DESIGN, IMPROVEMENT, AND TESTING OF A THERMAL-ELECTRICAL ANALYSIS APPLICATION OF A MULTIPLE BETA-TUBE AMTEC CONVERTER

A Thesis

by

ILIA V. PAVLENKO

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

December 2003

Major Subject: Health Physics

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Approved as to style and content by:

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ABSTRACT

Design, Improvement, and Testing of a Thermal-Electrical Analysis Application
of a Multiple Beta-Tube AMTEC Converter. (December 2003)

Ilia V. Pavlenko, M.S., Obninsk State Polytechnic University of Nuclear Power Engineering

Co-Chairs of Advisory Committee: Dr. John R. Ford
Dr. Michael Schuller

A new design AMTEC converter model was developed, and its effectiveness as a design tool was evaluated. To develop the model, requirements of the model were defined, several new design models were successively developed, and finally an optimal new design model was developed. The model was created within Sinda/Fluint, with its graphical interface, Thermal Desktop, a software package that can be used to conduct complex thermal and fluid analyses. Performance predictions were then correlated and compared with actual performance data from the Road Runner II AMTEC converter. Predicted performance results were within 10% of actual performance data for all operating conditions analyzed. This accuracy tended to increase within operating ranges that would be more likely encountered in AMTEC applications. Performance predictions and parametric design studies were then performed on a proposed new design converter model with a variety of annular condenser heights and with potassium as a working fluid to evaluate the effects of various design modifications.

Results clearly indicated the effects of the converter design modifications on the converter's power and efficiency, thus simplifying the design optimization process. With the close correlation to actual data and the design information obtained from parametric studies, it was determined that the model could serve as an effective tool for the design of AMTEC converters.

DEDICATION

I dedicate this work to my parents, Vladimir and Elena. It is unlikely I would be where I am today had it not been for their continual support and guidance throughout my life. It is to them that I owe many of my accomplishments.

I also dedicate this work to my wife and soul mate, Valerie. She is my dream come true.

ACKNOWLEDGEMENTS

I would like to thank my graduate advisor, Dr. Ford. He has been a true mentor, on both a personal and academic level. It is very hard to imagine a better graduate adviser than he was for me.

I would also like to thank Dr. Schuller for introducing and giving me an opportunity to participate and be useful in the AMTEC converter research project. The experience and confidence level I have gained working on such an interesting project has been invaluable.

I would like to acknowledge Igor Carron, my advisor at Commercial Space Center for Engineering, Texas A&M University. His confidence in my abilities and willingness to share his knowledge resulted in learning and practical experience that I received so far.

Last, but definitely not least, I would like to thank all those I worked with at the Center of Space Power and Commercial Space Center for Engineering, Texas A&M University. It was an honor to be a part of the solid team and participate in a number of interesting projects.

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INTRODUCTION

In the recent history of space exploration, space vehicles slated for missions that ventured into deep space, far from the sun, typically relied on radioisotope thermoelectric generator (RTG) power sources. The reason is that solar power, commonly used for Earth orbiting missions, becomes an inefficient energy source as the distance from the sun increases. RTGs, however, are considered high in mass and low in conversion efficiency by modern technological standards. RTG systems on past space exploration vehicles such as Pioneer (1972), Voyager (1977), and Galileo (1977) were only 5 to 6 percent efficient [1]. For this reason, several new technologies are under development for future missions that may involve travel to the farthest planets of our solar system and beyond [2].

To increase the power density of a radioisotope power system, higher energy conversion efficiencies are necessary. A promising design solution that may fulfill this need is a type of generator that uses technology known as alkali metal thermal-to-electric conversion (AMTEC). This device, like previous thermoelectric power systems, converts thermal energy directly into electricity. Developed at Ford Scientific Laboratory in Dearborn Michigan in 1968 and brought to the Jet Propulsion Laboratory (JPL) in the early 1980s, AMTEC achieved 19 percent conversion efficiencies in laboratory tests, and, with a few improvements, may yield efficiencies as high as 30 percents in the near future. Predicted converter power densities of approximately 80 watts per kilogram can reduce the power system mass needed for future Pluto missions to roughly 6 kg, 10 kg less than previous thermoelectric units. This is a significant savings in mass for a 100 kg spacecraft. With a comparatively high efficiency combined with low mass and

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This thesis follows the style and format of the American Society of Mechanical Engineers' Journal of Heat Transfer.

simplicity, AMTEC holds promise for use as an electrical power source on future deep space missions ([1,3]).

The primary component of an AMTEC converter, that enables it to achieve thermal to electric conversion, is a ceramic called β″-Alumina Solid Electrolyte (BASE), often simply referred to as “beta.” When sodium is heated on one side of the BASE in a vacuum environment, a vapor pressure difference occurs across the BASE. The result of this pressure difference is conduction of sodium ions through the BASE. An anode placed on the high-pressure side of the BASE collects electrons that have been dissociated from the neutral sodium and conducts them to a cathode placed on the low-pressure side of the BASE, where sodium ions recombine with the electrons to once again form neutral sodium. This flow of electrons is the electric current to the external load. An AMTEC converter thus converts the work of isothermal expansion of sodium vapor directly to electric power [3]. Further details of the converter process can be found in the BACKGROUND section.

It is not surprising that, although AMTEC has not yet been proven flight ready or been officially assigned to any space missions, interest has already developed in the use of AMTEC technology for terrestrial applications. AMTEC could prove to be a viable option for power production wherever there is a high temperature thermal source such as residential homes that receive natural gas, or it could even be used as a component in a cogeneration process within production and power plants. Many other potential terrestrial applications may become an integral part of AMTEC’s future [1].

The basic principles behind the operation and overall design of an AMTEC converter are relatively simple. AMTEC converters usually contain no moving parts. For these reasons, it is feasible to assume that, with some modifications, a new design for AMTEC may be possible that is affordable, reliable, and better tailored for industrial use. As an example, many factories and power production plants generate a great deal of waste thermal energy. Although this waste energy is often used to power gas and steam turbines to generate electricity, AMTEC is an attractive alternative when considering reliability, simplicity, and lower cost, particularly the cost of maintenance. AMTEC may be used in virtually any application where a heat source is available at the 600 to 850 degree Celsius temperature required for operation. Although a few industries have considered the implementation of AMTEC for power production, many unanswered questions have prevented implementation. These questions apply to AMTEC's cost, efficiency, and technological readiness.

AMTEC may be less expensive than using turbines, as an example, but turbines are currently capable of higher conversion efficiencies and have been proven technology for many years. Because recent AMTEC converters have been developed exclusively for space applications, the components of these converters are often constructed of materials such as molybdenum and niobium-zirconium to produce the highest power to weight ratios possible, with little concern for cost. Most industries, however, are more concerned about life cycle costs rather than performance to weight ratios. It is in an industry's best interest for an AMTEC system to be designed with more common, less expensive materials, even if the power production to weight ratio is lower than that designed for space vehicles. Under the assumption that weight is not a significant concern, it is theoretically possible for a combination of several less expensive, lower power production converters to exceed the overall performance of the more expensive space-designed converters for the same cost.

The development of an AMTEC converter system that meets industry's demands for alternative cost-effective electric generation by providing satisfactory performance at low cost is, for the most part, uncharted territory in relation to the status of AMTEC technology. It is, therefore, imperative that, during the conceptual and preliminary converter design stages, the designs are optimized as much as possible. This could be accomplished by using an analytical model to simulate operation and conduct parametric analyses, thus decreasing the need for engineering tests.

Objectives

The objective was to develop new AMTEC converter models for significantly different conceptions of AMTEC converter based on an existing model. The existing model was evaluated and developed during Phase I of the Roadrunner project initiated by Active Power Inc., with Advanced Modular Powers Systems (AMPS) in Ann Arbor, Michigan and Center of Space Power (CSP) in College Station, Texas [4]. The new AMTEC converter models were necessary as an effective design tools to predict converter performance within 10% of experimental results and to perform a variety of design studies.

Format

In order to satisfy the objective, the new AMTEC converter models were developed, predictions obtained from the models were evaluated, and the models were used to analyze the new AMTEC converter designs. This thesis is organized in sections based on this process. Within the BACKGROUND section, a description of AMTEC converter components and details of the AMTEC conversion process are provided. Also included in the Previous Models and Base Model sections is a brief history of other AMTEC models and description of the existing AMTEC converter model, which was developed earlier and used as a basis for the new models [4]. The development of the converter models, including the requirements and strategies used in the development process, is described in the NEW DESIGN-MODEL DEVELOPMENT section. Results of the performance predictions and design studies for the new AMTEC converter conceptions, with an annular condenser and with potassium as a working fluid, are provided in the APPLICATION OF THE MODEL AS A DESIGN TOOL section. The NEW MODEL CALIBRATIONS section contains information related to the calibration process of the model with Road Runner II AMTEC converter, which was manufactured and tested at AMPS, Ann Arbor, Michigan. The SUMMARY OF FINDINGS section summarizes major findings obtained from the studies and application of the models. Lastly, a CONCLUSIONS AND RECOMMENDATIONS section is provided.

BACKGROUND

Before describing the development of the models, it is important to understand the fundamental principles of how an AMTEC converter operates and to have an awareness of previous AMTEC converter models. This section contains four subsections related to these issues. Within The Basic AMTEC Components and The AMTEC Energy Conversion Process subsections, details associated with the principles of operation for AMTEC converters are provided. The Previous Models subsection briefly describes previous AMTEC converter models. Finally, The Base Model Development subsection reviews the AMTEC converter model, which was used as the base for the new models.

Basic AMTEC Components

Although a variety of AMTEC converter designs have been tested and evaluated, the fundamental function of any AMTEC converter is the same, to convert thermal energy to electricity. In order to do so, all AMTEC converters include the same basic components that perform the same basic functions. These components will be described in this section.

To convert thermal energy, the energy must first be transferred from the thermal source to the converter. A thermal source such as a radioisotope might be used for a space mission, yet for potential Earth-based applications the thermal energy source could even be a furnace in a residential home. The exhaust from a gas turbine or other combustion processes would be ideal for industrial cogeneration applications [1, 5].

The portion or surface of the converter that provides the function of heat transfer from the energy source is appropriately referred to as the hot side of the converter. When there is heat transferred into a system that is to operate continuously at some steady state temperature, the heat must also be rejected. The condenser, or cold side, of the converter performs this function.

Therefore, AMTEC is essentially a heat engine where heat is transferred from a high temperature source, rejected to a low temperature sink, and work (electricity) is extracted.

The central component of an AMTEC converter is the ceramic material, β″-Alumina Solid Electrolyte (BASE), which possesses some novel properties. The most notable of these properties is the excellent conduction of sodium ions and poor conduction of electrons [1]. In addition, BASE does not conduct neutral sodium, and although sodium is a highly reactive element, BASE does not react with sodium to any significant degree at AMTEC operating temperatures. BASE ceramic is typically manufactured in the form of a thin-walled tube, so, most AMTEC converters use BASE in this geometric form. Single or multiple tubes may be used within one converter. In multiple tube concepts, such as is shown in Figure 1, each tube is an electrochemical cell, connected in electrical series to provide higher voltage and output power. Many proposed and existing AMTEC converter designs are multi-tube. Increased voltage and power are clear benefits of the multi-tube design, but in addition, only one housing and electrical feedthrough is needed for several tubes. As a result, heat losses are typically reduced and efficiency increases. Although the production cost is likely to also increase in comparison to single tube AMTEC converters, the trade off is often worthwhile.

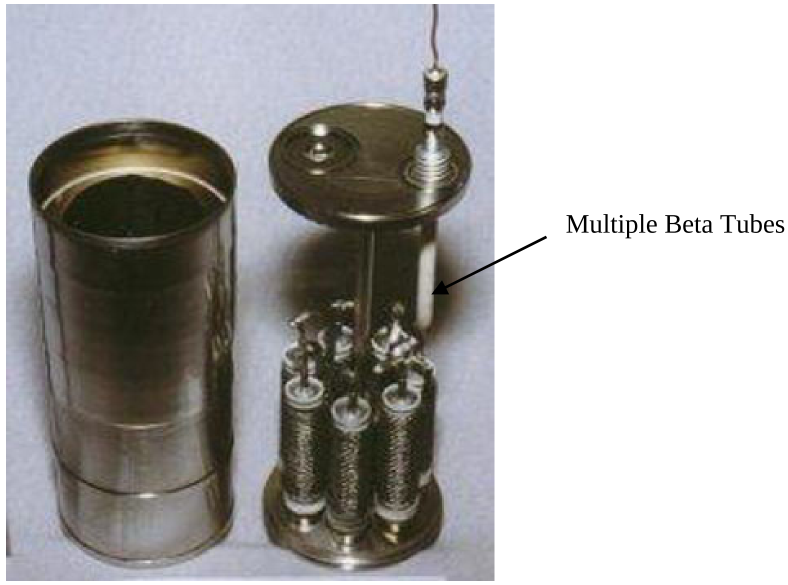

Figure 1. A particular configuration of an AMTEC converter with housing (left) removed

Another important aspect of an AMTEC converter is the working fluid. The working fluid in an AMTEC converter is typically sodium. Some research indicates potassium may be a more suitable selection when the hot side of the converter is in the lower temperature range of 500 to 600 °C, as opposed to the 600 to 850 °C temperature range required for sodium. Since the use of sodium is much more common than that of potassium, and all modeling was performed in relation to sodium converters, the working fluid will be referred to as sodium in this manuscript.

The AMTEC Energy Conversion Process

The AMTEC energy conversion process begins with the addition of thermal energy within the BASE, or beta, tube(s). The series of events that follow are the basis of AMTEC technology and are described in more detail in this section.

AMTEC converters typically operate in the temperature range of 600 to 850 °C, thermal energy is rejected, resulting in a temperature of 150 to 450 °C. The implementation of AMTEC technology is simple. Provided sufficient heating is available, electrical power is also available.

For the most part, conversion from thermal energy to electricity occurs at the interfaces of the beta tube assembly. An increase in temperature within the beta tube and a near vacuum environment external to the tube creates a high-to-low pressure difference between the inside and outside of the beta tube. This pressure difference creates charge separation and thus creates a voltage. As illustrated in Figure 2, when the electrical circuit is closed, sodium ions tend toward equilibrium by conducting through the BASE. The anode on the inside surface of the BASE tube(s), composed of an electrically conductive material, collects the electrons as they dissociate from the neutral sodium. Another electrically conductive path, such as copper, is provided for the electrons collected on the anode to bridge from the high-pressure side of the BASE tube(s) to the low-pressure side. Sodium ions, reaching the low-pressure surface of the BASE tube(s) recombine with the electrons on an outer electrode (cathode), once again forming neutral sodium. The “flow” of electrons through the external circuit, noted as “external load” on Figure 2, is the electrical current that provides power. Various electrical devices may be powered by connecting them within the external circuit, provided the electrical load falls within the capabilities of the particular AMTEC converter.

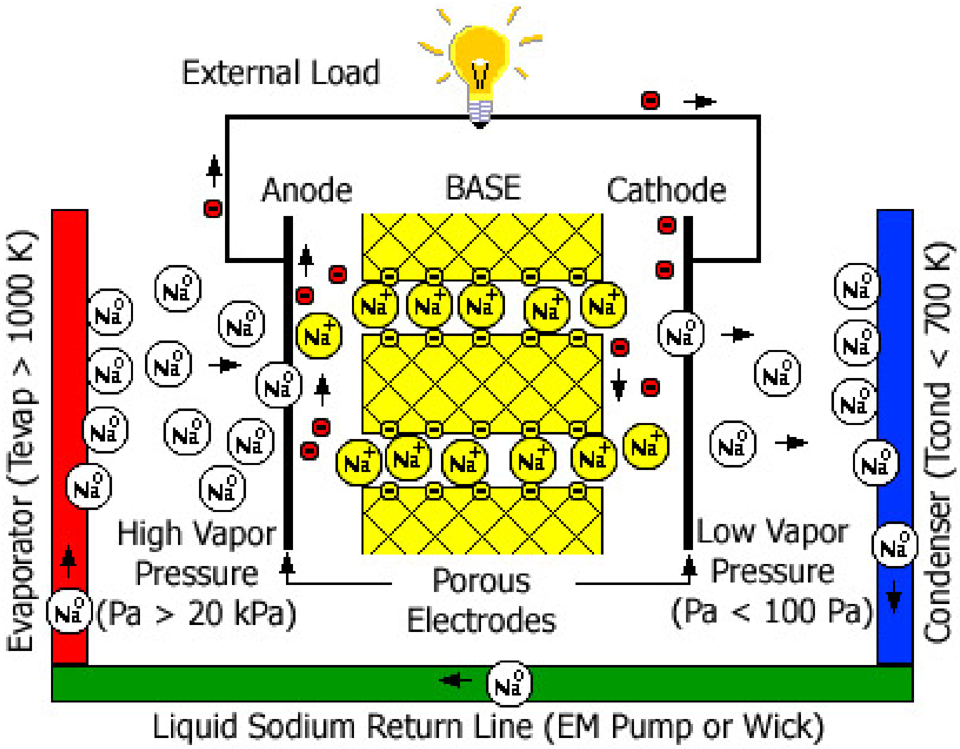

Figure 2. Diagram of AMTEC cross section with illustration of electrochemical process

The beta tube assembly may be the primary focus when referring to the energy conversion process, but it is only a component within a system. This system, referred to as the AMTEC converter, provides the required environment for the conversion process, integrates the necessary components, and provides the means for a continuous power generation process. Figure 3 illustrates a typical configuration for a converter containing a multiple BASE tube assemblies.

