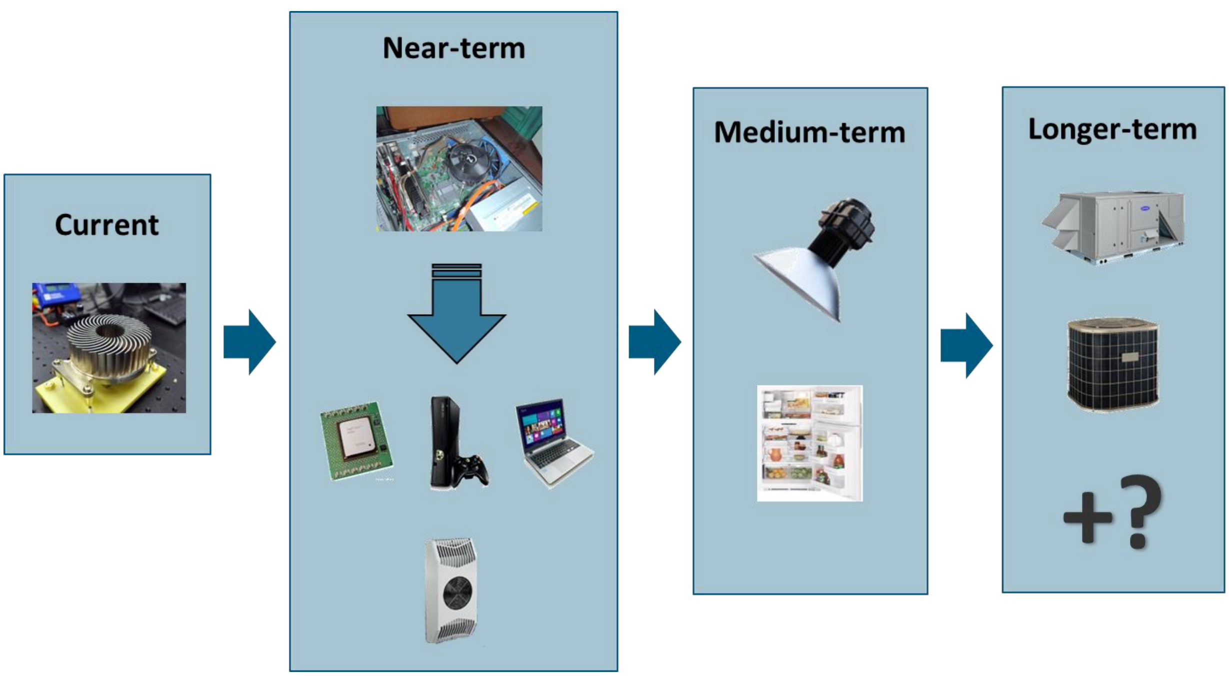
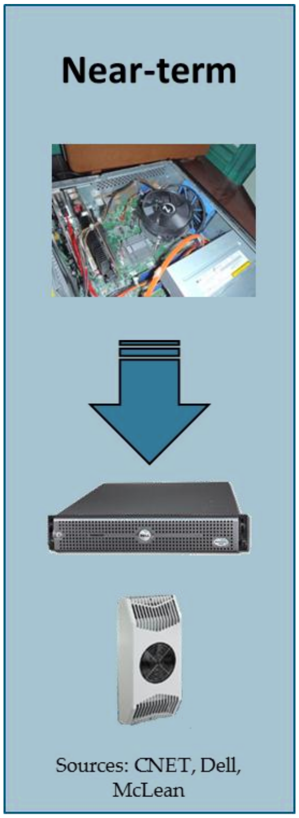


Figure 4-1. Recommended commercialization roadmap for Sandia Cooler technology

Sources: Sandia National Laboratories, CNET, Dell, ifixit, CPU-World, McLean, Solarone, GE, Carrier, Fraser-Johnson

4.1.1 Recommended Near-Term Initiatives

By design, the current version of the RSC is very well-suited for electronics applications. We see the high-performance PC market as the best entry point into the broader electronics market, for the following reasons:



Sources: CNET, Dell, McLean

- Of the six prioritized products, high-performance PCs carry the lowest barrier to initial introduction. This is due to:
  - A highly competitive marketplace for thermal solutions
  - A large technical community already interested in the RSC
  - Potential licensees that sell both to OEMs and directly to consumers
  - The market is driven by value-added benefits, not the lowest-cost supplier.
- Proving the viability of the RSC in this market will have a catalyzing effect on others, as the technical community reviews and discusses the RSC’s capabilities through online communities, print publications, and trade shows.
- Although high-performance PC sales numbers, product visibility, and energy-savings potential are lower than those of some other priority segments, the momentum gained from successful introduction in this early-adopter market will fuel partner engagement for the other most-promising electronics products.

While pursuing the high-performance PC market, communications activities and media outreach should also discuss the near-term viability for the other electronics products. Once initial market success is achieved in the high-performance PC market, industry partners in the laptop-desktop, data center server, and A/V equipment markets may be interested in evaluating the RSC and optimizing its design to fit their needs. Note that some partners may offer products in multiple electronics categories; they can integrate the RSC across their product portfolio.

We believe that the Peltier device market could logically follow the electronics market, once the RSC becomes a commercially available off-the-shelf thermal solution. Even so, there is still the potential for innovative RSC solutions, as the technology could enable even greater performance and efficiency by integrating the thermoelectric element directly into the base of a dual-sided impeller, rotating the entire system with a single motor. Work in this field is currently underway between SNL and a partner, Optimized Thermal Solutions. Together they are developing an advanced RSC prototype for thermoelectric refrigeration. This development work is consistent with the recommended commercialization strategy.

4.1.2 Recommended Medium-Term Initiatives

We recommend that SNL pursue lighting and residential refrigeration markets as medium-term goals because of their high visibility, potential for energy savings, and clearer development pathway in comparison with longer-term products. Industrial lighting and residential refrigeration can act as developmental bridges between the current RSC design for electronics cooling and advanced designs capable of much greater energy savings. Based on this potential, as well as institutional and industry interest, the team at SNL has already started medium-term research and development initiatives on these applications.

- Industrial lighting: SNL has developed an RSC design that involves directly mounting LED packages onto an impeller, without using an air bearing or baseplate (Koplow 2012b). This could improve thermal management of solid state lighting (SSL) fixtures, and permit the use of a smaller number of LED packages operating at higher amperage. Benefits could include lower upfront cost and greater lifetime, thus accelerating the acceptance of SSL in the marketplace and generating significant energy savings. Longer-term, using the rotating impeller also offers the potential for higher-efficacy fixtures through individual Red-Green-Blue (RGB) LED color mixing.

  Current development status: SNL is developing an SSL prototype in FY 2014. We recommend creating a roadmap that compares the cost trajectory of LED packages against the time frame for SSL concept development, to better understand the concept's viability in future years as LED prices drop (DOE SSL Roadmap 2012).

- Residential refrigeration: The RSC baseplate can be integrated with a condenser refrigerant coil to extend the RSC's performance to moderate heat flux. Benefits include improved COP from the increased air-side heat transfer coefficient and a reduction in long-term heat exchanger fouling. In the medium term, this could result in energy savings for a major group of products in the United States. It would also benefit the development cycle for higher-heat-flux applications, such as air-conditioning products that offer even larger energy savings potential.

  Current status: SNL is developing refrigerant-based RSC prototypes for multiple products during FY 2014–2015, including: a 1-kW heat pump (with United Technologies Research Center), a residential refrigerator (with the University of Maryland), as well as a heat pump water heater and other products (with Oak Ridge National Laboratories).

The current SNL research projects are fully consistent with our recommended strategy. To reduce the potential for losing focus on commercializing the RSC for the electronics markets, SNL may wish to addressing these more-advanced products through separate internal teams, if possible. Once RSC deployment in the electronics markets gets traction, those licensees will assume a larger role in product development, and any freed-up SNL resources could be transferred to the lighting and residential refrigeration initiatives.

Assuming that the current R&D projects result in good performance, we recommend using a commercialization framework similar to that developed for the electronics markets.

4.1.3 Recommended Longer-Term Initiatives

Commercial HVAC, industrial cooling, and other high heat flux applications are attractive longer-term prospects because of their greater energy savings potential. However, even with RSC improvements such as integrating refrigerant coils, that design appears to be most suitable for low-to-medium-heat-flux products. A different type of Sandia Cooler, such as the axial air flow design mentioned in Table 1-1, may provide a clearer pathway for the larger applications. The viability of such applications may be assessed through R&D projects:

Source: Carrier

- Work has already begun on the axial concept, referred to as the Axial Sandia Heat Pump. As mentioned, this design incorporates several rows of fins, connected to a central hub, that transfer heat to and from an airstream when refrigerant flows through the fins. The concept improves on the RSC by offering a compact, stacked design, and provides the necessary air flow for HVAC applications (Koplow 2012a). SNL has partnered with Trane (Ingersoll Rand) in this effort, and that project is currently developing a prototype.

- Advanced Sandia Cooler concepts have the potential to be an air-cooling breakthrough for industrial applications. For example, if used in a power plant cooling system it would reduce the use of water-intensive cooling towers, thus conserving water resources.

The knowledge gained from commercializing near-term electronics and medium-term residential refrigerator products will help resolve design, manufacturability, and operational issues for these advanced applications of the Sandia Cooler technology. We recommend continuing development on these longer-term goals, with periodic reassessment of their potential.

4.2 Conclusion

The recommendations above reflect our assessment of the Sandia Cooler technology's potential for each product, based on the development status of current activities. While we provide a suggested timeframe for each set of initiatives, the progress of each activity will depend on the level of resources available to SNL from BTO, industry partners, and others.

Work on medium- and longer-term goals should continue during initial commercialization, so that experiences with earlier products can accelerate development of later concepts and products. Successful commercialization in any product area is dependent on the level of interest and commitment of industry partners. This roadmap should be reviewed in the future based on marketplace interest, as well as the results of further RD&D activities.

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Appendix A Profiles of Potential RSC Applications

Table A-1. Basic Profiles of Products Considered for RSC Introduction

Sector	Application	Description	Heat transfer req. (W)	Source / ambient temperature (°C)	Available size (cm x cm)
Com. HVAC&R	Peltier devices	Non-specific applications (1–200W cooling)	240	45/35	40 x 18
Com. HVAC&R	Ice maker	R404, air-cooled head with collector, 400–600 lbs./day harvest rates	850	70/45	50 x 40
Com. HVAC&R	Reach-in refrigerator	R134a, 1/3 HP, 2,700 Btu/hr. reach-in refrigerator	800	80/45	50 x 25
Com. HVAC&R	Beverage vending machine	R134a, 35 cu.ft., 500 can capacity	850	70/45	30 x 20
Com. HVAC&R	Packaged terminal air-conditioner	R410a, 1-ton PTAC	3,250	120/45	90 x 40
Com. HVAC&R	Walk-in refrigerator	R404, 4-ton, 240 sq.ft. walk-in cooler (5 HP compressor)	13,200	90/45	50 x 50
Com. HVAC&R	Commercial CAC	R410a, 25-ton RTU	82,100	70/45	382 x 132
Data center	Data center processor	Intel Xeon processors	130	68/45	5.6 x 4.1
Data center	Radiator (generator)	500kW stationary diesel generator, 33% efficient	1,000,000	85/45	200 x 200
Data center	Uninterruptible power supply	Liebert UPS (225kW, 95% efficient)	11,250	60/35	175 x 55
Distributed power	Residential fuel cell (stationary 5kW)	PEM, with heat recovery (35% elec. eff.,40% thermal eff. with water loop)	1,760	65/45	40 x 40

Sector	Application	Description	Heat transfer req. (W)	Source / ambient temperature (°C)	Available size (cm x cm)
Distributed power	Commercial fuel cell (stationary 400kW)	PAFC, with heat recovery (35% elec. eff.,40% thermal eff. with water loop)	143,000	200/45	360 x 240
Distributed power	Portable fuel cells (0.5 kW)	PEM, no heat recovery (35% electrical efficiency)	470	70/45	27 x 13
Distributed power	Residential PV inverter (0.5kW)	SMA Sunny Boy w/ Opticool (0.5–20kW)	10	70/45	62 x 47
Distributed power	Residential PV inverter (20kW)	SMA Sunny Boy w/ Opticool (0.5–20kW)	400	70/45	62 x 47
Distributed power	Commercial PV inverter (100kW)	SMA Sunny Central w/ Opticool (100–500 kW)	2,000	70/45	274 x 251
Industrial processes	Motors	5 HP TEFC (totally enclosed fan cooled) motor 82.5% efficiency	790	95/45	19-cm diameter
Industrial processes	Motors	30 HP TEFC motor, 89.5% efficiency	2,600	95/45	28-cm diameter
Industrial processes	Motors	75 HP TEFC motor, 93% efficiency	4,200	95/45	36-cm diameter
Lighting	Solid state lighting (LEDs)	Residential application (Bulb) 500 lumens	10	100/75	9 x 9
Lighting	Solid state lighting (LEDs)	Commercial application (troffer or can) 1,500 lumens	32	70/35	9 x 9
Lighting	Solid state lighting (LEDs)	Industrial/outdoor application (high overhead or outdoor) 25,000 lumens	200	70/35	24 x 24
Res. HVAC&R	Compact refrigerator	R134a, 4.3 cu.ft.	100	70/45	60 x 43