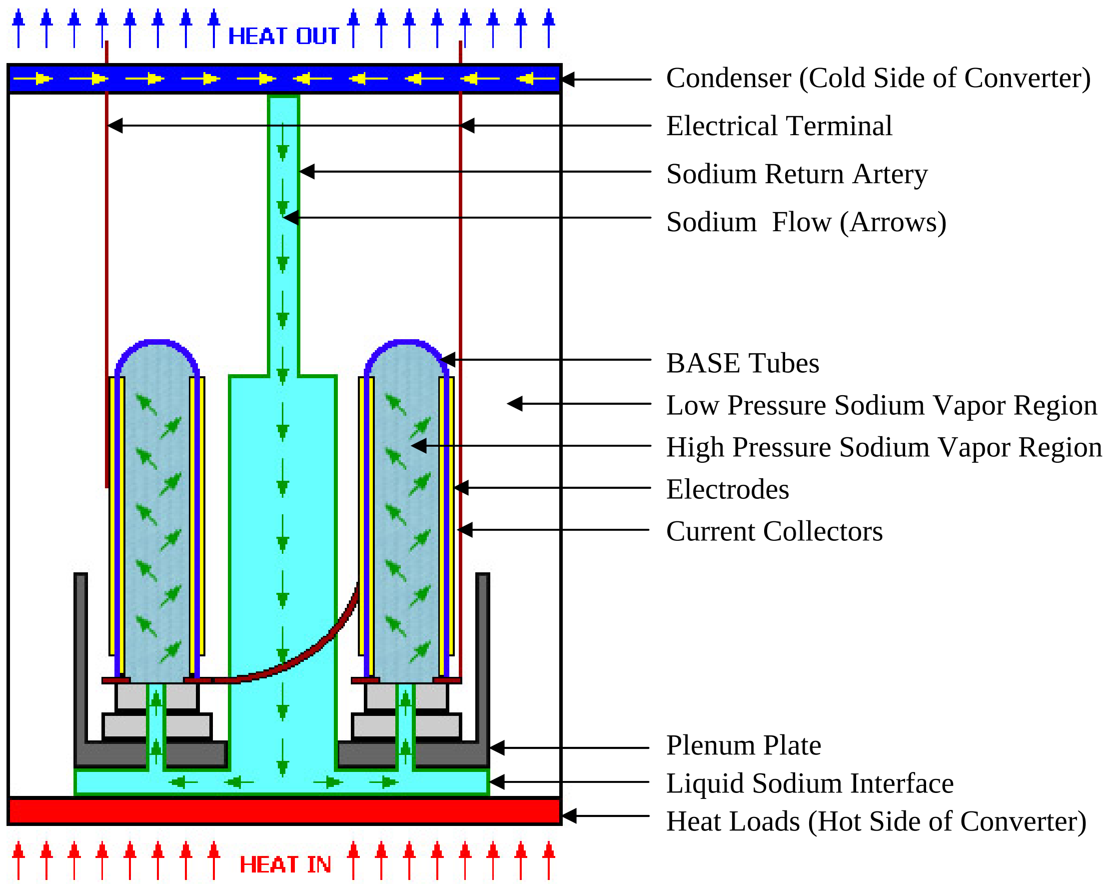

Figure 3. Operation schematics of a typical AMTEC multi-tube converter

Liquid sodium is heated either in an evaporator plenum or inside the External Load tube(s) on the hot side of the converter. After the electrons have conducted through the BASE and recombined with the sodium ions to form neutral sodium, the sodium evaporates from the cathode and sodium vapor flows to the cooler surface of the converter, or condenser. The evaporated sodium once again undergoes a phase transition to a liquid state. The liquid sodium returns to the hot end of the converter by means of capillary action with a fine-pore wick or by means of a small pump, such as an electromagnetic pump ([3,4]). The result is a continuous cycle, where a constant addition of thermal energy provides a constant supply of electrical power. Various models have been used in the past to model this conversion process or part of the conversion process.

Previous Models

Previous models of AMTEC converters have varied in complexity and purpose. Models have been created that, although lacking detail, were used as an effective analysis tool at the conceptual level. The effectiveness of these models, however, is often reduced when a higher degree of resolution is required. Models with increased detail and resolution have been created for these scenarios. This section briefly describes some of the previously developed models of AMTEC converters.

Historically, there are two software packages that were frequently used for AMTEC simulation, TK Solver and Sinda/Fluint, with the graphical interface, Thermal Desktop [6].

A top-level model has been used to analyze the performance and design of AMTEC converters when a particular application did not require a high level of resolution. This top-level model was created in a software package, called TK Solver, which is essentially a simultaneous equation solver. TK Solver solves for any unknowns including, but not limited to, converter voltage, power, heat loss, and conversion efficiency. Although the TK Solver model provides flexibility, a more detailed electrochemical and thermal model is necessary to truly simulate the operation of an AMTEC beta tube and converter. This is particularly important when the AMTEC design has preceded beyond the initial conceptual design stages and has entered the preliminary and final design stages. TK Solver is essentially a one node model of the beta tube, and will not account for axial or radial temperature distributions on the beta tube, nor will it account for the true effects of radiation heat losses within a given converter configuration. This limitation results in less accurate performance predictions, particularly when tubes are large (greater temperature distributions) or when the converter geometry is not as symmetric (radiation effects).

More detailed performance prediction models have also been used in the past to predict converter performance and/or perform design studies. A nodal thermal and fluid modeling software package called Sinda/Fluint, with the graphical interface, Thermal Desktop, has been used to model more detailed operating conditions such as thermal gradients, complex heat transfer scenarios, and pressure drops due to sodium vapor flow [7, 8]. A few of these models have integrated an electrical model with the thermal and fluid aspects of converter models to predict converter performance [6, 9]. An integrated model incorporates all aspects associated with converter performance and is therefore the most effective type of model for design analysis of AMTEC converters. The complexities associated with developing such a model should not be overlooked.

Sinda/Fluint employs user-developed nodal networks to analyze heat transfer and fluid dynamics within a system. Transient and steady-state solutions may be obtained. Because the software package is written in FORTRAN, the user may choose built-in routines provided by Sinda/Fluint for analysis and/or develop custom routines. A performance analysis of AMTEC requires a custom electrochemical routine that integrates with the thermal and fluid nodal network.

Thermal Desktop allows the user to interface with Sinda/Fluint by creating nodal networks within an AutoCAD platform. Results may be obtained in the form of graphs, color distributions representing the variation in the values of various parameters, or data. With the use of Sinda/Fluint and Thermal Desktop, it is possible to obtain results for steady-state or transient conditions on a node-by-node basis. Typical results include temperature distributions, heat transfer rates, and pressure distributions. Such an analysis can lead to needed design refinements that may increase performance, or may provide the designers with more detailed information on the operation of the system [6].

Base Model Development

The Base Model was developed and calibrated during the Phase I of the Roadrunner project initiated by Active Power Inc., with AMPS, Ann Arbor, Michigan and CSP, College Station, Texas. Comparison of the TK Solver and Sinda/Fluint has shown the later as a more effective tool for detailed AMTEC converter modeling. Previous models exist for AMTEC converters but are few in number and each has limitations. Unfortunately, models that are more detailed are not without problems either. Thus, The Sinda/Fluint, with its graphical interface Thermal Desktop, was chosen as a powerful tool to significantly decrease amount of the problems that can appear during the modeling process.

The idea of the model was to create “user-friendly”, multi-functional, parametric model that can be used for different AMTEC converter studies and can be relatively easily modified by the users who are unfamiliar with the model. All if the AMTEC converter models that were created during the Phase I and Phase II of the project were based on this concept.

Three categories were identified as important aspects of an AMTEC converter’s performance. These categories were thermal conditions, pressure losses due to sodium flow, and electrical conditions. To develop a model of an AMTEC converter, the necessary equations that quantify AMTEC performance with respect to these categories were evaluated [4]. Because of the thermal conditions of the converter were simulated using the software package, Sinda/Fluint, the studies were focused on the theory used for the electrical and pressure loss categories.

Since a parametrical and multi-functional model was desired, the model includes a system of “operations” and “subroutines” which can simulate different scenarios depending on several parameters such as electrical current, dimensions of BASE tubes, temperature of heat load and condenser. Manipulation of parameters gives users flexibility in simulations of most possible AMTEC converter performance by using the existing Base Model. Also the Base Model was designed as a universal tool, which could be used not only for certain AMTEC converter design, but also for any design. Based on the Base Model, simulation of any design of AMTEC converter can be done by graphical model and nodes combination changes simultaneously with operation and subroutines modifications for particular AMTEC converter design.

To comply with restriction that the model should predict converter performance within 10% of accuracy, the model was calibrated by modeling two converters, the Universal Miniature Electrode Test Cell (UMETC) and the Engineering Converter (EC), recently built and tested by Advanced Modular Power Systems (AMPS). The performance predictions obtained from the model for both converters were compared to the experimental results obtained by AMPS for a wide range of temperatures and operating currents. Critical design parameters such as electrical contact resistance between cathode and beta tube ($R_{contact}$), surface enhancement factor (F_c), electrode morphology factor (G), and cathode exchange current coefficient (B_{cath}) were adjusted until performance predictions were within 10% of experimental results for the two converters [4]. An illustration of the geometric aspect of the model UMETC and the steady state thermal distributions derived by Thermal Desktop are shown in Figure 4.

Once the model was calibrated with the performance data acquired from the UMETC and the EC, the model was ready for its intended purpose. A seven-tube converter design was proposed by CSP, TAMU, and necessary model was developed based on previous single-tube model calibrations and modifications that were assumed for multiple-tube AMTEC converters [4]. Figure 5 illustrates geometry of the multi-tube converter; the steady state thermal distribution derived by Thermal Desktop; and labels the major components.

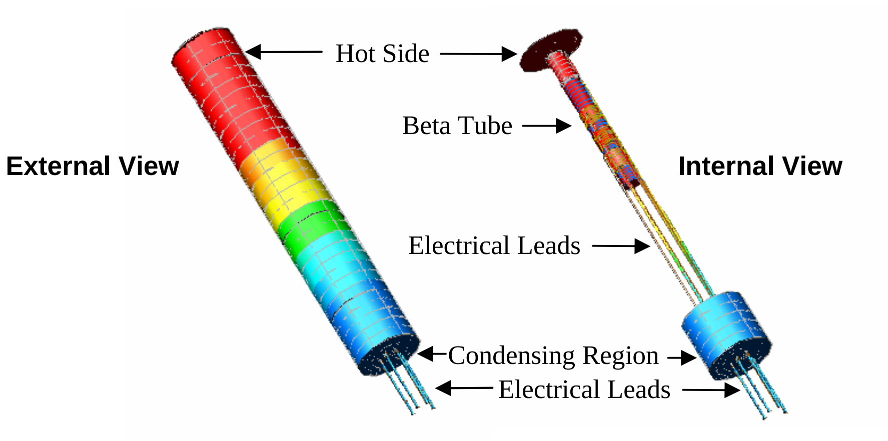

Figure 4. UMETC geometric nodal model internal and external views

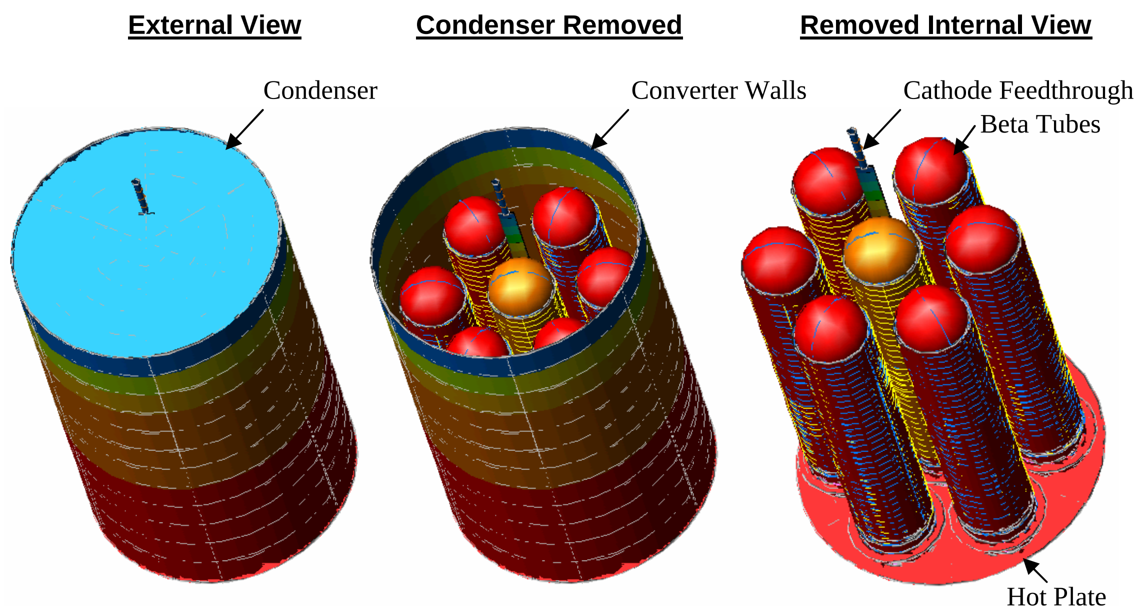

Figure 5. Multiple-tube AMTEC converter geometric nodal model internal and external view

Eventually, after successful results in single-tube model development and calibration and multiple-tube model development, a six-tube "Goal-size" converter design for an industrial application was proposed by AMPS and CSP, TAMU. The "Goal size" design is significantly different in conception including changes in the dimensions of the BASE tubes. The model has the following changes:

- Condenser region separated from entire converter by narrow Neck structure to decrease heat loss at critical area.
- Sodium return structure with Sodium return artery and Evaporator.
- Two Feedthroughs simulated current collectors from anode and cathode surfaces.
- Heat load not only at the bottom, but also inside of evaporator structure to accelerate sodium evaporation process.

An illustration of the geometric aspects of the "Goal Size" multiple-tube AMTEC converter model and the steady state thermal distributions derived by Thermal Desktop are shown in Figure 6. The "Goal Size" AMTEC converter model was chosen as the Base Model for the Phase II of the research project that will be described at next chapters.

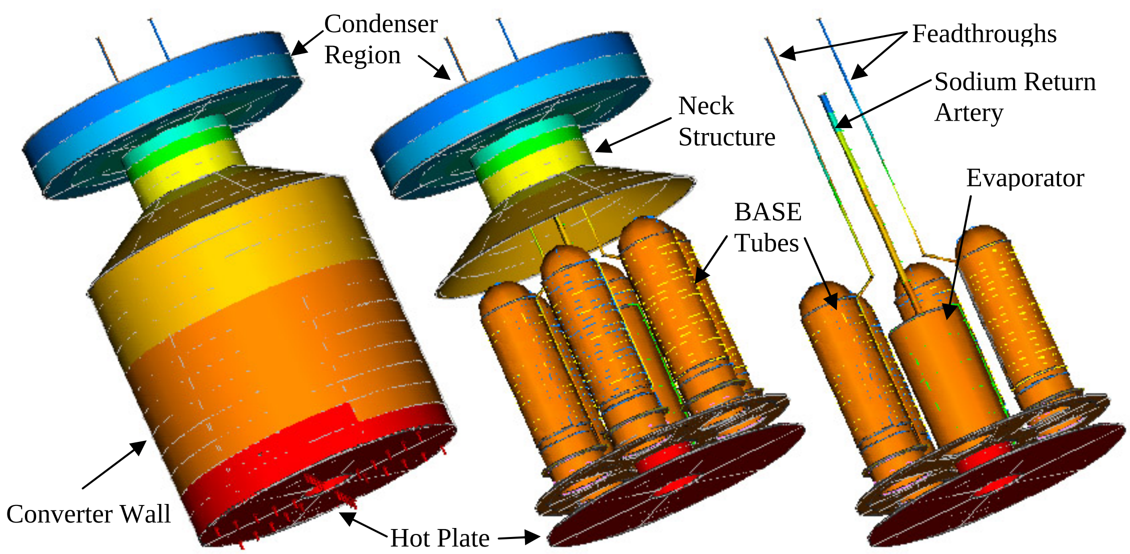

Figure 6. "Goal-Size" multiple-tube AMTEC converter model internal and external view

NEW DESIGN-MODEL DEVELOPMENT

Developing a new design for the AMTEC converter model included careful analysis of the previous models as well as design, development and research of three models for conceptually new designs of AMTEC converter. This chapter contains three sections devoted to explaining the development of the model. The first section defines the need for a new AMTEC converter model, and the second section defines the requirements of such a model. The third section, Model Evaluations, contains three subsections that describe the process of new design models evaluation with their significant differences in design, properties and results of performance.

The Need for a New Design-AMTEC Converter Model

The Base Model for multiple-tube AMTEC converter existed, when the current research project began. During Phase I of the project, the goals regarding model development were reached successfully, a more flexible and powerful software package was chosen, the new model was created and calibrated with existed data, and, finally, model for multiple-tube AMTEC converter was created too. The new model proved itself to be an excellent parametric analysis tool. It has also proved that Sinda/Fluint is an excellent tool and it satisfied model requirements much better than other software packages that could be used for AMTEC converter analysis. Thus, a solid foundation for future AMTEC converter research was created

During Phase II of the project several models for significantly different designs of the AMTEC converter were created and use for converter performance prediction. The new models had to show how converter performance would be changed by the changes in design and help decide whether the changes were useful or not. In these circumstances, even unsatisfactory results can be considered as useful and valuable. For example, if a new design model shows inefficient operation and disadvantages of the design due to intrinsic flaws, the analysis of the model performance and results can suggest how the design has to be modified to fix the problem. It is needless to quantify the amount of money, labor, and time saved by computer simulated design disadvantages rather than performing actual experiments that are labor intensive, expensive and time consuming. Thus, it was decided to simulate several converter designs, predict how converter with particular design would be performed, and optimize if necessary. The model was chosen as a tool that could completely satisfy the requirements in achieving the goal. Modeling is an important process that can illustrate advantages and disadvantages of the new design as well as help to optimize it before actual converter manufacturing.

Model Requirements

Since previous performance in AMTEC converter modeling gave successful results, it was decided to keep the conception of the model as a solid foundation for future modeling as it was established at the time of its evaluation.