Sector	Application	Description	Heat transfer req. (W)	Source / ambient temperature (°C)	Available size (cm x cm)
Res. HVAC&R	Residential refrigerator	R134a, 28 cu.ft.	285	70/35	21.5 x 20
Res. HVAC&R	Room air conditioner	R410a, 0.5-ton room unit	1,760	70/45	40 x 40
Res. HVAC&R	Residential CAC	R410a, outdoor split-system condenser (3 ton)	10,500	70/45	110 x 110
Res. HVAC&R	Ductless multi-split	R410a, indoor evaporator (0.75 ton each)	2,600	70/45	30 x 75
Res. HVAC&R	Heat pump clothes dryer	R134a, 1-3kW, either evaporator or condenser	2,500	70/35	18 x 23
Res./com. electronics	TVs	42 in. plasma and LCD TVs (50–150 W)	85	50/35	10 x 10
Res./com. electronics	Small battery	Li-ion 18650 design (3.7V, 2.2 Ah, 1-4W cooling per cell), 1–6 cells	3	50/40	6.5 x 6.5
Res./com. electronics	Microwave	Magnetron cooling fan (assume 60% efficiency of power to food heating)	450	90/35	15 x 15
Res./com. electronics	Audio video equipment	Xbox 360 (stereo, gaming, cable, projector)	200	55/35	10 x 10
Res./com. electronics	Mobile processor	QUALCOMM Snapdragon S4-S6 processors	0.5-10	90/40	2.2 x 2.2
Res./com. electronics	High-performance PC processor	Intel Core 3rd Gen i7	95	72/40	3.75 x 3.75
Res./com. electronics	Standard PC processor	Intel Core 3rd Gen i5	77	67/40	3.75 x 3.75
Transportation	Radiator (light duty vehicle)	Based on HP rating (240 HP), 33% of fuel consumption	60,000	85/45	65 x 50
Transportation	Electric vehicle battery packs	Li-ion 18650 design (3.7V, 2.2 Ah, 1–4W cooling per cell), 6,000cells/pack	6,000	80/45	65 x 25

Appendix B RSC Thermal Resistance Calculations

Fin Component of RSC Thermal Resistance

$$R_{fin} = \frac{1}{h_{fin} \cdot A_{ftot} \cdot \eta_{ftot}}$$

$$\eta_{ftot} = 1 - \frac{A_f}{A_{ftot}} \cdot (1 - \eta_f)$$

$$A_{ftot} = A_f + A_{nofin}$$

$$A_f = per \cdot height \cdot num_{fin}$$

$$A_{nofin} = \pi \cdot {r_{of}}^2 - num_{fin} \cdot A_c$$

$$A_{fin} = per \cdot height$$

$$\eta_f = \frac{tanh(X)}{X}$$

$$X = \beta \cdot height$$

$$\beta = (\frac{h_{fin} \cdot per}{k_{fin} \cdot A_c})^{0.5}$$

$$h_{fin} = 2.75 \cdot (r_{ave} \cdot \omega)^{2.85}$$

$$r_{ave} = 0.5 \cdot (r_{if} + r_{of})$$

ω = speed (RPM)
num_{fin} = 80
r_{if}= radius of inner fin (m)
r_{of} = radius of outer fin (m)
k_{fin}= thermal conductivity of fin = 190 $\frac{\text{W}}{\text{mK}}$
per = perimeter of fin (m)
A_c = cross-sectional area of fin (m²)

To determine performance at other sizes and speeds, the following values must be scaled for diameter:

- Radius of inner fin (r_{if})
- Radius of outer fin (r_{of})
- Fin perimeter (*per*)
- Cross-sectional area of fin (A_c)

Impeller Base Thermal Resistance

$$R_{base} = \frac{t_b}{k_b \cdot A_b}$$

t_b= Required thickness to maintain impeller base deflection, scales with diameter (m)

k_b= Thermal conductivity of base = 190 $\frac{\mathrm{W}}{\mathrm{mK}}$

A_b= Area of baseplate, scales with diameter (m^2)

Air Gap Thermal Resistance

$$R_{airgap} = \frac{t_a}{k_a \cdot A_a}$$

t_a= Assumed 10 micron air gap thickness (m)

k_a= Thermal conductivity of air gap = 0.026 $\frac{\mathrm{W}}{\mathrm{mK}}$

A_a= Area of air gap (i.e., baseplate), scales with diameter (m^2)

Baseplate Thermal Resistance

For the solid copper baseplate configuration:

$$R_{baseplate} = \frac{t_b}{k_b \cdot A_b}$$

$t_{baseplate}$= Required thickness to maintain impeller base deflection, scales with diameter (m)

$k_{baseplate}$= Thermal conductivity of copper baseplate = 401 $\frac{\mathrm{W}}{\mathrm{mK}}$

$A_{baseplate}$= Area of baseplate, scales with diameter (m^2)

Table B-1 provides thermal resistance of the RSC with a solid copper baseplate configuration, for different sizes and speeds.

Table B-1. RSC Thermal Resistance, Solid Copper Baseplate Configuration

		RSC Thermal Resistance (°C/W) with Solid Copper Baseplate Configuration																	
		Radial Sandia Cooler Outer Diameter (cm)																	
		0.5	1	2.5	5	7.5	10	12.5	15	17.5	20	22.5	25	27.5	30	32.5	35	37.5	40
Radial Sandia Cooler Speed (RPM)	1000	60.51	16.34	2.927	0.805	0.380	0.217	0.149	0.107	0.081	0.063	0.051	0.042	0.035	0.030	0.026	0.023	0.020	0.018
	1500	48.77	13.10	2.337	0.644	0.306	0.175	0.121	0.087	0.066	0.052	0.042	0.035	0.029	0.025	0.022	0.019	0.017	0.015
	2000	42.58	11.39	2.026	0.560	0.266	0.153	0.106	0.076	0.058	0.046	0.037	0.031	0.026	0.022	0.019	0.017	0.015	0.013
	2500	38.71	10.32	1.832	0.506	0.241	0.139	0.096	0.069	0.053	0.042	0.034	0.028	0.024	0.020	0.018	0.015	0.014	0.012
	3000	36.06	9.585	1.699	0.470	0.224	0.129	0.090	0.065	0.049	0.039	0.032	0.026	0.022	0.019	0.016	0.014	0.013	0.011
	3500	34.11	9.047	1.601	0.443	0.212	0.122	0.085	0.061	0.047	0.037	0.030	0.025	0.021	0.018	0.016	0.014	0.012	0.011
	4000	32.62	8.635	1.526	0.422	0.202	0.117	0.081	0.059	0.045	0.035	0.029	0.024	0.020	0.017	0.015	0.013	0.012	0.010
	4500	31.44	8.308	1.466	0.406	0.194	0.112	0.078	0.057	0.043	0.034	0.028	0.023	0.019	0.017	0.014	0.013	0.011	0.010
	5000	30.48	8.042	1.418	0.393	0.188	0.109	0.075	0.055	0.042	0.033	0.027	0.022	0.019	0.016	0.014	0.012	0.011	0.010
	5500	29.68	7.821	1.377	0.381	0.182	0.106	0.073	0.053	0.041	0.032	0.026	0.022	0.018	0.016	0.014	0.012	0.011	0.009
	6000	29.01	7.635	1.343	0.372	0.178	0.103	0.072	0.052	0.040	0.031	0.025	0.021	0.018	0.015	0.013	0.012	0.010	0.009
	6500	28.43	7.475	1.314	0.364	0.174	0.101	0.070	0.051	0.039	0.031	0.025	0.021	0.017	0.015	0.013	0.011	0.010	0.009
	7000	27.93	7.336	1.289	0.357	0.171	0.099	0.069	0.050	0.038	0.030	0.024	0.020	0.017	0.015	0.013	0.011	0.010	0.009
	7500	27.49	7.214	1.266	0.351	0.168	0.097	0.068	0.049	0.037	0.030	0.024	0.020	0.017	0.014	0.013	0.011	0.010	0.009
	8000	27.10	7.107	1.247	0.345	0.165	0.096	0.066	0.048	0.037	0.029	0.024	0.020	0.017	0.014	0.012	0.011	0.010	0.009
	8500	26.75	7.011	1.229	0.340	0.163	0.094	0.065	0.047	0.036	0.029	0.023	0.019	0.016	0.014	0.012	0.011	0.009	0.008
	9000	26.44	6.925	1.213	0.336	0.161	0.093	0.065	0.047	0.036	0.028	0.023	0.019	0.016	0.014	0.012	0.011	0.009	0.008

Appendix C RSC Power Consumption Calculations

Total RSC electric power

$$P_{total} = P_{fan} + P_{ab}$$

Fan power

$$P_{fan_{P-Q}}(HP) = \frac{P \cdot Q}{6356 \cdot \eta_{fan}}$$

$$P_{fan_{P-Q}}(W) = P_{fan_{P-Q}}(HP) \cdot 745.7 \frac{W}{HP}$$

P = pressure (in. H_2O)
Q = flow rate (CFM)
η_{fan}= fan efficiency (%)

Fan affinity laws allow this test data to be scaled to all diameters and speeds under investigation.

Air bearing drag:
The drag at the air bearing was calculated from air gap shearing torque equations.

$$P_{ab}(W) = \tau_{ab} \cdot \omega \cdot k$$

$$\tau_{ab} = \left(\frac{\pi \omega k \mu}{2h}\right) \cdot ({r_{of}}^4 - {r_{if}}^4)$$

ω = speed (RPM)
k = RPM to rad/s = $\frac{2\pi}{60}$
μ = air viscosity ($\frac{kg}{m-s}$)
h = air bearing height (m)
r_{of}= radius of outer fin (m)
r_{if} = radius of inner fin (m)

To determine performance at other sizes and speeds, the following values must be varied:

- Radius of inner fin (r_{if})
- Radius of outer fin (r_{of})
- Rotational speed (ω)

Electrical power consumption for different sizes and speeds of RSCs is listed in Table C-1.

Table C-1. Total RSC Electrical Power

Total RSC Elec. Power (W) at Various Outer Diameters and Speeds																			
		Radial Sandia Cooler Outer Diameter (cm)																	
		0.5	1	2.5	5	7.5	10	12.5	15	17.5	20	22.5	25	27.5	30	32.5	35	37.5	40
Radial Sandia Cooler Speed (RPM)	1000	0.0	0.0	0.0	0.1	0.2	0.6	1.2	2.4	4.1	6.8	11	16	22	31	42	56	72	92
	1500	0.0	0.0	0.0	0.1	0.6	1.5	3.3	6.3	10.9	17.6	27	40	56	77	104	137	178	226
	2000	0.0	0.0	0.0	0.3	1.2	3.2	6.9	12.9	22.0	35.3	54	78	110	151	202	266	342	435
	2500	0.0	0.0	0.1	0.6	2.3	5.8	12.3	22.8	38.7	61.4	93	135	189	258	343	449	577	730
	3000	0.0	0.0	0.1	1.0	3.7	9.5	19.9	36.6	61.8	97.6	147	212	295	402	534	695	891	1124
	3500	0.0	0.0	0.2	1.6	5.7	14.5	30.1	55.1	92.4	145.2	217	312	434	589	780	1013	1294	1629
	4000	0.0	0.0	0.3	2.3	8.3	21.0	43.3	78.8	131.5	205.9	307	439	610	824	1088	1410	1797	2257
	4500	0.0	0.0	0.4	3.3	11.6	29.1	59.8	108.4	180.2	281.1	417	596	825	1111	1465	1894	2409	3021
	5000	0.0	0.0	0.5	4.4	15.7	39.1	80.0	144.5	239.5	372.4	551	785	1084	1458	1917	2474	3141	3932
	5500	0.0	0.0	0.7	5.8	20.6	51.1	104.3	187.8	310.3	481.2	711	1010	1391	1867	2451	3158	4003	5002
	6000	0.0	0.1	0.9	7.5	26.5	65.4	133.0	238.9	393.7	609.1	898	1273	1751	2345	3074	3954	5004	6245
	6500	0.0	0.1	1.1	9.5	33.3	82.1	166.6	298.4	490.7	757.7	1115	1578	2166	2897	3791	4870	6155	7672
	7000	0.0	0.1	1.4	11.8	41.3	101.5	205.3	367.0	602.4	928.4	1363	1927	2641	3527	4610	5914	7466	9294
	7500	0.0	0.1	1.7	14.4	50.4	123.6	249.6	445.4	729.7	1122.7	1646	2324	3180	4241	5536	7094	8946	11126
	8000	0.0	0.1	2.1	17.4	60.7	148.7	299.8	534.1	873.7	1342.2	1965	2770	3787	5045	6577	8419	10606	13177
	8500	0.0	0.2	2.5	20.8	72.4	177.0	356.3	633.8	1035.3	1588.5	2323	3271	4465	5942	7739	9897	12456	15461
	9000	0.0	0.2	3.0	24.6	85.5	208.7	419.5	745.2	1215.7	1862.9	2721	3827	5219	6938	9029	11535	14506	17990