There was not any reason to change modeling tools since Sinda/Fluint shows excellent flexibility in AMTEC converter thermal simulation, as well as results that predict AMTEC converter performance very well.

The model has to perform parametric analysis. It is not necessary to say how much it increases research ability. However, parameterization of some other properties and/or dimensions of the model could open more opportunities for future research. It was required to continue studies in model parameterization.

The previously evaluated modeling equations were successfully proved based on the model performance and calibrations. However, the new model designs are significantly different from previous one. It was suggested to change model equations with respect to changes in the model design if necessary. At the same time, numerical simulation subroutines as part of the model were qualified as very good, but it was recommended to make careful analysis and optimize them in order to decrease time of simulation and to make numerical simulation more precisely.

Lastly, since the model design, evaluation, and development would be carried out by different individuals as different phases of the project emerge, it was decided to keep "user-friendliness" a key concept during model development, and try to make a model more understandable for future users. The personal experience gained in understanding the model while working on different design aspects were very important and helpful while adding further improvements in tandem with the "user-friendly" concept.

Model Evaluation

The primary objective of this work was to develop a new, significantly different, converter model in response to design changes. To comply with this requirement, three different models (Design # 4, 5, and 6) were developed consecutively. After design and development of each model, results of their performance were studied and conclusions were drawn. Each updated model design was evaluated with respect to recommendations and corrections that were made from previous ones. Eventually, the last model design (Design # 6) was developed and tested. The design was accepted as the design for the Road Runner II experimental model, whose production commenced subsequently. This section describes the process of the model design development and study and contains three subsections, one for each design, respectively. Each of these subsections, named after the number of design, describes features of each design as well as the model developed for it. Also, the results obtained from the model testing, recommendation, and conclusions that were made based on the results are included in these subsections.

Design 4

The Design 4 differs significantly from the previous, Goal-Size design. Only the dimensions and structure of the BASE tubes were unchanged. The most significant difference from previous model was that the BASE tubes were facing down and a condenser plate was placed at the bottom of the converter. The BASE tubes were mounted on a thick plenum plate with sidewalls that shielded BASE tubes from the cooler regions. The heat load was modified from a plate at the bottom of the converter to a cylinder, which was surrounded by beta tubes and placed in the middle of converter wall cylinder. The plenum plate was mounted on the heat load cylinder. Shielding was provided from the bottom and top of the beta tubes assembly to separate conversion areas from the colder regions. The sodium return system consisted of a sodium return artery, which delivered condensed sodium from the bottom of converter to the beta tubes through cylindrical sodium distributor at the top of the plenum plate. Lastly, the shape of the converter was changed. It was designed as a straight cylinder without a narrow neck to separate the condenser from the rest of converter as was done in the previous model. An illustration of the geometry of the Design 4 model is shown in Figure 7.

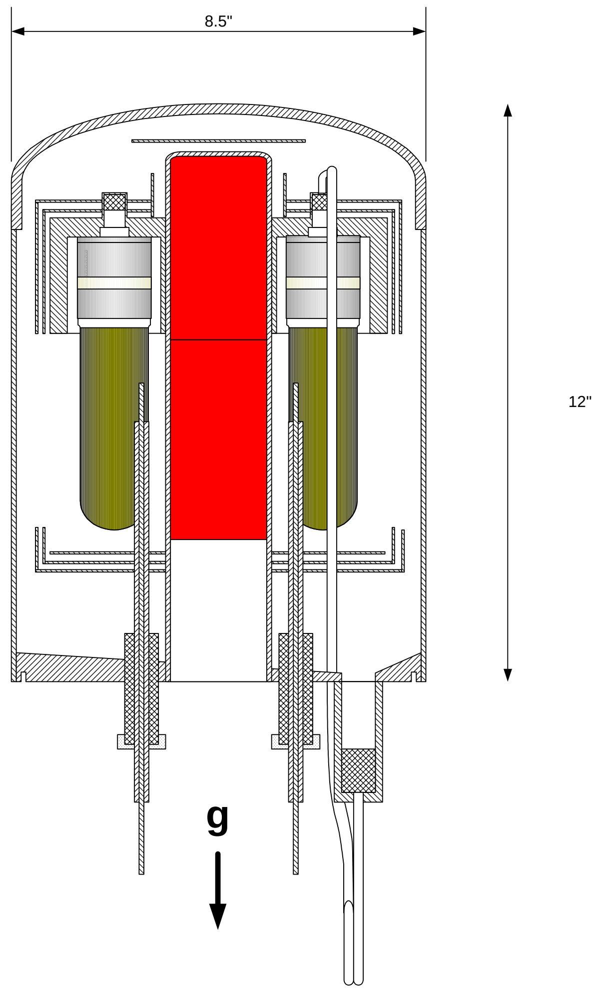

Figure 7. Cross-section of Design 4 model

The principle of operation is as follows. Liquid sodium is injected into the system through the sodium return artery by an Electrico-Magnetic pump (EM pump) and delivered to the beta tubes through the cylindrical sodium distributor. The sodium is then heated within the beta tube. The electrochemical details of operation are the same as those within a typical AMTEC converter. Once the sodium condenses on the condenser surface, it is collected and injected back into the system by the EM pump.

The Design 4 converter was geometrically modeled in Thermal Desktop as accurately as possible and experimental temperature data from previous actual models' performance was used to set the initial temperatures of appropriate nodes in the model. This method ensured that variations in the thermal aspect of the model would be minimal, and therefore, a true evaluation of the model would be possible. The programming code required to run a parametric analysis simulation was created by modifying the code from the previous model. The code was significantly changed since the model included many changes as compared to the previous ones, however, main equations and correlation were kept the same, and the changes were mostly concerned with changed geometry. Basic operating scenarios were used to predict experimental results. An illustration of the geometry of the model and the thermal distribution for a simple steady state analysis is shown in Figure 8

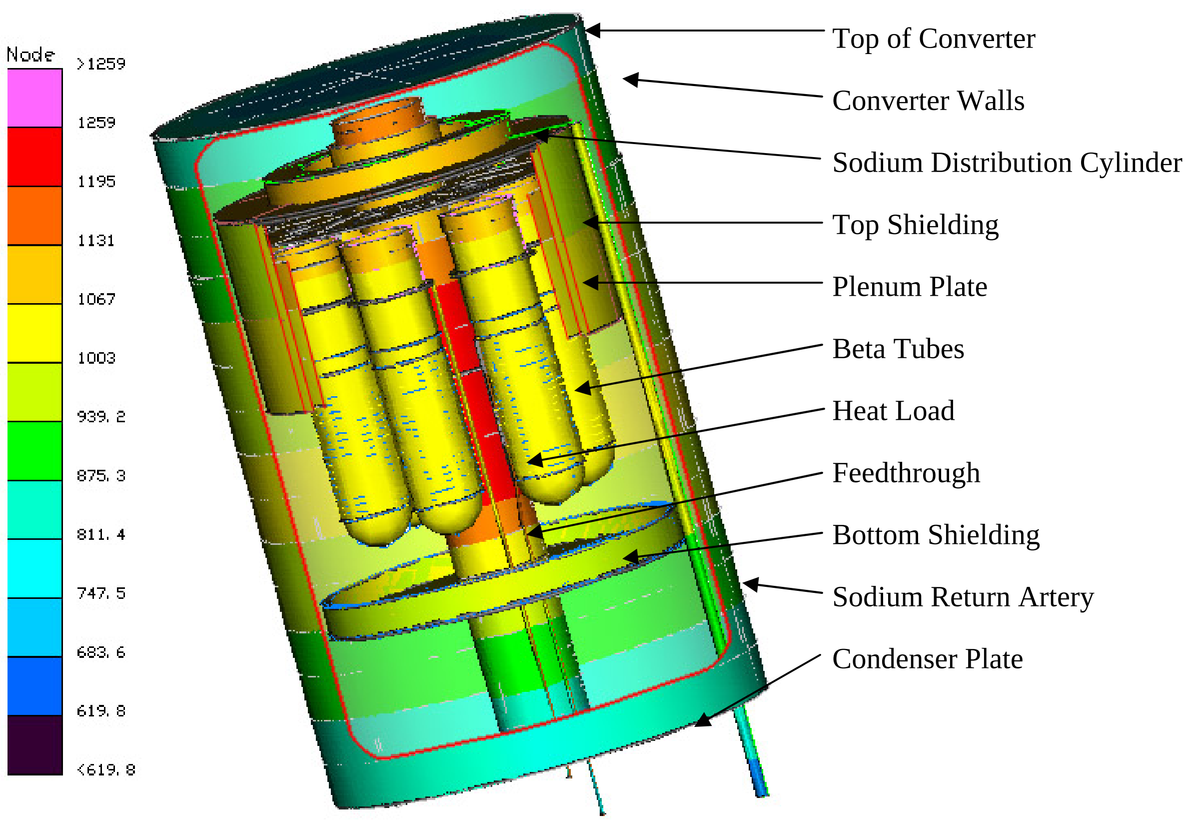

Figure 8. Thermal Desktop Design 4 model thermal analysis results

From the beginning of the modeling it was seen that some parameters of the system had to be changed. For example, the plenum plate walls and the bottom shielding walls were not high enough to separate the beta tube assemblies from cooler region that cause significant heat leakage and, as a result of instability in the system, and it was decided to increase their height from 2.1 inches to 3.0 inches. This change gave some stability in the system, but did not solve all problems. Then, the analysis of the model was continued. It was seen that the temperature distribution at the converter walls and condenser was not as expected. For example, simulation results showed that the temperature of the top side of the converter was not only much cooler than the converter walls but also cooler than the condenser. This fact was one of the reasons for instability in the system. At the time, when the model design was created, it was not recognized that the top side of the converter walls, separated from the heat load as well as from the heating area by shielding, would not reach the necessary temperature range, thus, it would cause additional loss of heat from the system.

The simple steady state simulation showed that to operate the converter with this particular design would require at least 1200 Watts to achieve the required hot side and condenser temperature range of 800 and 300 °C respectively without any electrical current. However, it was expected that the converter would not require more that 1000 Watts thermal input. The 1000 Watts line was established as a maximum acceptable required input energy for the system.

After performing the analyses, the design was considered inefficient. Corrections for the new Design 5 were following:

- Invert the beta tubes back to the original position (facing upwards)
- Relocate the condenser to the top of converter
- Connect heat load cylinder to both ends of converter walls

- And to increase shielding between beta tubes assembly and colder regions, especially the bottom of the converter cylinder

The future analysis of the Design 4 model was stopped, however, it was suggested to use this model as basis for future AMTEC research where the beta tubes would be assembled facing down.

Design 5

The Design 5 was proposed by AMPS. It was a modification of the Design 4 updated in line with suggestions described in the previous subsection. The new model had a beta tube assembly, which faced upwards and was mounted on a plenum plate with sidewalls. The bottom shielding and cylindrical sodium distributor were exactly the same as in the previous design and were assembled from the bottom of the plenum plate. Additional conical shielding was assembled between the condenser at the bottom plate and the plenum plate in order to decrease parasitic heat losses. The heat load cylinder was split into two cylinders, top and bottom, in order to be able to use two different heat sources to study how it affects system performance. Lastly, the beta tubes were placed closer to the top of condenser to use it as the top shielding to concentrate heat around the beta tube assembly. The principle of operation was similar to the principal of Design 4 operation.

The Design 5 converter was geometrically modeled using Thermal Desktop with as much accuracy in representation as possible, and experimental temperature data from previous actual models' performance was used to set the temperatures of appropriate nodes in the model. An illustration of the geometry of the model and the thermal distribution for a simple steady state analysis is shown in Figure 9.

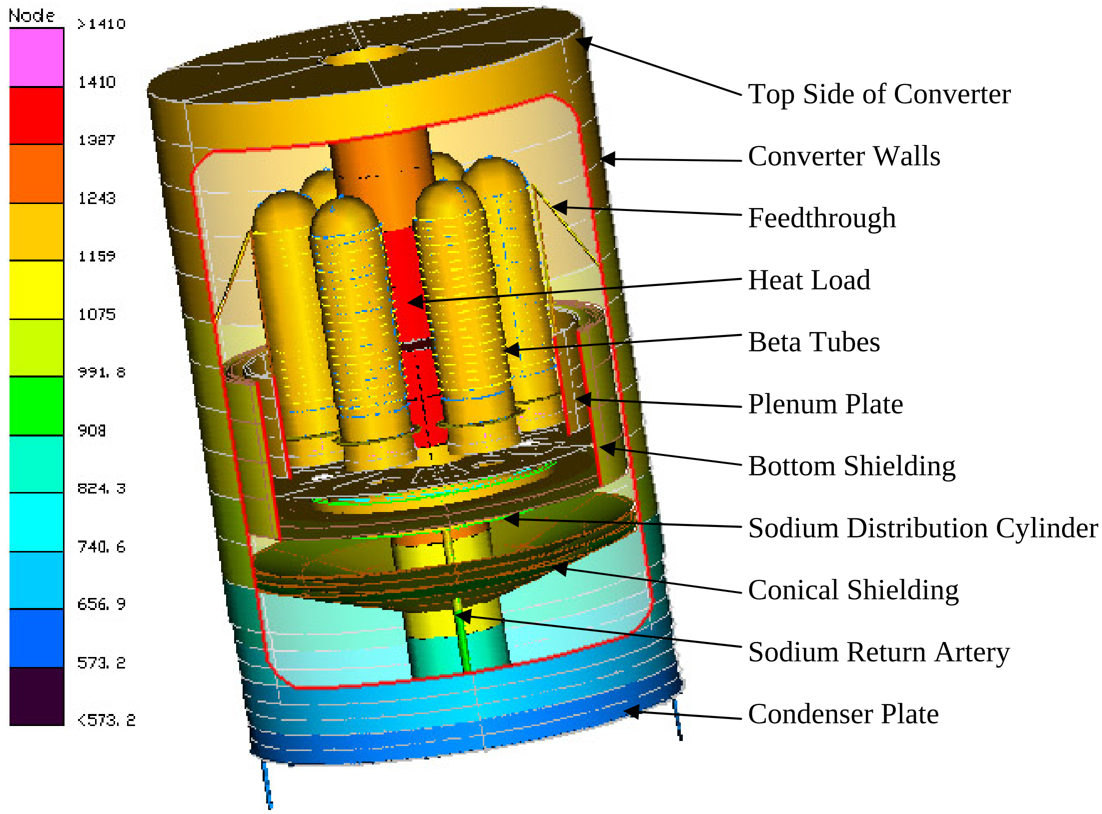

Figure 9. Thermal Desktop Design 5 model thermal analysis results

Unlikely the previous model, the Design 5 model showed excellent stability during testing. The new shielding system perfectly separated the beta tube assembly from the condensing region and conical shielding helped in maintaining the necessary temperature conditions around sodium return system and did not lead to overheating of the condenser. Finally, the simple steady state simulation showed that to operate the converter with the present configuration would not require energy input of more than 1000 Watts to achieve the required hot side and condenser temperature range of 800 and 300 °C respectively. Thus, it was proved that the Design 5 was functioned as expected, and the simulation contrived to predict converter performance for various scenarios.

To evaluate the performance of the model the predicted power, voltage, and efficiency with respect to current were needed. Efficiency was not the main concern at that time because it was known that results of the studies would be used to evaluate the next design which was to be the final AMTEC converter design for fabrication and experimenting. However, an efficiency analysis was performed as well.

Initial runs of the simulation were carried out to predict model performance in the range of current from 10 to 200 Amps with varying heat input given to the system in the range of 1000 to 1500 Watts. These scenarios are provided in Table 1. With this in mind, the results of the voltage, power, and efficiency analyses are provided in Figure 10, Figure 11, and Figure 12 respectively.