Appendix D RSC Weight and Start-Up Torque Calculations

RSC Weight

Figure D-1 outlines the estimated weight of the RSC impeller at various diameters. Note: baseplate and motor weight are not included in this estimate.

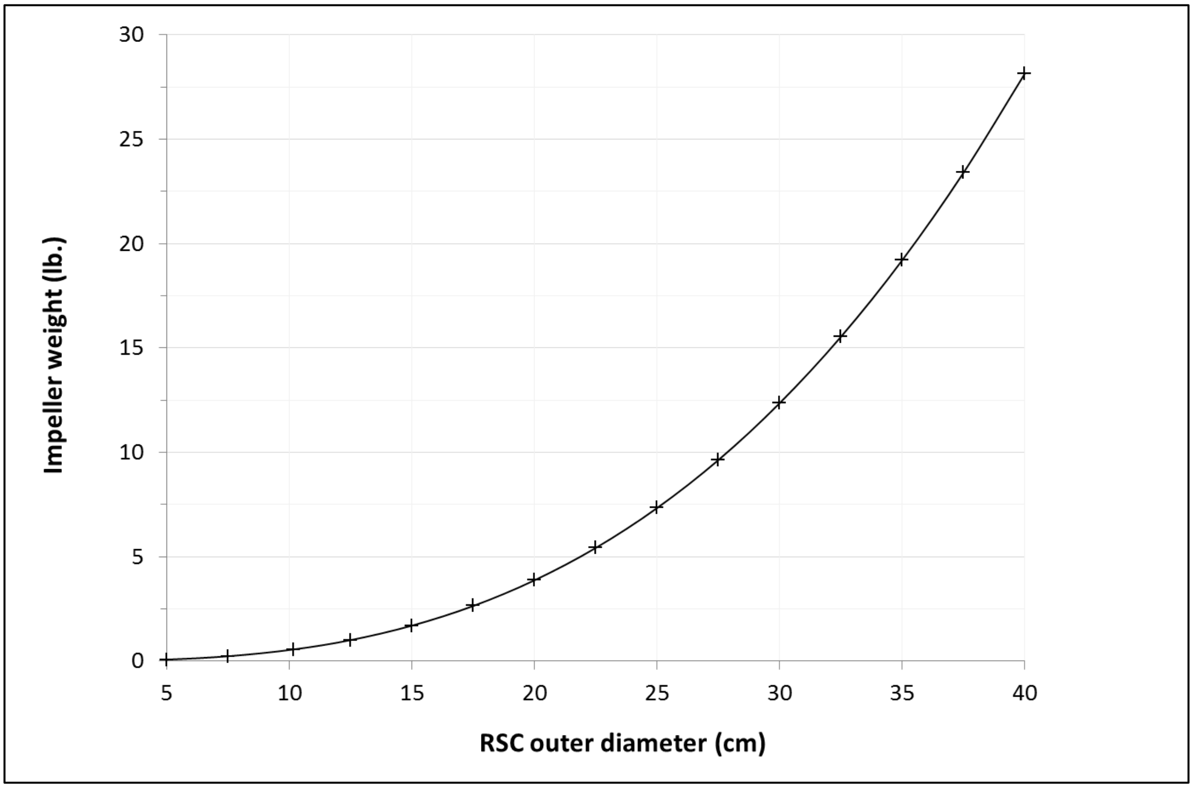

Figure D-1. RSC impeller weight, scaled for different diameters

Impeller weight is scaled according to the following equations:

$$W_{impeller}(lb) = V_{impeller}(in^3) \cdot d\ (\frac{lb}{in^3})$$

$$V_{impeller} = V_{platen} - V_{motor} + V_{fins}$$

$$V_{platen} = \pi \left(\frac{OD^2}{4} - \frac{CD^{\ 2}}{4}\right) \cdot\ t_b$$

$$V_{motor} = \pi \left(\frac{MD^2}{4} - \frac{CD^2}{4}\right) \cdot\ t_m$$

$$V_{fins} = \left(\frac{OD - ID}{2}\right) \cdot\ t_f \cdot F\% \cdot N_{fins} \cdot h_{fin}$$

d = density of aluminum impeller = 0.1030 $(\frac{\text{lb}}{\text{in}^3})$

OD = Outer diameter of impeller (in.)

CD = Center hole diameter = 0.3125 in.

t_b = Required thickness to maintain impeller base deflection, scales with diameter

MD = motor mount diameter = 0.96 in.

t_m = Motor mount depth = 0.16 in.

t_m = Fin thickness = 0.03 in.

$F\%$ = Fin curvature percentage = 111%

N_{fins}= number of fins = 80

h_{fin} = fin height = 0.95 in.

Table D-1 provides the scaled RSC weight estimates for the impeller at various diameters.

Table D-1. Estimates of RSC Impeller Weight for Different Sizes

RSC weight estimates					
Metric units			**English units**		
Outer diameter (cm)	Assumed platen thickness (cm)	Impeller weight (N)	Outer diameter (in)	Assumed platen thickness (in)	Impeller weight (lb.)
10.0	0.6	2.5	3.9	0.3	0.6
12.5	0.9	4.6	4.9	0.3	1.0
15.0	1.1	7.6	5.9	0.4	1.7
17.5	1.3	11.6	6.9	0.5	2.6
20.0	1.5	16.8	7.9	0.6	3.8
22.5	1.8	23.6	8.9	0.7	5.3
25.0	2.0	31.9	9.8	0.8	7.2
27.5	2.2	42.2	10.8	0.9	9.5
30.0	2.5	54.5	11.8	1.0	12.2
32.5	2.7	69.1	12.8	1.1	15.5
35.0	3.0	86.1	13.8	1.2	19.4
37.5	3.2	105.9	14.8	1.3	23.8
40.0	3.4	128.6	15.7	1.4	28.9

Start-up Torque

Figure D-2 provides the required torque to start the RSC for various diameters.

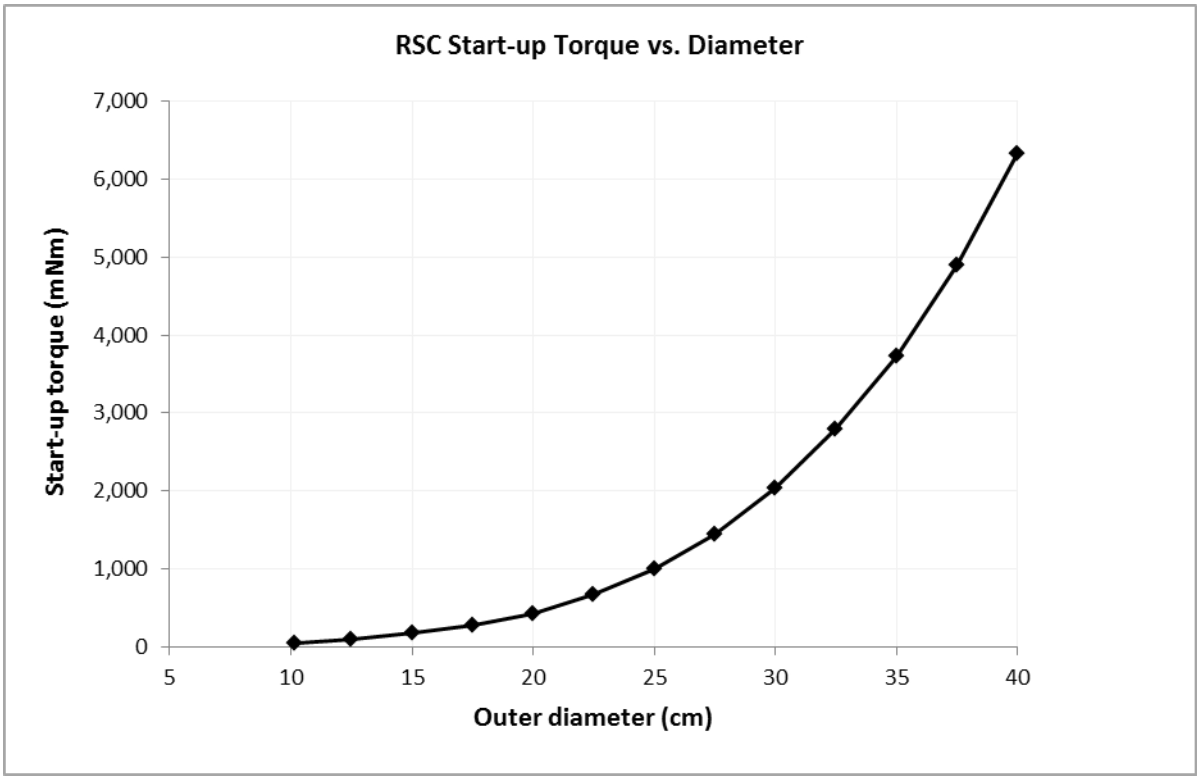

Figure D-2. Required RSC start-up torque

Start-up torque was calculated using the following equations:

$$\tau\ (mN\text{-}m) = W_{total} \cdot r_{eff} \cdot \mu_s$$

$$W_{total}(N) = W_{impeller} + W_{pre-load}$$

$$W_{pre-load} = 2 \cdot W_{impeller}$$

$$r_{eff}(m) = \frac{2}{3} \cdot \left(\frac{\left(\frac{OD}{2}\right)^3 - \left(\frac{ID}{2}\right)^3}{\left(\frac{OD}{2}\right)^2 - \left(\frac{ID}{2}\right)^2} \right)$$

OD = Outer diameter of impeller (m)

CD = Center hole diameter = 0.0244 m

μ_s=static friction coefficient determined by test data

Table D-2 summarizes the estimated start-up torque for different sized RSCs.

Table D-2. Required Start-Up Torque for Various RSC Sizes

Outer diameter (cm)	Required start-up torque (mN-m)
10.0	55
12.5	102
15.0	176
17.5	279
20.0	424
22.5	665
25.0	1,000
27.5	1,448
30.0	2,035
32.5	2,787
35.0	3,733
37.5	4,904
40.0	6,333

Appendix E RSC Pressure and Air Flow Rate Calculations

Figure E-1 shows the estimated pressure vs. air flow (P-Q) curves for the various RSC sizes and Table E-1 provides the P-Q values provided by SNL for the 10-cm RSC.