Table 1. Design 5 model operating scenarios

	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Minimum Current (A)	10	10	10	10
Maximum Current (A)	200	200	200	200
Heat Input in the System (Watts)	1000	1100	1200	1500
Temperature of Condenser (°C)	300	300	300	400

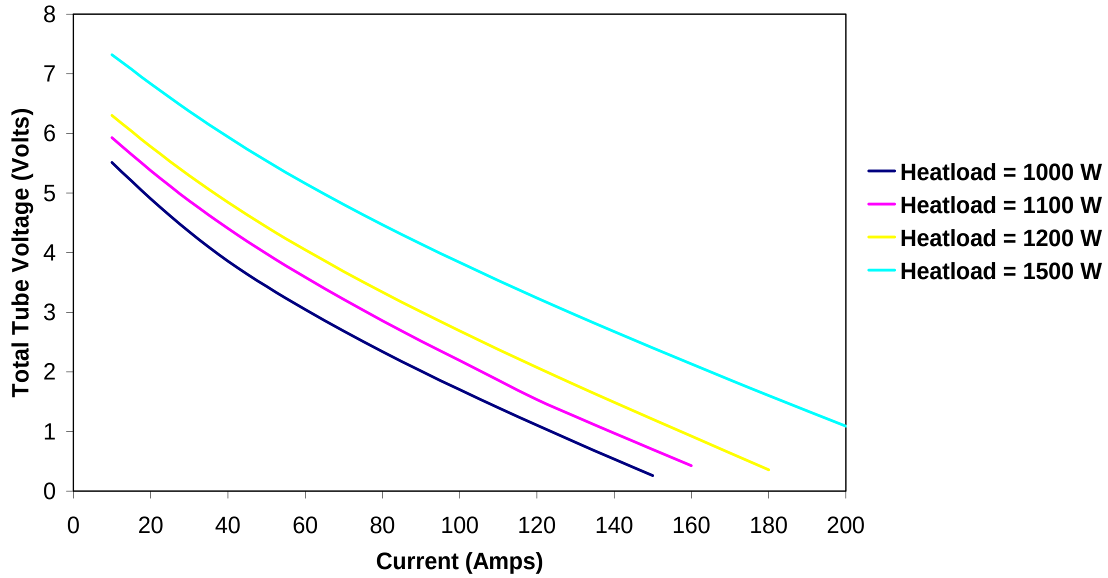

Figure 10. Design 5, voltage analysis

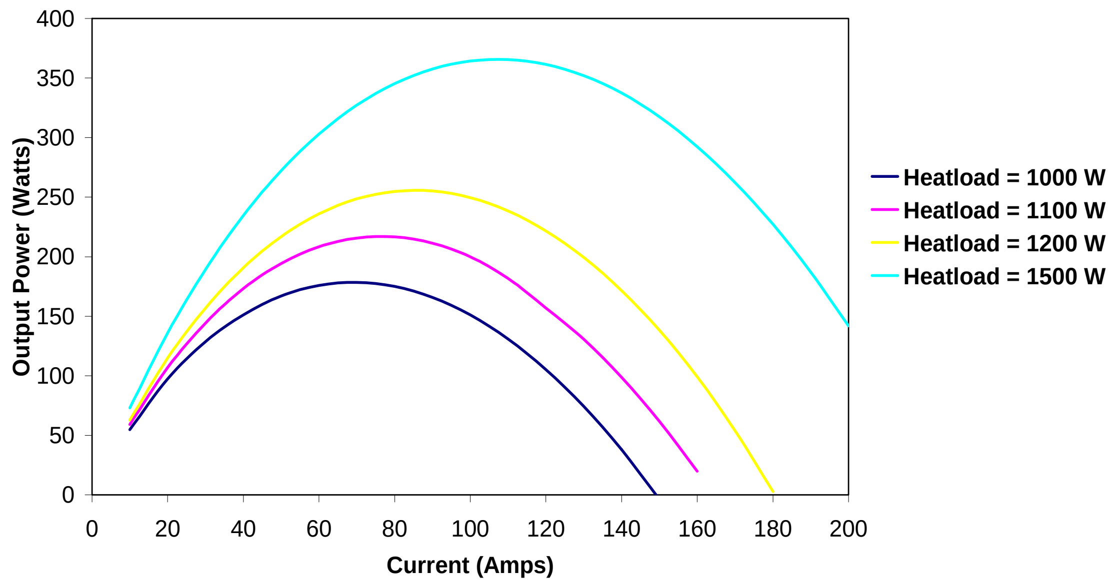

Figure 11. Design 5, power analysis

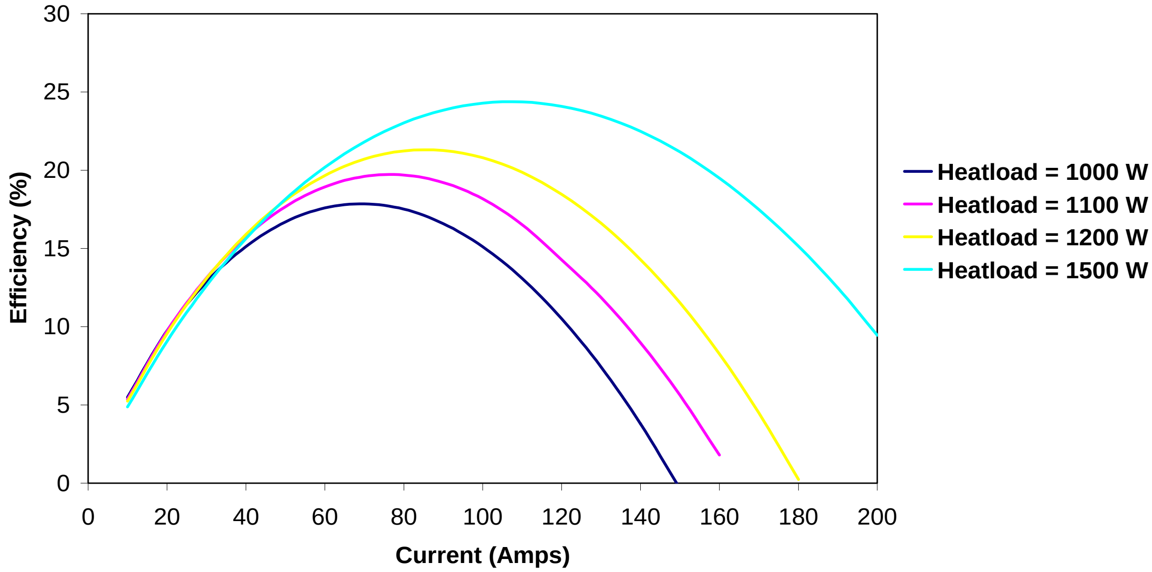

Figure 12. Design 5, efficiency analysis

The evaluated results of prediction were along expected trends; all associated parameters, namely voltage, output power, and efficiency increased with the increase in heat input to the system. The current range of 60 to 120 Amps was found to be the most efficient. The model performed very well without any instability, gave satisfactory results, and was ready for further performance studies.

Since the Design 5 model had two different heat loads instead of one as in the previous model, it was interesting to analyze the changes in system performance by changing the ratio between top and bottom heat input. The bottom heat load was placed near the Sodium distributor, plenum plate, and beta tubes foundation region. The most important concern was that this combination would require more energy input in the bottom heat load so as to keep it at the required temperature conditions. At the same time, the top heat load was placed in the center of the beta tubes at a certain height so that they were kept at the required temperature conditions. Different scenarios were simulated to predict model performance by varying the ratio between heat load inputs with current in the range of 10 to 120 Amps and by keeping the condenser and thermocouple temperatures at 300 and 800 °C respectively. These scenarios are provided in Table 2. With this in mind, the results of the voltage, power, heat required, and efficiency analyses are provided in

Figure 13, Figure 14, Figure 15, and Figure 16 respectively.

Table 2. Design 5 model operating scenarios for different heat input ratios

	Scenario 1	Scenario 2	Scenario 3
Minimum Current (A)	10	10	10
Maximum Current (A)	120	120	120
Heat Input Ratio (Top: Bottom Heat Input) (%)	25:75	50:50	75:25
Temperature of Condenser (°C)	300	300	300
Temperature of Thermal Couple (°C)	800	800	800

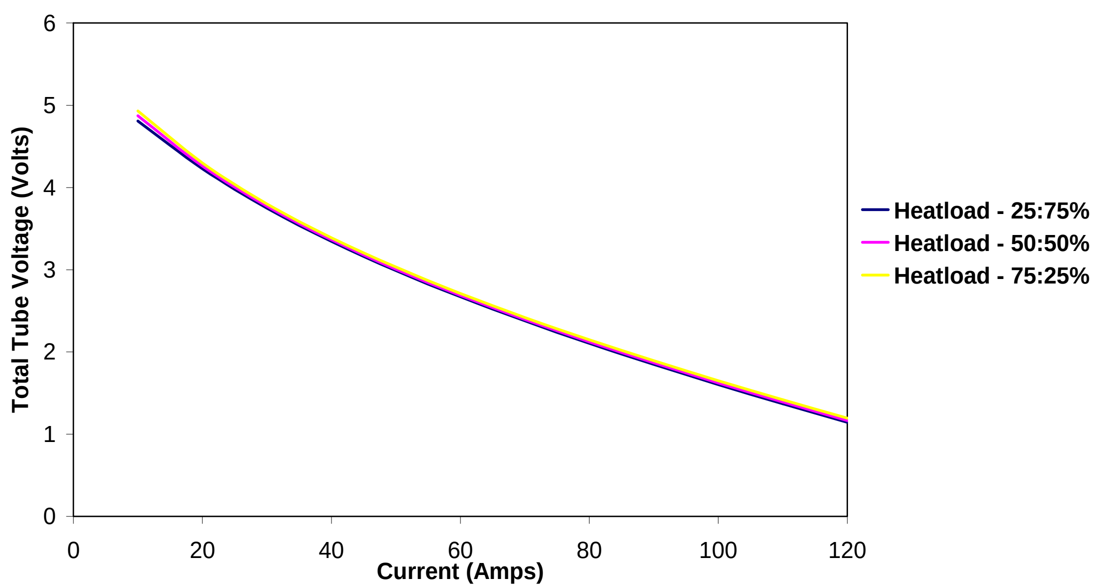

Figure 13. Design 5, voltage analysis for different heat input ratio

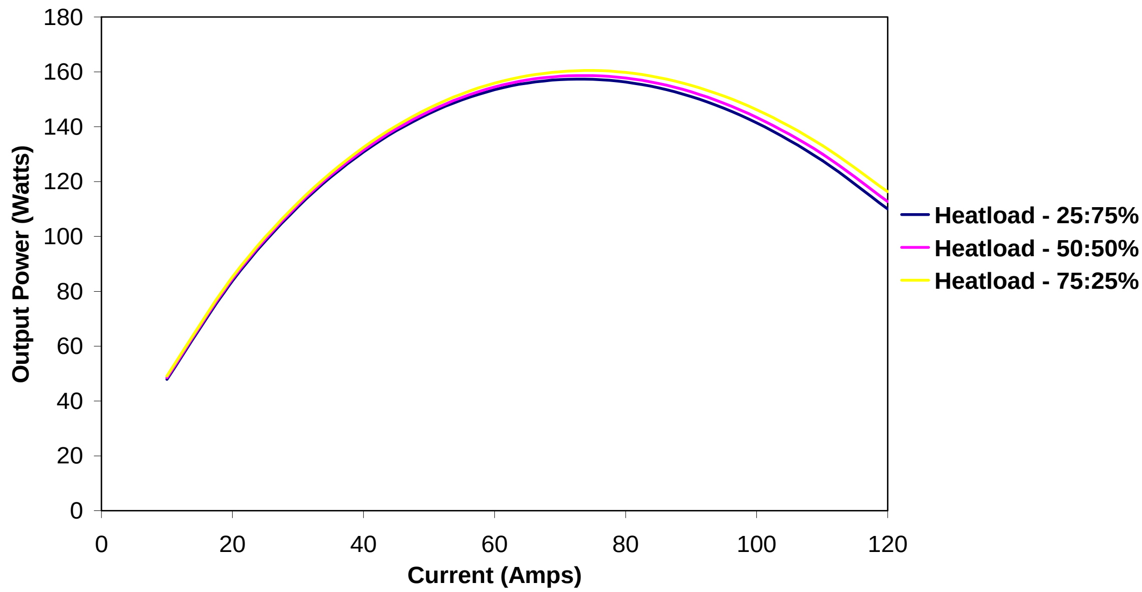

Figure 14. Design 5, power analysis for different heat input ratio

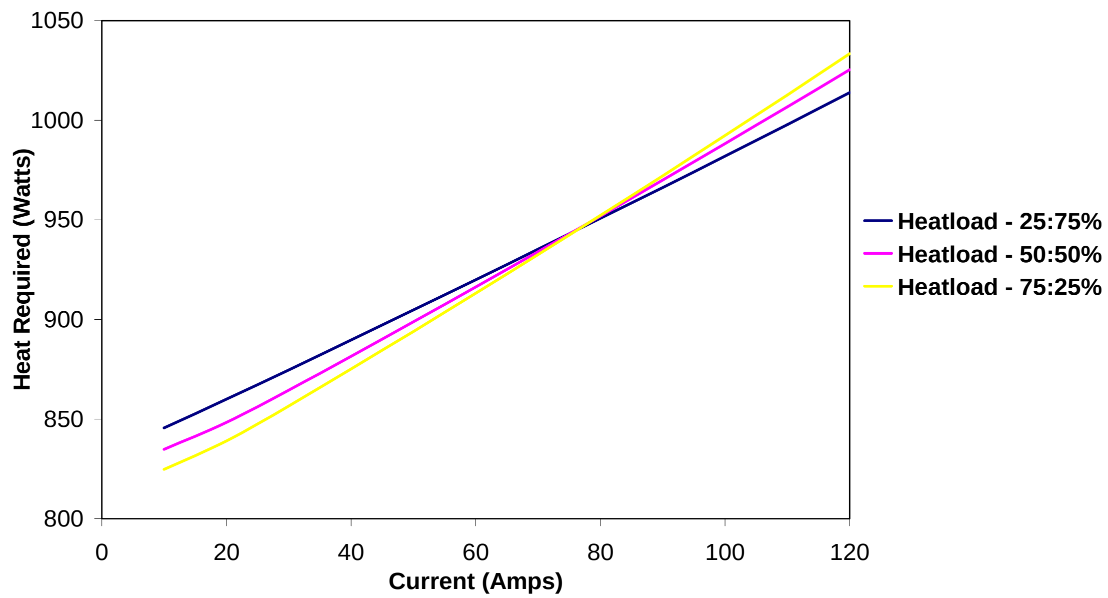

Figure 15. Design 5, heat required analysis for different heat input ratio

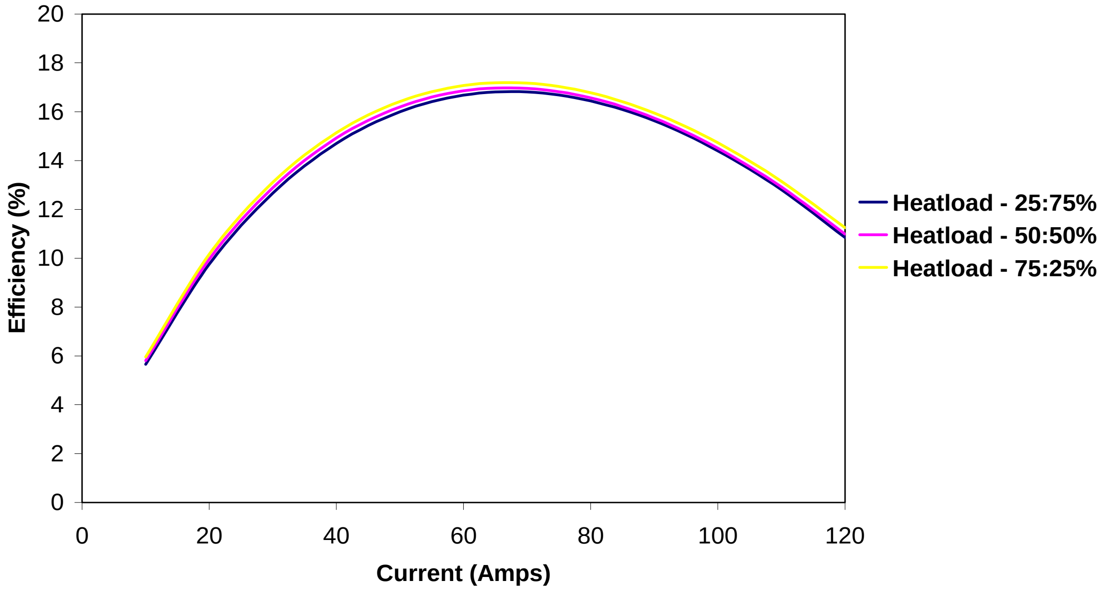

Figure 16. Design 5, efficiency analysis for different heat input ratio

The results of the simulations did not show big differences in voltage, power, and efficiency curves. This fact only highlighted that both heat loads successfully compensated each other regardless of the changes in heat input ratios and the bottom shielding provided very efficient protection by not letting the bottom of the tube assembly lose heat as seen especially in Scenario 3 where bottom heat input was only 25% of the total. However, there was slight difference in the heat required. It showed that with the current ranging between 10 and 80 Amps the system required less heat if bottom heat load input in the system was reduced. At the same time, in the range of current between 80 to 120 Amps, if the ratio of bottom heat input was maintained at more than 50% of the total, was found to reduce the required heat. This was expected because at the higher current the beta tubes had additional heat input compensating for evaporation processes, which liberate thermal energy from the tubes.

The results of model prediction were assumed as successful and the model was considered as the basis for the next design model. It was not necessary to continue model analyses since the new design with few significant differences became the design of the Road Runner II experiment, which was manufactured later. The results of the next design model prediction were more important because they could be calibrated with actual results.

Design 6

Design 6 was a slight modification of Design 5. The main difference has being a significantly modified design of the beta tubes and their basement. A couple of Niobium – 1% Zirconium (Nb-1Zr) cylinders were attached at the bottom of beta tubes to decrease electrical resistance at the bottom of beta tubes. The Nb-1Zr is a well-known alloy. A stainless steel footing was also provided, which was directly connected to the heat load, in order to make an additional compartment to further heat up the liquid sodium before it was injected into the tubes. The design did not have a lot of modifications, since nothing except the beta tubes footing was changed, and it stayed similar to the principle of Design 4 and 5. Figure 17 illustrates the differences in the beta tube's design for Design 5 and 6 respectively.

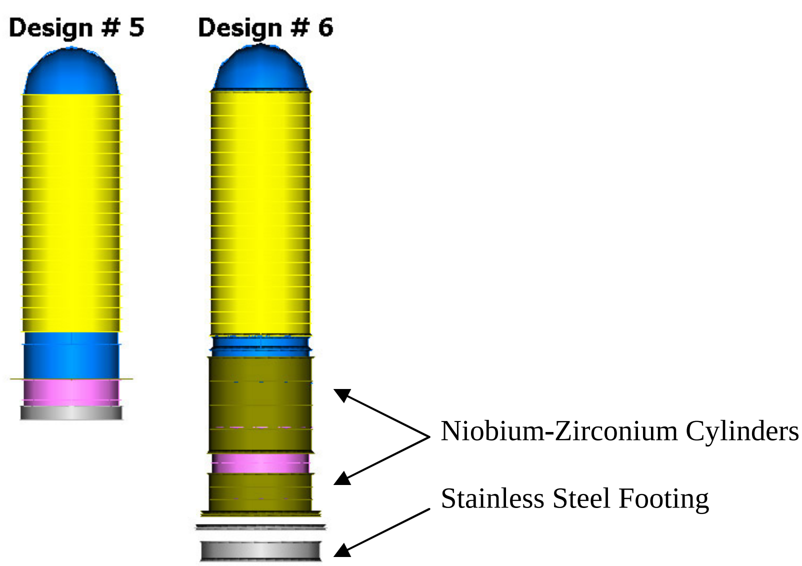

Figure 17. Design 6, improved beta tube design

The Design 6 converter was geometrically modeled using Thermal Desktop with as much accuracy in representation as possible, and experimental temperature data from previous actual models performance was used to set the temperatures of appropriate nodes in the model. An illustration of the geometry of the model and the thermal distributions derived by Thermal Desktop for a simple steady state analysis is shown in Figure 18.

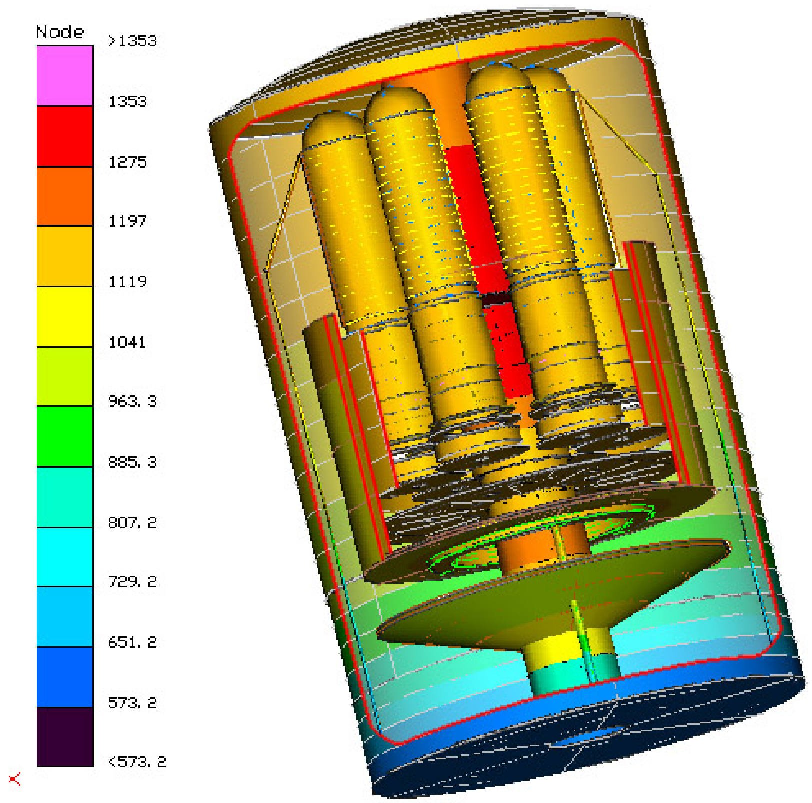

Figure 18. Thermal Desktop Design 6 model thermal analysis results

To evaluate the performance of the design model, the relation of current with respect to the predicted power, voltage, power, and efficiency were needed. The same procedure was used to predict the model performance as for previous models. Since Design 6 model also had two separated heat loads, it was interesting to see the kind of results that could be evaluated for different heat input ratio between heat loads. Thus, the following scenarios were run to predict model performance with different ratios between heat load inputs in the range of current from 10 to 200 Amps and keeping condenser and thermocouple temperatures at 300 and 800 °C respectively. These scenarios are provided in Table 3. The results of the heat required and efficiency analyses are provided in Figure 19 and Figure 20 respectively.

Table 3. Assumed Design 6 model operating scenarios for different heat input ratio

	Scenario 1	Scenario 2	Scenario 3
Minimum Current (A)	10	10	10
Maximum Current (A)	200	200	200
Heat Input Ratio (Top: Bottom Heat Input) (%)	25:75	33:67	50:50
Temperature of Thermal Couple (°C)	800	800	800
Temperature of Condenser (°C)	300	300	300

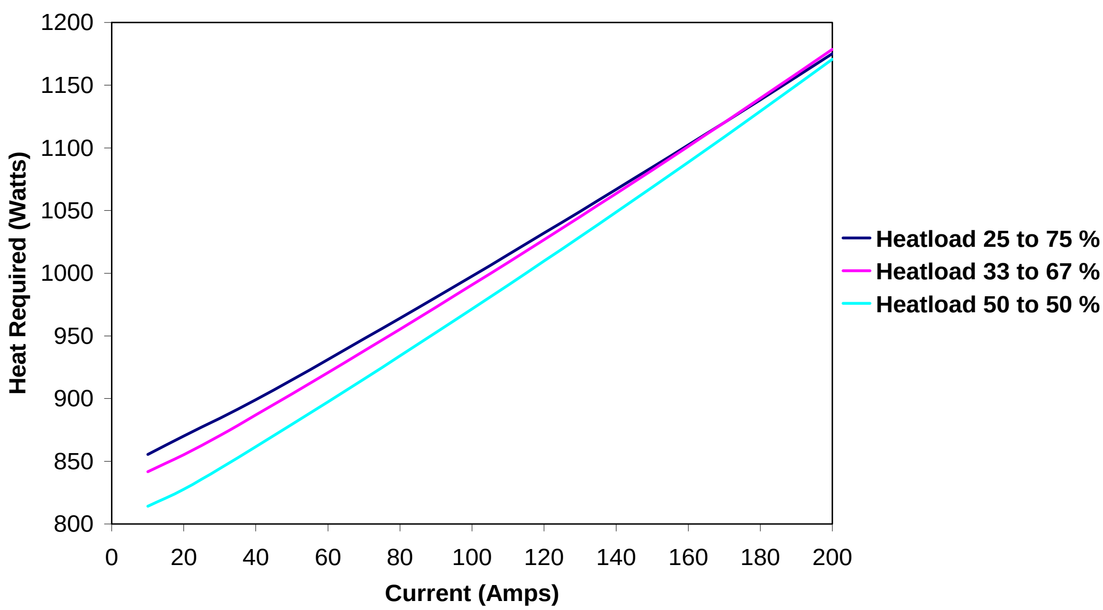

Figure 19. Design 6, heat required analysis for different heat input ratio

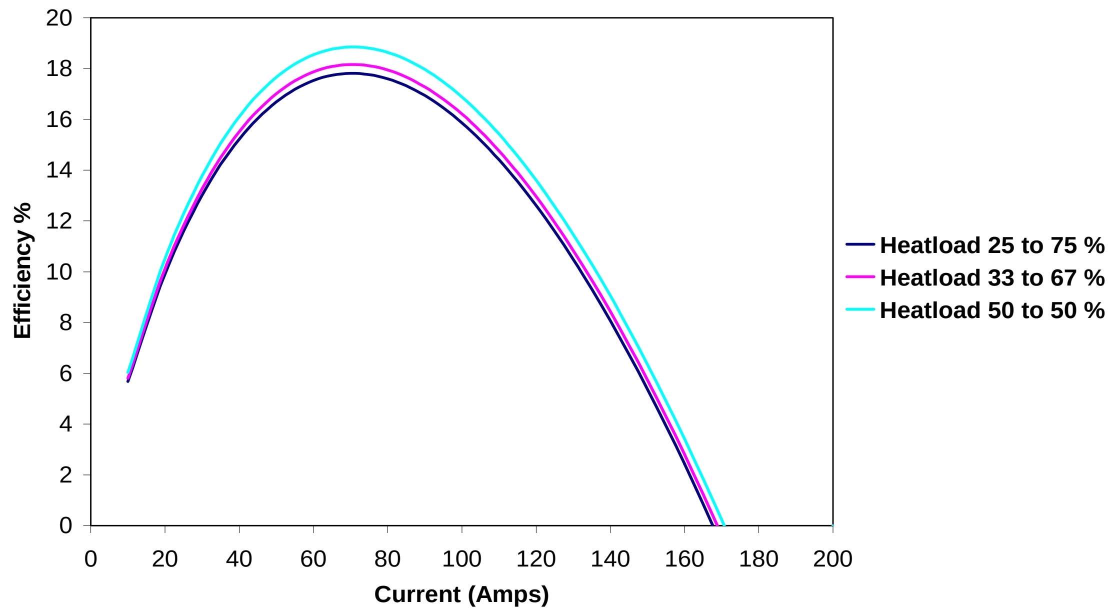

Figure 20. Design 6, efficiency analysis for different heat input ratio

The evaluated results of prediction did not show big difference in voltage, and power, however, they showed that heat required is significantly less for 50:50% case and the efficiency is slightly higher for the same case. At the same time, results did not show that other case of heat loads ratio would decrease ability of the system significantly. Thus, it was decided to use 50:50% heat load split as a basis for future studies.

The next predictions that were performed were aimed at studing model performance with different thermal couple temperatures in order to evaluate ability of the system in frequently used range of thermal couple temperature. Five scenarios of simulation were performed to simply predict model performance in the range of current from 10 to 150 Amps with different thermocouple temperature from 750 to 850 °C. These scenarios are provided in Table 4. The results of the voltage, power, and heat required, and efficiency analyses are provided in Figure 21, Figure 22, Figure 23, and Figure 24 respectively.

Table 4. Assumed Design 6 model operating scenarios for different hot side temperatures

	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
Minimum Current (A)	10	10	10	10	10
Maximum Current (A)	150	150	150	150	150
Temperature of Thermal Couple (C)	750	775	800	825	850
Temperature of Condenser (C)	300	300	300	300	300

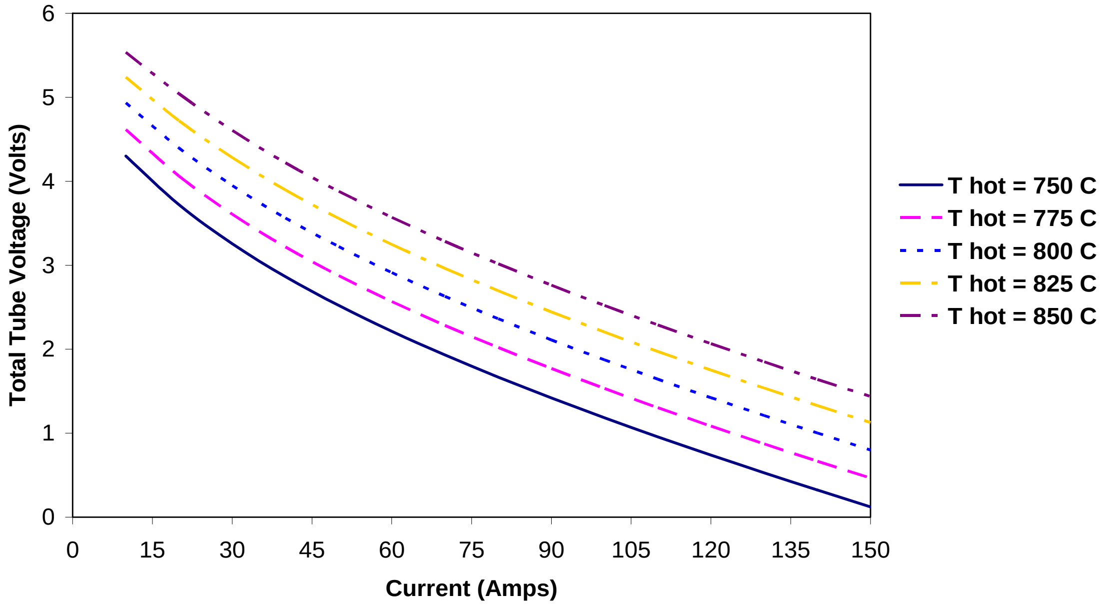

Figure 21. Design 6, voltage analysis

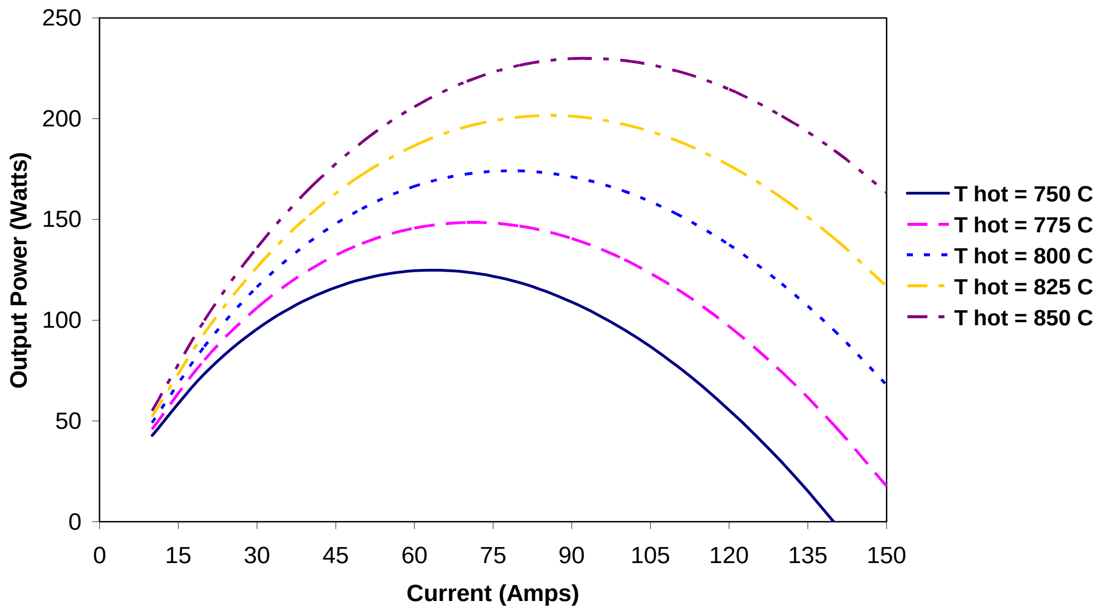

Figure 22. Design 6, power analysis

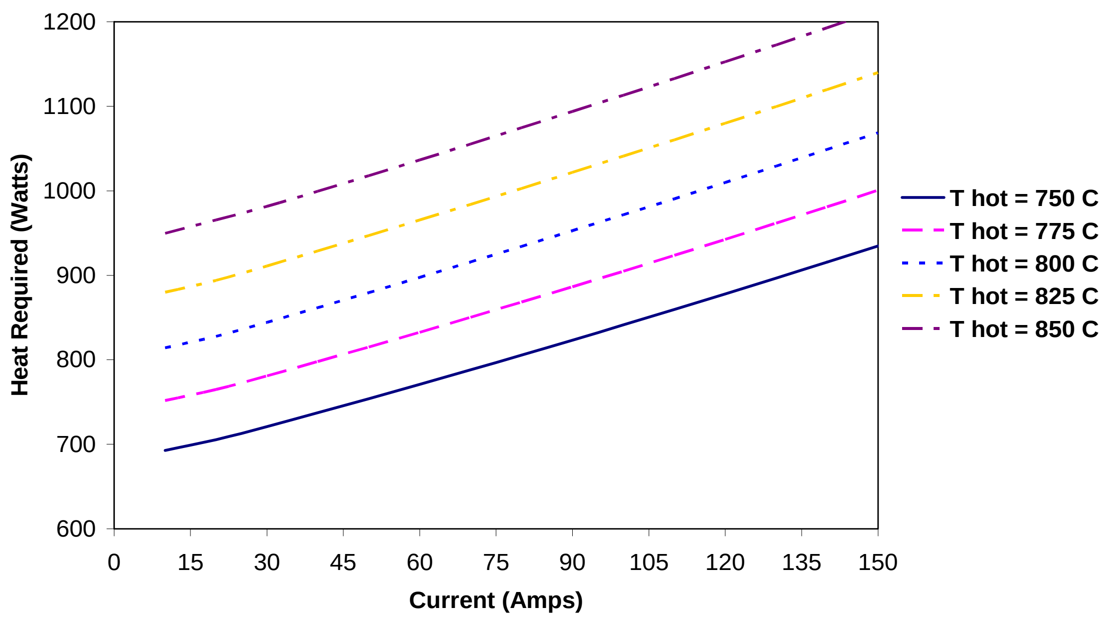

Figure 23. Design 6, heat required analysis

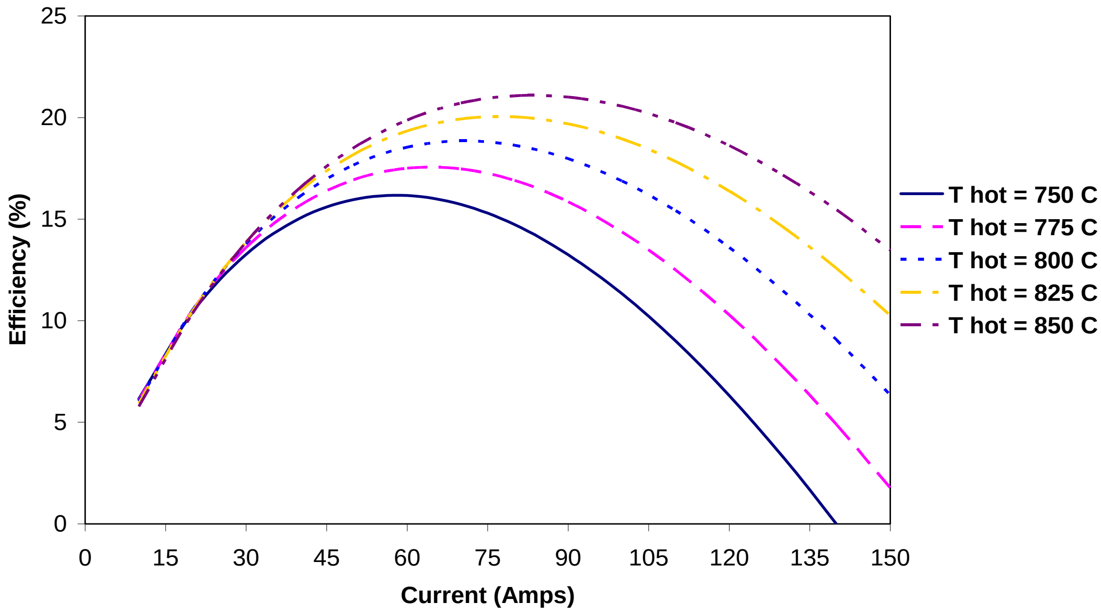

Figure 24. Design 6, efficiency analysis

The evaluated results of the predictions were well along expected lines; all associated parameters, voltage, output power, heat required and efficiency increased with corresponding increase in thermocouple temperature. The model performed very well without any instability, gave satisfactory results, and was ready for the next set of performance studies.