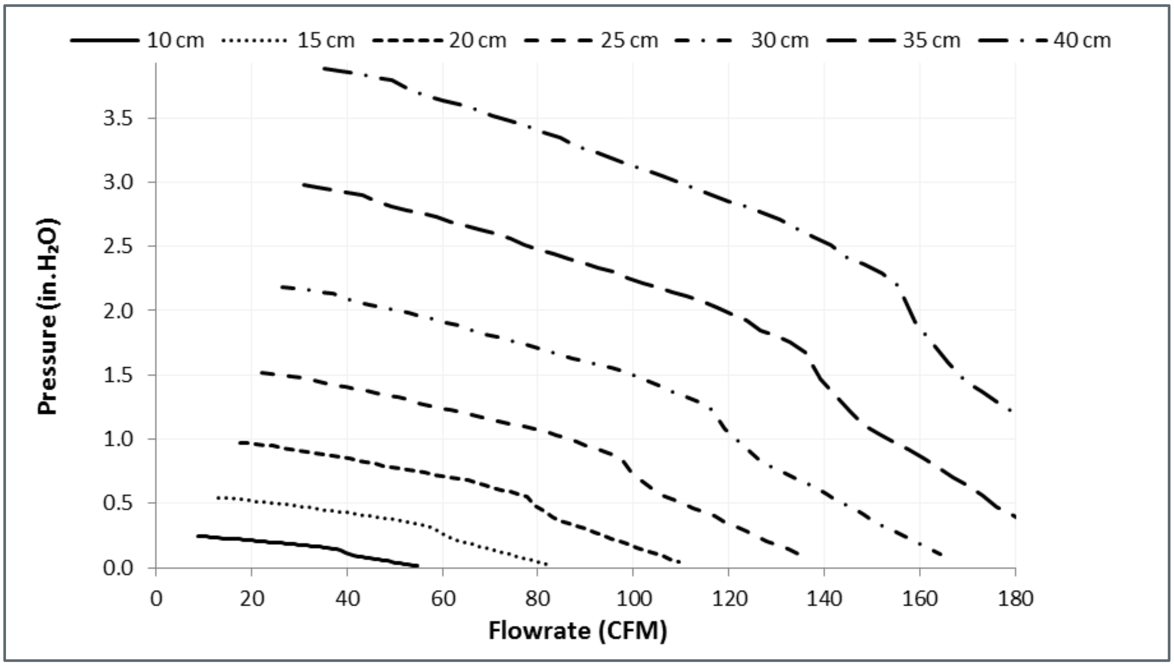

Figure E-1. RSC pressure vs. air flow rate curves

Table E-1. SNL P-Q Test Data for the 10-cm RSC at 2,500 RPM

Air flow rate (CFM)	Pressure (in. H_2O)
8.8	0.24
11.5	0.24
14.1	0.23
16.8	0.22
19.4	0.21
22.1	0.21
24.7	0.20
27.4	0.19
30.0	0.18
32.7	0.17
35.3	0.16
38.0	0.14
40.6	0.11
43.3	0.09
45.9	0.07
48.6	0.05
51.2	0.03
53.9	0.02

Appendix F Scoring Methodology and Results

Table F-1. Technology Attractiveness Scores

Technology name	Design complexity (40%)	Product integration (25%)	Market advantages (25%)	Potential for breakthrough (10%)	Overall score
High-performance PC processor	3	3	3	3	**3.00**
Peltier devices	3	3	3	3	**3.00**
Data center processor	3	3	2	3	**2.75**
A/V equipment	3	3	2	2	**2.65**
Standard PC processor	3	2	2	2	**2.40**
Res. RF condenser	3	1	2	3	**2.25**
PRODUCTS LISTED ABOVE SCORED IN TOP HALF					
Res. PV inverter (0.5 kW)	3	2	1	1	**2.05**
Com. LED bulb	3	1	1	3	**2.00**
Portable fuel cell (0.5kW)	2	2	2	2	**2.00**
Res. LED bulb	3	1	1	3	**2.00**
Mobile processor	2	3	1	1	**1.90**
Res. PV inverter (20 kW)	2	2	2	1	**1.90**
Small battery	2	3	1	1	**1.90**
Beverage vending machine	2	1	2	3	**1.85**
Reach-in RF condenser	2	1	2	3	**1.85**
5 HP motor (TEFC)	3	1	1	1	**1.80**
Compact refrigerator	3	1	1	1	**1.80**
Ind. LED bulb	3	1	1	1	**1.80**
TVs	3	1	1	1	**1.80**
Room air conditioner	2	1	2	2	**1.75**
Microwave	2	2	1	1	**1.65**
Res. fuel cell (5kW)	1	2	2	1	**1.50**
30 HP motor (TEFC)	2	1	1	1	**1.40**
75 HP motor (TEFC)	2	1	1	1	**1.40**
Ice maker	2	1	1	1	**1.40**
Com. PV inverter (100 kW)	1	2	1	1	**1.25**
PTAC	1	1	2	2	**1.35**
Res. CAC condenser	1	1	2	2	**1.35**
Uninterruptible power supply	1	2	1	1	**1.25**

Table F-2. Market Attractiveness Scores

Technology name	U.S. market size (50%)	Market adoption of new technologies (35%)	Allowable cost premium (15%)	Overall score
Mobile processor	3	3	3	**3.00**
A/V equipment	3	3	2	**2.85**
Standard PC processor	3	3	2	**2.85**
Data Center processor	2	3	3	**2.50**
Com. LED bulb	3	2	1	**2.35**
Ind. LED bulb	3	2	1	**2.35**
Res. LED bulb	3	2	1	**2.35**
Small battery	3	2	1	**2.35**
TVs	3	2	1	**2.35**
High-performance PC processor	1	3	3	**2.00**
Microwave	3	1	1	**2.00**
Peltier devices	1	3	3	**2.00**
Res. fuel cell (5kW)	1	3	3	**2.00**
Res. RF condenser	3	1	1	**2.00**
Room Air conditioner	3	1	1	**2.00**
PRODUCTS LISTED ABOVE SCORED IN TOP HALF				
Com. PV inverter (100kW)	1	3	2	**1.85**
Res. CAC condenser	2	2	1	**1.85**
Res. PV inverter (0.5 kW)	1	3	2	**1.85**
Res. PV inverter (20 kW)	1	3	2	**1.85**
Portable fuel cell (0.5kW)	1	3	1	**1.70**
Beverage vending machine	2	1	1	**1.50**
Compact refrigerator	2	1	1	**1.50**
PTAC	2	1	1	**1.50**
Uninterruptible power supply	1	2	2	**1.50**
5 HP motor (TEFC)	1	1	1	**1.00**
30 HP motor (TEFC)	1	1	1	**1.00**
75 HP motor (TEFC)	1	1	1	**1.00**
Ice maker	1	1	1	**1.00**
Reach-in RF condenser	1	1	1	**1.00**

Appendix G Promising Products for Future RSC Developments

The products below were not considered to be highly attractive for initial RSC introduction, but may become more appropriate as the RSC technology matures.