APPLICATION OF THE MODEL AS A DESIGN TOOL

Once the model was developed and tested, the model was ready for its intended purpose. Two of the scenarios were investigated to simulate model performance for a variant annular condenser at the condenser wall and for potassium as the working fluid instead sodium. Performance predictions and design studies were needed to determine if the converter would meet the requirements for industrial use and to identify possible design modifications that would optimize converter performance.

This was the first potassium as a working fluid analysis attempt for the model. Although no experimental data was available for comparison, the results of performance and design analyses for the annular condenser model and potassium as working fluid model, which will be referred to simply as the AC Model and K-BASE Model through the remainder of the paper respectively, are included in this section. The reason for the inclusion is to illustrate the modularity and adaptability of the model's construction when transitioning among different design concepts, such as a different condenser design and working fluid variety. In addition, a model that can identify the design tradeoffs between such different condenser concepts would be considered a more effective design tool than one that lacks this ability. Because the objective was to develop an effective design tool, it is necessary to verify the ability of the model to perform these design studies and to evaluate if the information obtained from these studies would be useful to AMTEC converter designers.

Two subsections are included in this section. The Annular Condenser Simulation subsection briefly describes the assumptions that were needed to model the annular condenser, the basic characteristics of AC Model, and the results of the performance analyses. The Simulation of Potassium as a Working Fluid subsection provides list of changes that were made in order to switch from sodium to potassium in the model, and the results of the performance analyses. Although it is possible to perform countless other design studies using the model, the results presented from the selected studies provide a simple means of measuring the effectiveness of the model.

Annular Condenser Simulation

The Design 6 model was used as a basis for the annular condenser simulation. The wall of the converter was split into two cylinders. The top cylinder represented the converter wall with insulation on the outside. The bottom cylinder represented the annular condenser, which did not have any insulation on the outside and had the same temperature as the bottom plate condenser. The height of the two cylinders was set as a parameter - annular condenser height as a percentage of the height of the converter sidewalls (AnnCndH), and their individual heights could be changed by changing the value of the AnnCndH parameter. Moreover, the subroutine for calculation was changed completely to accommodate this new condition in the model. It used the AnnCndH parameter to recalculate the length of a path between beta tube assembly and condensing region. For example, if the annular condenser height was 30% of converter sidewalls, the length of the 30% sidewalls was subtracted from the pressure drop path. Based on this recalculation, the subroutine calculates the pressure drop in the same way as it was done before for the model with remote condenser.

The heights of annular condenser for simulation were chosen based on the converter geometry. Figure 25 illustrate annular condenser location for each simulation. The 30, 40, and 50 % annular condensers ended at heights corresponding to the bottom of the plenum plate shielding, the bottom of the beta tube assembly, and the middle of the shielding height, respectively. The 90% condenser ended at height corresponding to the top of the beta tubesassembly.

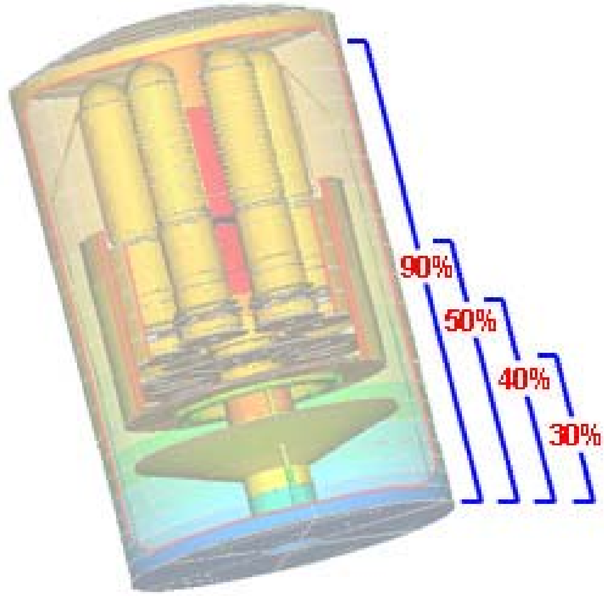

Figure 25. Illustration of simulated heights of annular condenser

To evaluate the performance of the model, the prediction of power, voltage, heat required, efficiency, and pressure drop, as a function of current was required. Hence, the following scenarios were run to evaluate model performance with different height of the annular condenser, with current in the range of 10 to 120 Amps, and keeping condenser and thermocouple temperatures at 300 and 750 °C respectively. These scenarios are provided in Table 5. The results of the heat required, efficiency and pressure drop analyses are provided in Figure 26, Figure 27, and Figure 28 respectively.

Table 5. Assumed Design 6 model operating scenarios for different annular condenser height

	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
Minimum Current (A)	10	10	10	10	10
Maximum Current (A)	120	120	120	120	120
Annular Condenser Height (%)	0	30	40	50	90
Temperature of Thermal Couple (C)	750	750	750	750	750
Temperature of Condenser (C)	300	300	300	300	300

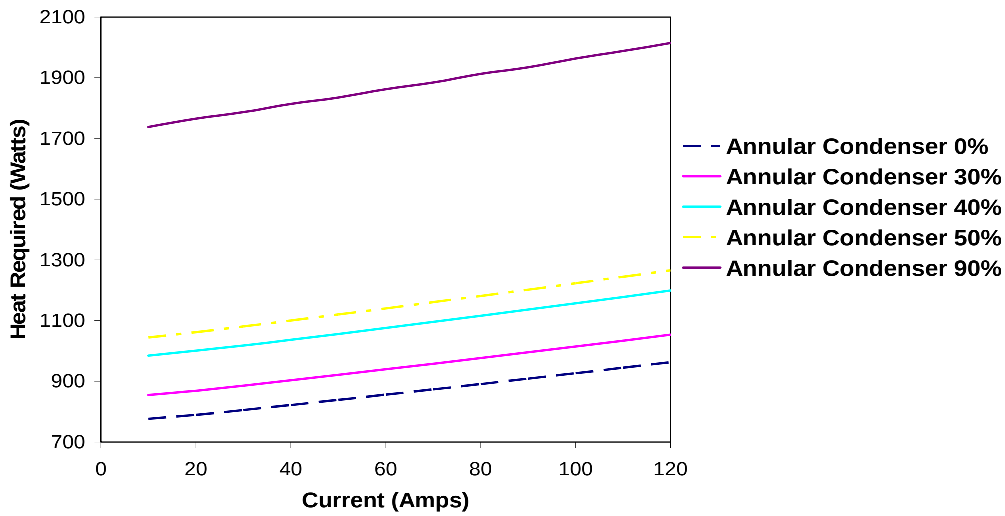

Figure 26. Design 6, heat required analysis for annular condenser model

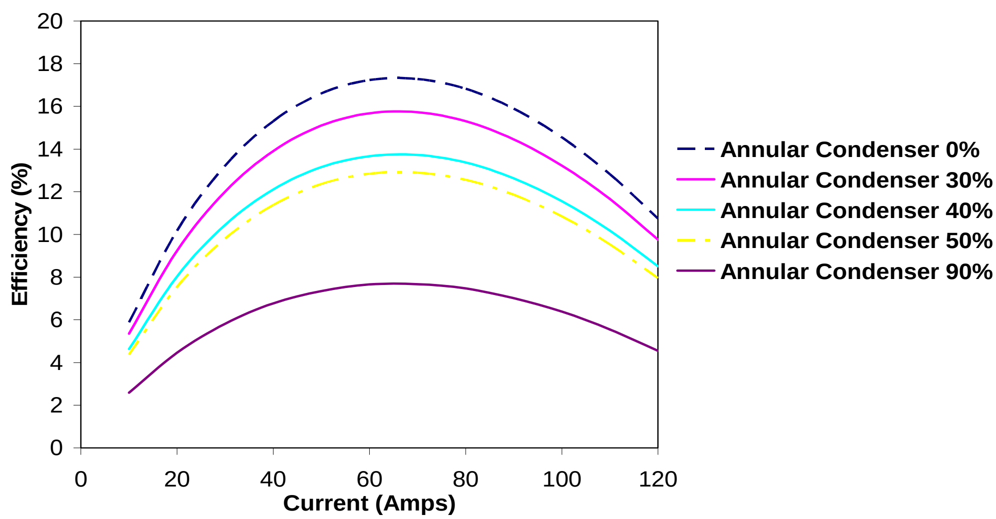

Figure 27. Design 6, efficiency analysis for annular condenser model

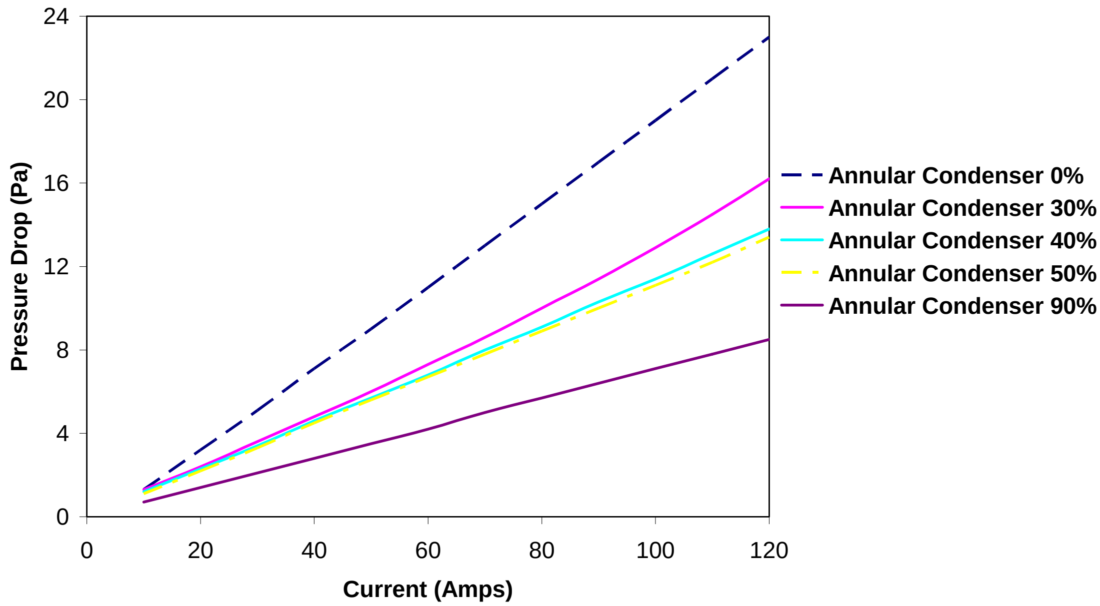

Figure 28. Design 6, pressure drop analysis for annular condenser model

The evaluated results from the model justified the expectation that increasing annular condenser height would decrease pressure drop. The efficiency of the model also increased with increasing in annular condenser height. However, increasing annular condenser height beyond that of 50% of the converter walls, the heat required dramatically increased and became too high for the converter. In spite of the decrease in pressure drop between the condenser and beta tubes assembly, the system required higher heat input because the shielding could not provide necessary insulation from the condenser consequently the beta tubes assembly cooled down much quicker than it did in the previous models. More careful analysis showed that annular condenser height of 30% of the converter sidewalls provided satisfactory decrease in pressure drop and increased efficiency while the heat input did not increase much. As mentioned earlier the model had instability in simulating models with annular condenser height more than 50% of sidewalls height for regular converter temperature conditions (300-800 °C). This instability raised a question regarding change in the emissivity of stainless steel with respect to temperature. It was found that stainless steel emissivity strongly depends on temperature. The calibration of the model with respect to this is described in the NEW MODEL CALIBRATIONS subsection.

Simulation of Potassium as a Working Fluid

To create a model for potassium as the working fluid was proposed right after the annular condenser model was developed and analyzed. Thus, the Design 6 model with annular condenser simulation was used as a basis for the simulation AMTEC converter model with potassium as the working fluid instead of sodium that is usually used. It was evaluated that the geometric model did not need to be changed at all; only thermal and optical properties had to be changed for the surfaces that simulated sodium in the previous model. The subroutines did not have many changes, since most of parameters related to sodium properties were kept as constants. More time was spent to evaluate necessary thermal-electrical properties for potassium with respect to temperature. The main difficulty faced was lack of literature on potassium, because potassium has not been as widely investigated as sodium with respect to AMTEC technology. Sometimes it was hard to find the same properties for potassium as for sodium. The model required all these properties, since it used them for numerical simulation. Hence, necessary thermal-electrical properties for potassium with maximum available accuracy were obtained and put in the system [10]. The model was then ready for use.

To evaluate the performance of the model, the prediction of power, voltage, heat required, efficiency, and pressure drop, as a function of current was needed. Hence, the following scenarios were run to evaluate model performance with differing heights of the annular condenser for current ranging from 10 to 120 Amps and keeping condenser and thermal couple temperatures at 300 and 750 °C respectively. These are the same scenarios that were described in the previous subsection with only one difference that these were made for the new model with potassium as a working fluid. These scenarios are provided in Table 3. The comparison of results for sodium and potassium models, namely the voltage, power, heat required, efficiency and pressure drop analyses are provided in Figure 29, Figure 30, Figure 31, Figure 32, and Figure 33 respectively.

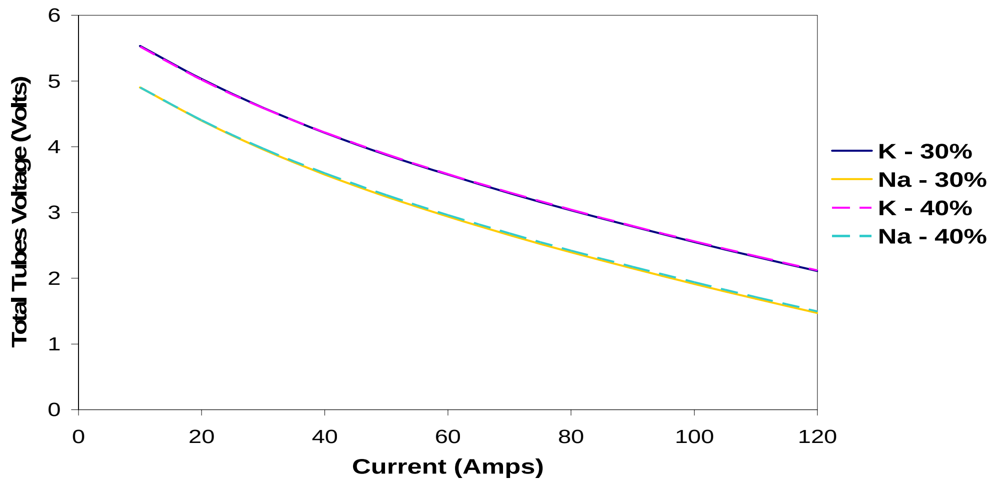

Figure 29. Design 6, voltage output comparing for sodium and potassium models

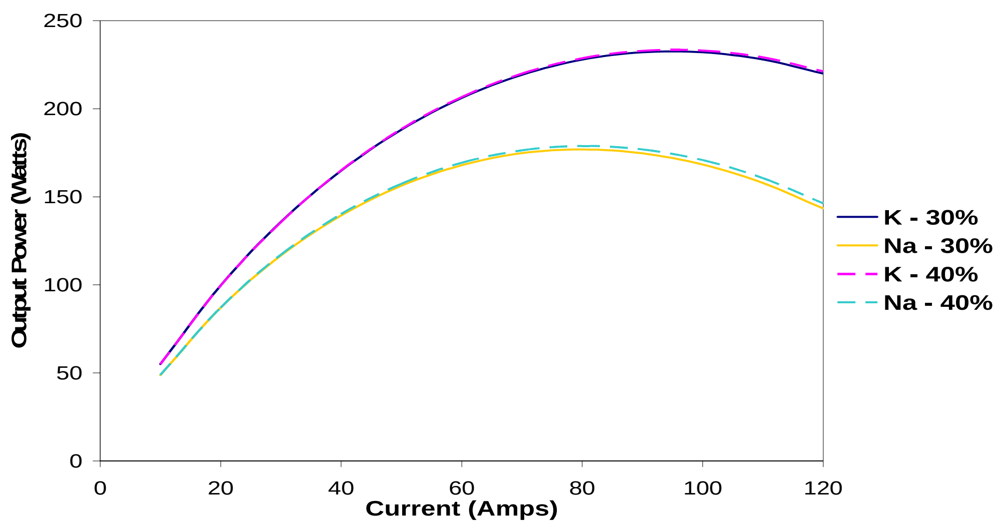

Figure 30. Design 6, power output comparing for sodium and potassium models

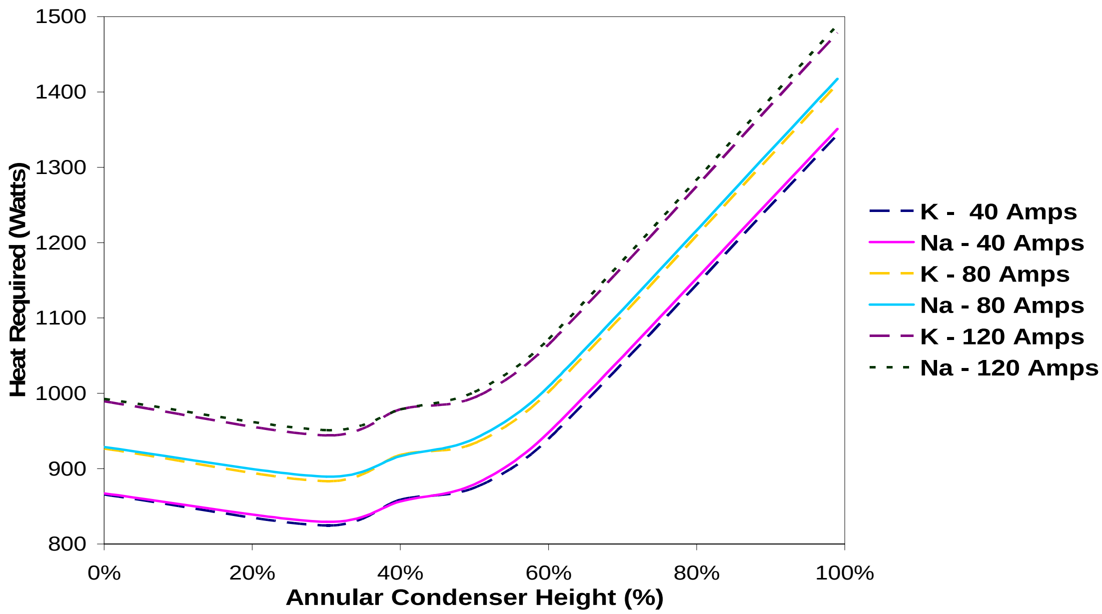

Figure 31. Design 6, heat required output comparing for sodium and potassium models

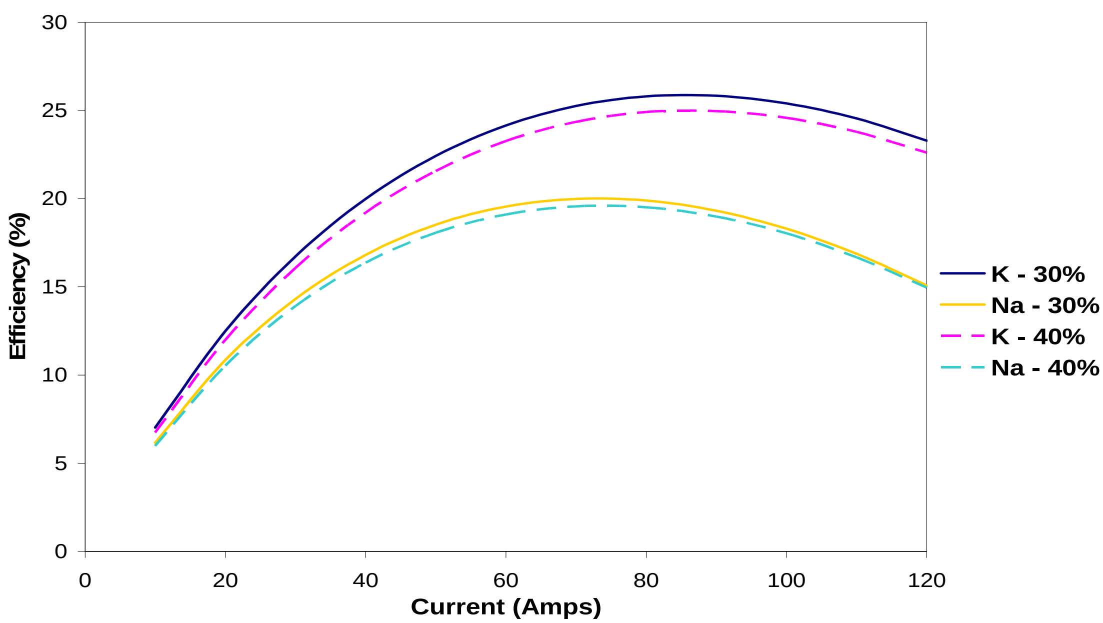

Figure 32. Design 6, efficiency output comparing for sodium and potassium models

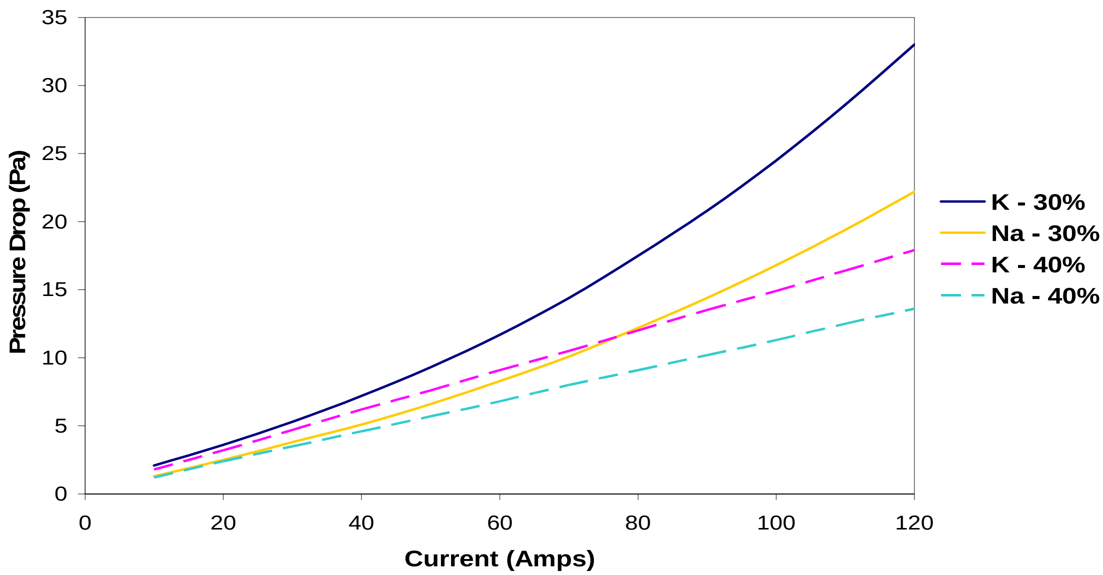

Figure 33. Design 6, pressure drop output comparing for sodium and potassium models

Comparing the results of sodium and potassium simulations did not disprove the existing knowledge about potassium's utility in AMTEC technology. It is well known that a potassium AMTEC converter usually operates at a lower hot side temperature than a comparable sodium converter, and can perform at the same efficiency as the sodium converter, with the hot side temperature maintained at least 50 °C lower than the sodium converter. The evaluated result showed significantly higher voltage, power and efficiency for the potassium model for any height of the annular condenser with relatively the same heat input in the system in all cases. Increasing of these important system characteristics proves the superiority of potassium when compared with sodium in AMTEC technology. The most important advantage being potassium converters could operate with lower hot side temperature, implying lesser power input required by the system. The pressure drop, which appeared to be the only disadvantage in the potassium model based on the model performance, was less important since converter power and efficiency characteristics were significantly increased. It also could be solved by reducing of the shielding between beta tubes assembly and condenser. However, it was not done because it can decrease the converter power production and efficiency that were more important at that time. Thus, to conclude it can be said that potassium has not been as widely used as sodium, and AMPS has not performed any actual converter performance tests with potassium as a working fluid. However, other groups evaluated the technology of K-BASE tubes several years ago, and their results on converter performance prove the excellent adaptability of potassium to AMTEC. It is a matter of time before potassium would be used instead of sodium in AMTEC technology. The performed research supports this stand.

NEW MODEL CALIBRATIONS

In order to comply with the objective of this work, the new design model should predict converter performance within 10%. To comply with this restriction, the model was calibrated by comparing results obtained from the model performance with the results obtained from recently built and tested new design AMTEC, Road Runner II (RR II), converter by Advanced Modular Power Systems (AMPS). The performance predictions obtained from the model for converter were compared to the experimental results obtained by AMPS for a wide range of temperatures and operating currents. Critical design parameters, such as stainless steel emissivity and converter resistances, were adjusted until performance predictions were within 10% of experimental results. The details concerning the calibration of the model are divided into three subsections within this section. The first subsection, Adjustment of the Stainless Steel Emissivity, briefly describes a correlation determined between the emissivity of stainless steel and its temperature. The second subsection, Adjustment of Resistance in the Model, briefly describes an evaluation of resistance corrections for the new design model and results of model performance after the corrections applied. Lastly, the third subsection, Calibration with Road Runner II, describes the RR II converter and provides results of the model calibration with results obtained from RR II testes.

Adjustment of the Stainless Steel Emissivity

The annular condenser analysis performed showed instability in evaluated results with annular condenser height more than 50% of the sidewalls height for regular converter temperature conditions (300-800 °C). The required heat input in the system was also higher than expected, starting from annular condenser height at 40% of the sidewalls. This instability raised the issue of change in the emissivity of stainless steel with respect to temperature. It was found that thermal emissivity, especially stainless steel emissivity, had to be changed corresponding to the change in temperature of the materials in the system. Unfortunately, Thermal Desktop does not have ability to change thermal emissivity of a material as a function of temperature; it was decided to split different materials into groups with approximately same temperatures during the model performance simulations. Stainless steel was split into condenser (300-350 °C), heat load (around 1000 °C), and regular stainless steel (600-800 °C). New emissivities were calculated and assigned for each group. The new model prediction performances were made in order to see that difference between previous results and results obtained after corrections. The Figure 34, Figure 35, Figure 36, and Figure 37 show results of analyses of power, heat required, pressure drop, and efficiency respectively before and after the model emissivity correction. The corrected model not only gave much better results, but also demonstrated excellent stability for any hot side and condenser temperature condition requirements. The model also performed well for varying heights of annular condenser with excellent stability and the system became more efficient and responsive.

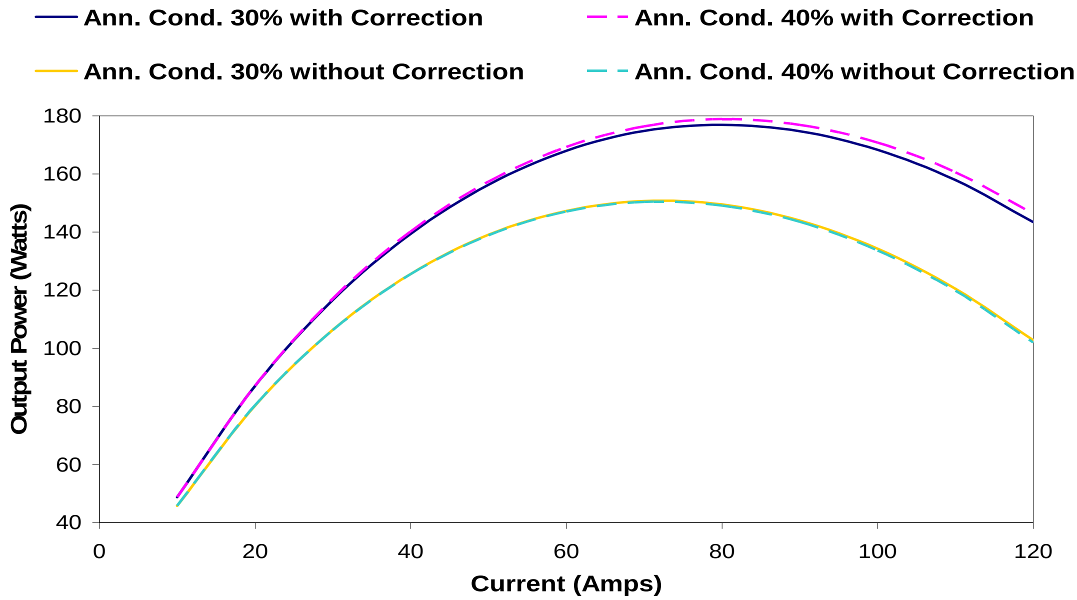

Figure 34. Design 6, power analysis before and after the stainless steel emissivity correlation

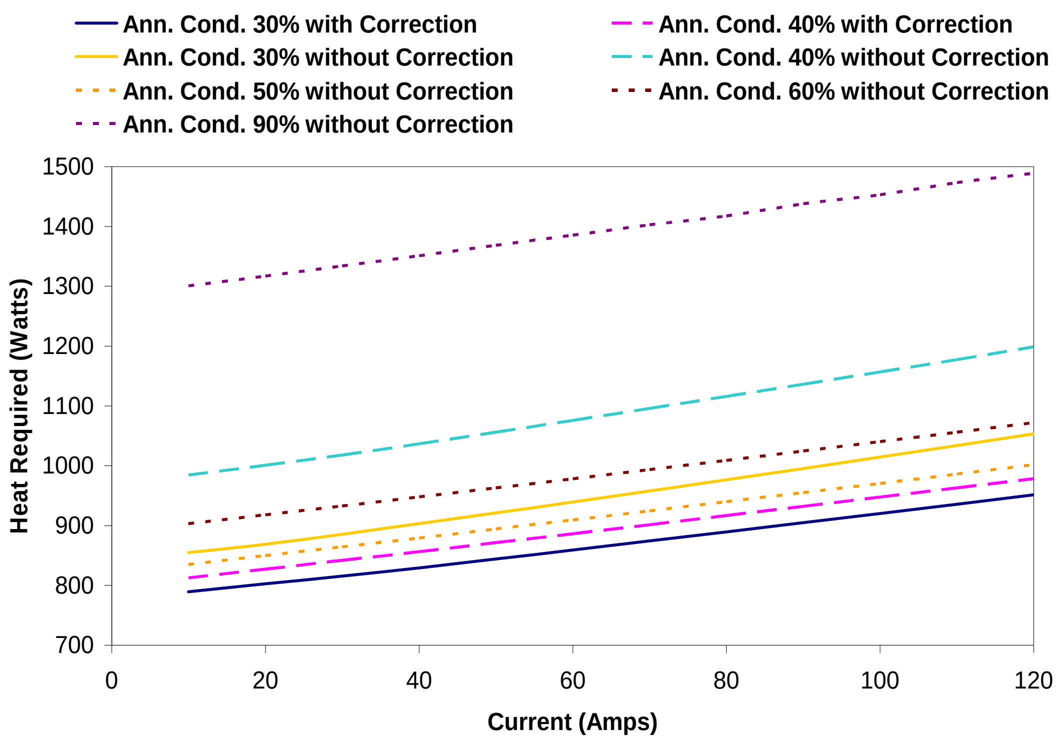

Figure 35. Design 6, heat required analysis before and after the SS emissivity correlation

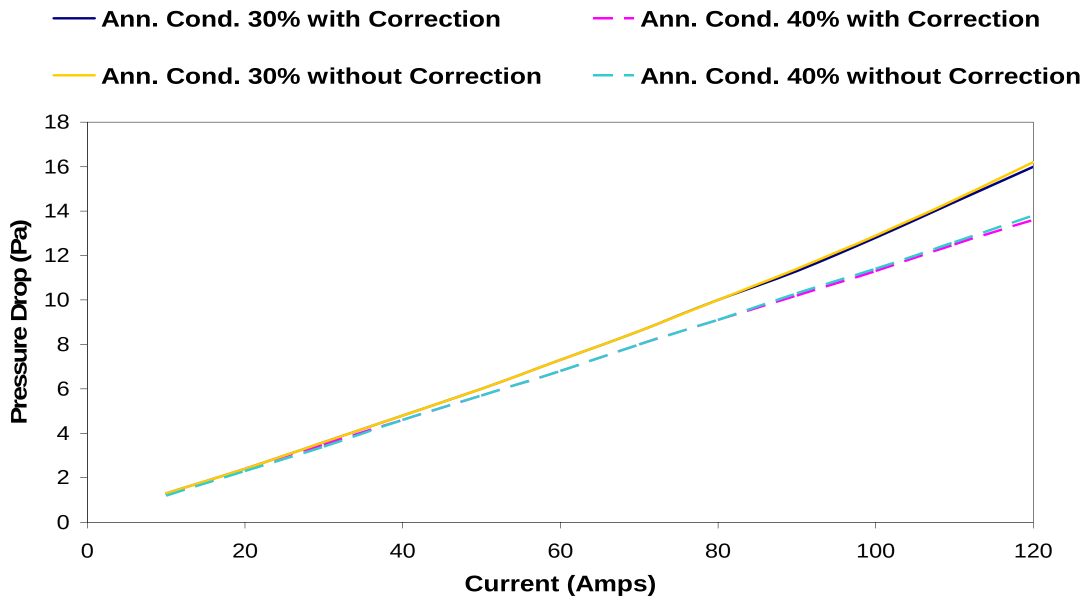

Figure 36. Design 6, pressure drop analysis before and after the SS emissivity correlation

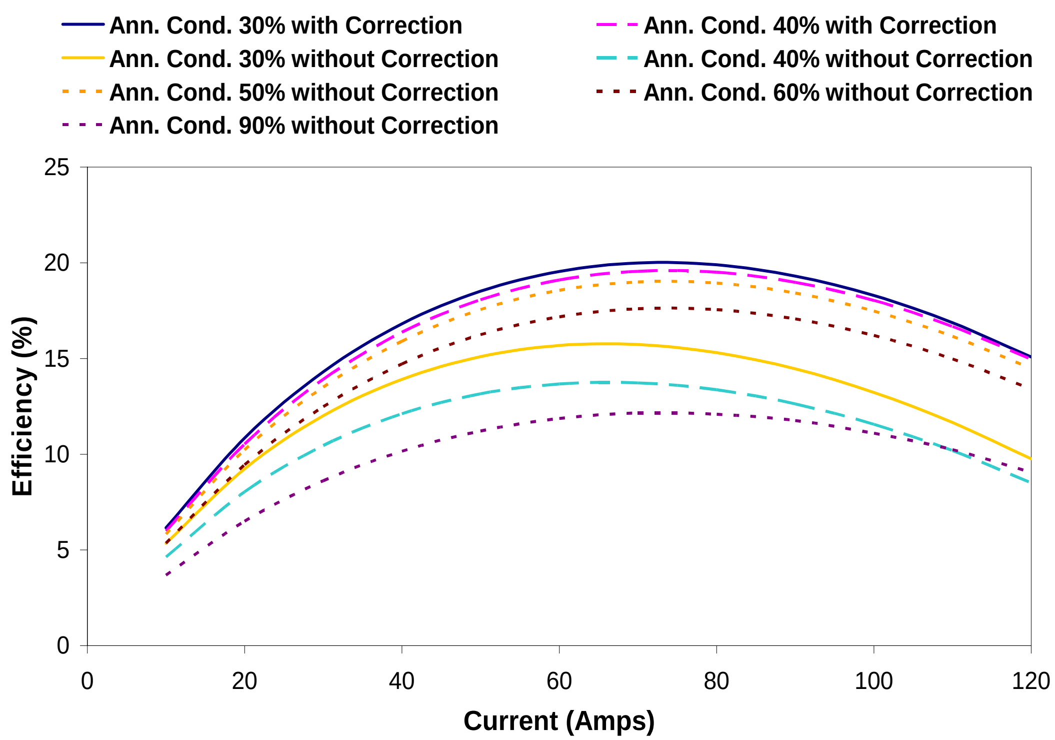

Figure 37. Design 6, efficiency analysis before and after the SS emissivity correlation

The evaluated results showed significant converter efficiency reduction and heat input increase with increasing annular condenser height when the converter output power and voltage stayed in the same range. Based on the efficiency and required heat input analyses it was founded that a converter with annular condenser height of 30% of the converter sidewalls provided the best combination of power production and efficiency characteristics. The condenser height of 30% of the converter sidewalls was suggested as an optimal converter design improvement.