- Mobile electronics is a large, growing market where heat transfer is a key consideration as devices are expected to be slim, powerful, and feature long battery life. Examples include: cell phones, tablets, e-readers, music players, etc. Most products in this space currently can meet their heat transfer requirements through passive means, often using the relatively large, flat, back-plate of the device as a the heat transfer surface.[5] Introducing an active heat transfer mechanism adds cost, complexity, and other issues that would act as a market introduction barrier unless the RSC could enable additional product capabilities and features. For this reason, we do not recommend pursuing mobile electronics for initial RSC deployment, but the RSC may be important in the development of future products, as battery technology and other components allow for more powerful devices.
- LED lighting is an emerging product category that requires careful thermal management with high potential for energy savings compared to current light fixtures. Although some products employ forced convection, most LED fixtures currently incorporate fins or fluid chambers to passively remove heat from the LED packages, driver, and other components. The main issue impeding RSC adoption for LED lighting is integrating the RSC impeller and motor into the fixture. Work is underway in FY 2014 at SNL to develop a solid-state lighting prototype utilizing the RSC.
- Small-scale distributed power includes residential and commercial PV inverters (≤ 20 kW) and portable fuel cells. These products score relatively well in both the Technology and Market Attractiveness scorecards due to their good alignment with the RSC's capabilities and allowable cost premium, but ultimately do not make the most promising list because of small annual sales numbers and the limited market advantage. Once commercialized in other areas and made available as an off-the-shelf product, these markets would be expected to utilize the RSC.
- Residential & commercial HVAC and commercial refrigeration are attractive product categories where potentially the RSC could provide breakthrough performance and energy savings, but do not score well due to integration issues, the uncertainty of using several larger or dozens of smaller RSCs, and slow market adoption of new technologies. These sectors are most likely longer-term goals of the Sandia Cooler technology and could employ alternative concepts or advanced RSC designs. Work is underway in FY 2014–2015 at SNL to integrate refrigerant coils into the RSC baseplate and explore the potential of advanced RSC designs and other concepts for these sectors. Section 5 discusses these concepts further.

[5] The tablet and laptop product categories encompass products with different capabilities ranging from personal entertainment to business applications and utilize different form factors. Some tablets geared toward business use do incorporate active heat transfer through fanned heat sinks. Conversely, some laptops do not incorporate active heat transfer and act more as personal mobile devices. For simplicity, we segmented these two categories based off the heat transfer strategy for the majority of products: tablets in Mobile Electronics (Passive), and laptops in Computing (Active).

Appendix H Prioritization of Deployment Activities

Table H-1. Communication Activities

Activity name	Description	How does this activity advance SNL goals?	Key steps
Advanced Research Projects Agency-Energy (ARPA-e) Technology Showcase	Participate in the trade show portion of the Innovation Summit	Provides opportunity to meet with entrepreneurs and investors focused on energy efficiency breakthroughs	• Submit exhibit application • Construct trade show booth with demonstration • Attend summit
Federal computing group outreach	Present to federal research and industry groups working for more efficient data center cooling	• Utilize experience and in evaluating low-energy data centers • Informs industry contacts	• Make introduction • Develop presentation • Hold meeting/webinar
DOE Product Team outreach	Lead discussions among appliance standards project teams to raise awareness for future efficiency rulemakings	• Long-term exposure of RSC to different product categories • Product teams can provide guidance for future development	• Develop presentation • Hold meeting/webinar
ENERGY STAR Product Team outreach	Initiate discussions with server and A/V electronics group to engage industry representatives.	Communication with OEMs and industry experts focused on efficiency and earning the ENERGY STAR label	• Make introduction • Develop presentation • Hold meeting/webinar
Print/online publicity update	Update media publications, periodicals, websites, etc. on RSC development	• Engages interested media outlets • Shows audience continued research in RSC technology	• Generate press release • Contact journalists and media outlets • Interview participation
Public/private webinar	Present introduction and update to RSC technology through online webinar	• Directly reaches audience • Facilitates Q/A discussion • Registers interested parties for future updates	• Advertise and/or invite participants • Develop presentation • Host webinar
Industry or developers conference presentation	Update RSC white paper and present to technical audience in target sectors	Engages and updates those that would be most interested in advanced cooling products	• Update white paper • Submit conference paper • Develop presentation • Attend conference
Innovation conference presentation	Discuss importance of heat exchanger break-throughs, including RSC	Engages industry leaders, entrepreneurs, investors	• Submit application • Develop presentation • Attend event

Table H-2. Demonstration Activities

Activity name	Description	How does this activity advance SNL goals?	Key steps
Complete development tasks at SNL	Continue laboratory work to understand and refine RSC operation	Provides answers to the questions potential partners may ask	Conduct testing to determine RSC operation pertaining to: ducts/ enclosures, multiple RSCs, airstream, reliability, fouling, noise, safety, variable speed
Conduct testing at federal computing facilities	Work with federal data center staff to integrate RSCs into current or retired systems	• Engages experts within data center community to help refine product • Demonstrates performance in actual environment	• Initial contact with federal computing facilities, especially those evaluating new technology • Identify appropriate servers, test protocol, and measurement equipment • Conduct testing
Test RSC in actual products at SNL	Integrate prototype RSCs in computer, server, and A/V electronics at SNL	• Allows for RSC evaluation in real world applications • Helps anticipate issues with product integration, controls, and unforeseen issues	• Obtain prototype RSCs, test products, and test plan • Construct test stand and measurement system • Conduct testing
RFP/FOA for demonstration	Offer funding or cost share to demonstrate the technology in actual product applications or separate concepts	• Allows organizations with interest in technology to apply their expertise for a specific application • Potential to start licensee based on results	• Identify any gaps in SNL expertise • Create RFP/FOA guidelines • Evaluate proposals and select project • Integrate project results
Provide prototype to interested OEMs/suppliers	Invite interested industry partners to evaluate an RSC prototype	• Reengages partners who showed interest before • Allows testing in each partner's R&D facility • Begin manufacturing or supplier outreach	• Engage or announce the opportunity for demo units • Manufacture finalized RSC design • Distribute to partners and provide guidance

Activity name	Description	How does this activity advance SNL goals?	Key steps
Develop tools and CFD modules	• Create a CFD module that simulates RSC operations in different environments. • Could enhance a trade show kiosk with a simulator.	• Partners have the opportunity to evaluate RSC capabilities in their own applications. • Provides feedback for how RSC would operate in common enclosures.	• Create RSC module in CFD software • Construct one or more trade show workstations where visitors can customize the RSC module in the software. • Release module or other tool to partners.
Invitation for press to benchmark	Provide interested media members the opportunity to conduct performance testing on an RSC prototype.	• Improves the content of the media article • Provides direct comparison to existing products to help refine future designs.	• Contact journalists and media outlets • Manufacture finalized RSC design • Distribute to press and provide guidance
Co-sponsor development or business plan competition	Partner with industry organization or university to create competition focused around RSC technology	Generates interest in the RSC throughout, research, and entrepreneurial community	• Announce the competition • Manufacture finalized RSC design • Distribute to teams and provide guidance • Oversee competition results
Pre-order and direct manufacture	Offer public to pre-order a prototype version of RSC	• Hobbyists create excitement in electronics community. • Provided feedback will help refine designs.	• Announce the opportunity to purchase demo units • Manufacture finalized RSC design • Distribute and provide guidance

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