Adjustment of Resistance in the Model

When the actual Road Runner II AMTEC converter was manufactured, it was found that the actual converter had some additional resistances that were not included in the converter model. A list of these additional resistances, which were not included in the initial model, is included in Table 6 with their descriptions. It was also mentioned that this correction in resistances is not certain and could have slight variation [11]. The R_{bt} was calculated in the code during simulation and was in agreement with the given value. Thus, the additional resistance was included in the model immediately and new results were obtained. Figure 38 shows how the corrections affected the output power curve when they were added one by one. The following calibration with actual results is described in the next subsection.

Table 6. Assumed resistance correction for the model

Symbol	Value	Description
R_a	0.0015 Ohms	Total anode resistance from poor cage welds
R_{gb}	0.0055 Ohms	Total increased resistances from not grid blasting the BASE tubes
R_{bt}	0.001 Ohms	Increasing in resistance due to BASE tube temperature difference

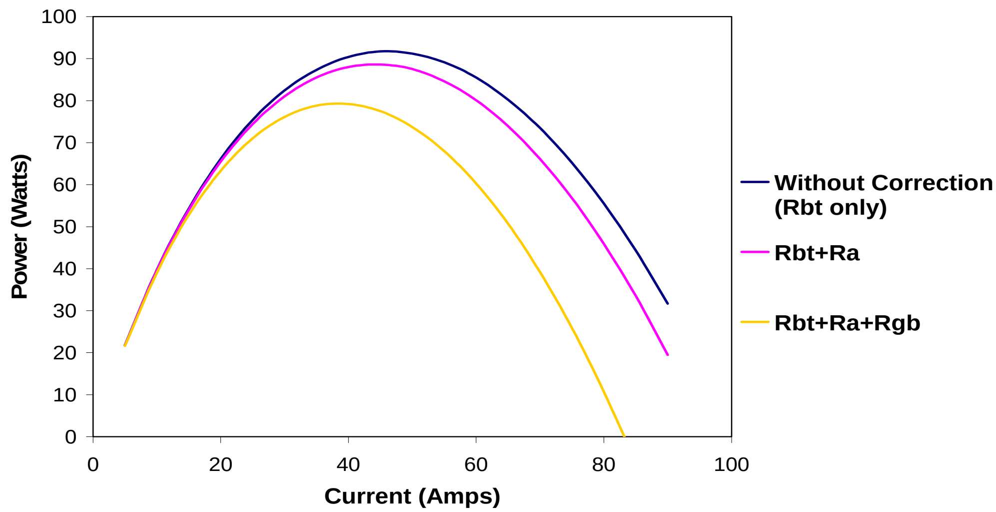

Figure 38. Design 6, power analysis during model resistances correlations

Calibration with Road Runner II

The results of actual AMTEC converter performance were available right after AMPS obtained experimental results from the RR II AMTEC converter. These results consist of parameters such as current, voltage and output power. There were more than two hundred different results that gave a very good data set. The only difference in design between the RR II and designed model was that the RR II model had two dummy tubes. All beta tubes were assembled in the same way as modeled in the design, and dummy tubes separated one beta tube from the other three. The dummy tubes were used in the system to maintain heat balance and were filled with liquid sodium. The lack of time and funds were reasons why AMPS manufactured that model instead of two with three and six tubes respectively. The evaluated results showed output voltage and power from the three tubes and one tube depended on the current. Most of the results were obtained for hot side temperatures between 720 and 730 °C, and 350 °C condenser temperature [11]. Based on the actual performance data, curves for voltage and power versus operating current were obtained. Model run with the same thermal conditions were performed. The results of these runs were correlated to estimate three tube performance instead of six. Based on the studies done before, the voltage and power are directly proportional to the number of tubes with 95% confidence levels. The Figure 39 and Figure 40 illustrate voltage and power calibrations for RR II actual results and the model prediction results. The errors, which appeared during voltage and power calibrations, are shown in Figure 41. It proved that the new model could be used as an efficient design tool with 10% accuracy. Finally, the last objective of the research was achieved.

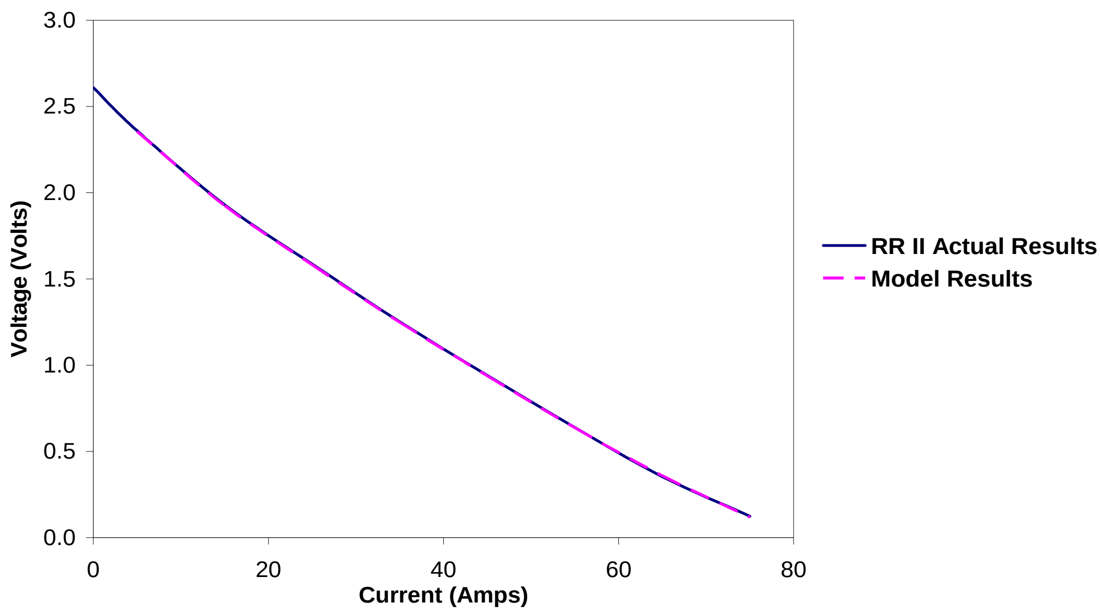

Figure 39. RR II voltage analysis calibrations results

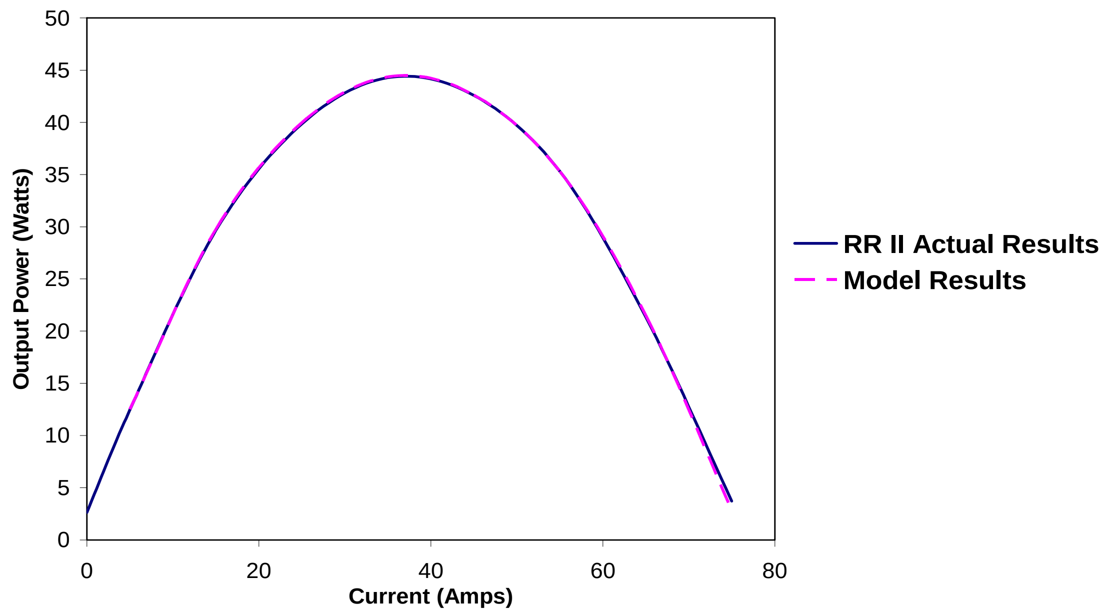

Figure 40. RR II power analysis calibrations results

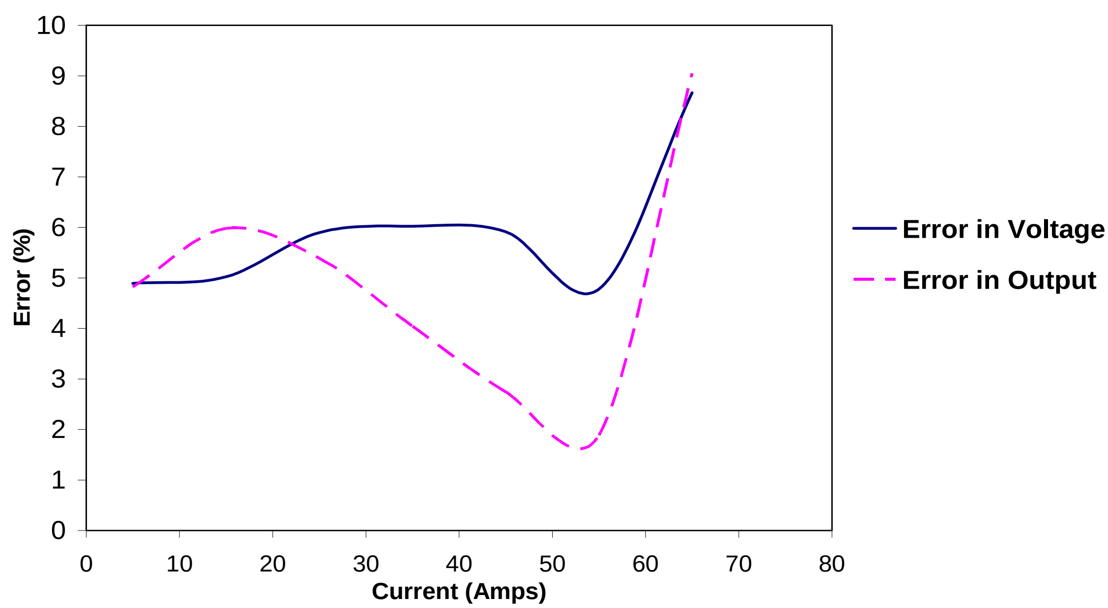

Figure 41. Prediction deviation from the experimental data

SUMMARY OF FINDINGS

Design 4 showed instability in the design of the converter. Performed studies highlighted the lack of the shielding, which was required to decrease heat loss from the system. The assembly of the beta tubes facing down did not improve the converter performance in that design. It was established that the topside of the converter, which was not connected to the heat load cylinder and was separated from heated area by shielding, caused excessive heat leakage from the system.

Design 5 significantly improved stability of the system and predicted model performance very well. Basic performance analysis was performed and satisfactory results were obtained.

Finally, Design 6 retained the stability of the system. Study of heat loads ratios were performed and the 50:50 ratio between two heat loads in the system was found to be the most efficient. The model was completed and is ready for further research.

Annular Condenser studies were performed on the Design 6 model. Based on this model, results were obtained which showed that increasing annular condenser led to significant decrease in pressure drop, which cause heat leakage from the system. However, the system required more energy input in order to maintain required thermal conditions. The efficiency of the system reduces with increasing annular condenser height. It was found that annular condenser with height of 30% of the converter sidewalls was optimal for the system.

During the annular condenser studies, it was also determined that the system became unstable when annular condenser height was above 50% of the converter sidewalls. It raised a question about thermal emissivity in the system, which was used as a constant. It was evaluated that thermal emissivity, especially stainless steel emissivity, had to be changed in correspondingly with change in temperature of the materials in the system. Since Thermal

Desktop does not have ability to change thermal emissivity of material as a function of temperature, it was decided to split different materials into groups with approximately same temperatures during the model performance simulations. Stainless steel was split into condenser, heat load, and regular stainless steel. New emissivities were calculated and assigned for each group. The obtained results confirmed this correlation. The model performed well for any height of annular condenser with excellent stability and the system became more efficient and responsive.

When the actual Road Runner II AMTEC converter was manufactured, it was found that there was additional resistance in the system, which was not included in the model. Thus, the additional resistance was included in the model and new prediction results were obtained.

Experimental data obtained from RR II AMTEC converters was used to calibrate the Sinda/Fluint model. Despite the unavoidable uncertainty of several critical parameters determined by previous converter models, the Sinda/Fluint model predictions agreed with actual performance data within 6% for all temperature and current ranges for the RR II model after calibration. Deviation from the experimental results decreased in operating ranges typically considered more relevant for an AMTEC converter (300-800 °C, 50-80 Amps).

Studies of the model performance with potassium as a working fluid instead sodium were initiated. The model was changed in order to simulate potassium instead of sodium. The achieved results showed better performance of potassium in AMTEC as compared to sodium; however, pressure drop was significantly higher. There was also a dearth of information on thermal and electrical properties of potassium when compared with the amount of literature available for sodium. The obtained results were pertinent and useful for future research of potassium as a working fluid in AMTEC.

Carrying out parametric analyses like those presented in the APPLICATION OF THE MODEL AS A DESIGN TOOL and NEW MODEL CALIBRATIONS sections provided crucial information when evaluating design tradeoffs. When the needs of a particular industry have been prioritized, the results of these studies, and other studies like them, can serve as an excellent tool for making design changes and implementations.

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

Based on the model's capabilities, it was determined the model serves as an excellent design tool for AMTEC converters.

The performance of the annular condenser raised a question about stainless steel emissivity, and its dependence on the temperature of the material. It was concluded that the model does not have this flexibility. However, necessary changes were made and better results were obtained.

When the emissivities were correlated, and annular condenser performance simulations were redone, it was evaluated that the annular condenser height in the range of 30-40% of converter sidewalls significantly reduced the pressure drop without sacrificing the converter power production and efficiency.

Some of uncertainty and inconsistency still exists in several key AMTEC design parameters, such as materials' emissivity and pressure drop numerical simulation. Hence, it is doubtful that *any* AMTEC model will *consistently* predict the performance of *any given converter* within 10% for all operating conditions.

The methodology used to develop the model proved to be a more stable method resulting in increased application flexibility in comparison to some previous and similar converter models.

The information obtained from parametric design studies significantly simplifies design decisions that are required during the AMTEC converter design process.

The prediction of model performance with potassium as a working fluid instead sodium was performed. The evaluated results showed that the potassium has a big potential to improve AMTEC converter technology, and the model could be used for this analysis after careful studies and correction of the model.

Recommendations

1. There was a lack of time for more careful research of the Design 4 model, however the design with beta tube facing down assembly could be efficient subject to changes in design that would provide more stability to the model. The newly created model could then be used as a basis for the future research of particular model design.
2. To insure the model is an equally effective design tool for multiple tube converters with annular condenser, the model should be compared with experimental results from the RR II when annular condenser applied when available.
3. The correlations of emissivity with respect to temperature of material was performed only for the, critical at that time, stainless steel, however, it would more likely that other materials emissivity have this kind of strong correlation with their temperature. It would decrease errors in prediction if such correlation were provided for other materials in the model.
4. Also, to insure the model is an equally effective design tool for multiple tube converters with Potassium as a working fluid, the model should be compared with experimental results from the similar converter designs when available.
5. The model was used for a few basic transient analysis scenarios, but the results were not presented in this paper. Although the results were similar in comparison to those derived from experiments performed by AMPS, key parameters such as convection coefficients or the parameters needed to calculate the key parameters were not measured. Therefore, comparison of the model’s predictions with the experimental results would be inconclusive. It is recommended that further studies be performed to determine the effectiveness of the transient abilities of Sinda/Fluint.

6. Reducing computer analysis time would result in increased modeling flexibility, and therefore an increase in the effectiveness of the model as a design tool. The development of strategies to reduce the analysis time, without sacrificing accuracy, is recommended. Optimization of the computer processes can be a key-method, which was successfully used before and could be used in future.

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VITA

Ilia V. Pavlenko was born in October of 1977 in Obninsk, Russia. He resided in Obninsk for most of his life and attended Obninsk State Polytechnic University of Nuclear Power Engineering. It is from here that he received the degree of Master of Science in applied mathematics in February 2000. In January 2001 he moved to College Station, Texas to attend Texas A&M University. It is from here that he received the degree of Master of Science in health physics in December 2003.

He was involved in several IT projects when he was in Russia. As a member of the IT department at Central Experimental-Methodical Expedition of Geophysical Survey of Russian Academy of Sciences, he developed and tested a monitoring system for a complex Oracle database, which collects seismological data from monitoring stations on Eurasian Plateau. Then, as a leader of the IT department, he implemented databases and web applications for storage and analysis of polymer research data in “Technologiya”, the State Research Center of Russian Federation. He also took a part in design and thermal analysis tests of STARNAV-I system flown on shuttle Columbia STS-107 space. Currently, he works as a Research Assistant with the Center for Space Power (CSP) at Texas A&M University in College Station, Texas where he has been actively involved with developing computer simulation of multiple tube AMTEC converter model for thermal analysis since May 2001.

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