In-Space Radiator Shape Optimization using Genetic Algorithms

Patrick V. Hull[1], Ken Kittredge[2], Michael Tinker[1], and Michael SanSoucie[1]

[1]Systems Analysis and Integration, NASA Marshall Space Flight Center, AL 35812, USA
[2]Structural Design and Analysis Division, NASA Marshall Space Flight Center, AL 35812, USA

Abstract.

Future space exploration missions will require the development of more advanced in-space radiators. These radiators should be highly efficient and lightweight, deployable heat rejection systems. Typical radiators for in-space heat mitigation commonly comprise a substantial portion of the total vehicle mass. A small mass savings of even 5-10% can greatly improve vehicle performance. The objective of this paper is to present the development of detailed tools for the analysis and design of in-space radiators using evolutionary computation techniques. The optimality criterion is defined as a two-dimensional radiator with a shape demonstrating the smallest mass for the greatest overall heat transfer, thus the end result is a set of highly functional radiator designs. This cross-disciplinary work combines topology optimization and thermal analysis design by means of a genetic algorithm. The proposed design tool consists of the following steps; design parameterization based on the exterior boundary of the radiator, objective function definition (mass minimization and heat loss maximization), objective function evaluation via finite element analysis (thermal radiation analysis) and optimization based on evolutionary algorithms. The radiator design problem is defined as follows: the input force is a driving temperature and the output reaction is heat loss. Appropriate modeling of the space environment is added to capture its effect on the radiator. The design parameters chosen for this radiator shape optimization problem fall into two classes, variable height along the width of the radiator and a spline curve defining the material boundary of the radiator. The implementation of multiple design parameter schemes allows the user to have more confidence in the radiator optimization tool upon demonstration of convergence between the two design parameter schemes. This tool easily allows the user to manipulate the driving temperature regions thus permitting detailed design of in-space radiators for unique situations. Preliminary results indicate an optimized shape following that of the temperature distribution regions in the "cooler" portions of the radiator. The results closely follow the expected radiator shape.

Keywords: optimization, radiator, genetic algorithms, heat rejection

PACS:

INTRODUCTION

Future space, lunar and Mars missions will require highly efficient, lightweight, deployable heat rejection systems. Typical radiators comprise a sizeable percentage of the vehicle total mass, thus any efficiency improvement of a radiator design could greatly increase vehicle performance gains. Considerable research efforts must be dedicated to improving space heat rejection systems by reducing mass. This presented work intends to address the need for an advanced radiator development and design method. Offered here is a biologically inspired analysis tool for designing geometrically optimal in-space radiator designs. Benefits of this tool include minimizing excess material and creating more optimal designs. The technique to be explored and developed as a part of this presented work is directly applicable to highly efficient heat rejection systems.

The total heat rejected for manned space missions is commonly measured in megawatts; therefore radiators of immense mass are routinely sized to dissipate the high heat loads. This is especially familiar for a low-level heat rejection cycle, such as the Brayton cycle (typically, 400-485K). For liquid metal Rankine and thermoelectric conversion cycles, the heat rejection temperatures are typically in the 850-1000K range. The above mentioned heat rejection cycles operate at temperature ranges much higher that what has traditionally been experienced by NASA missions, but these heat cycles will be used for future missions. Reduced mass radiator designs are an essential part of future space exploration.

Nuclear Propulsion and Surface Power Applications

Although many types of space and lunar/planetary surface systems can benefit from improved heat rejection technologies, nuclear fission spacecraft and surface power systems will be discussed in more detail as specific applications. As shown in Figure 1, a nuclear energy source (fission reactor) provides intense heat or thermal energy. In the case of nuclear electric propulsion (NEP) or lunar/planetary surface power systems, this thermal energy must be converted to electrical power. For surface bases, the electricity would be used to power habitation and laboratory modules, scientific equipment, in-situ resource utilization (ISRU) plants, surface rovers, and other equipment. In the case of a NEP vehicle, the electrical power is required to drive thrusters for propulsion (Fig. 1). Nuclear thermal propulsion (NTP) vehicles would utilize thermal energy from the reactor directly to heat propellant to very high temperatures for expansion through a nozzle and for thrust generation. Unfortunately, the power conversion systems used in these space nuclear power systems, are typically inefficient. Therefore, a large amount of waste heat is generated that must be removed from the system.

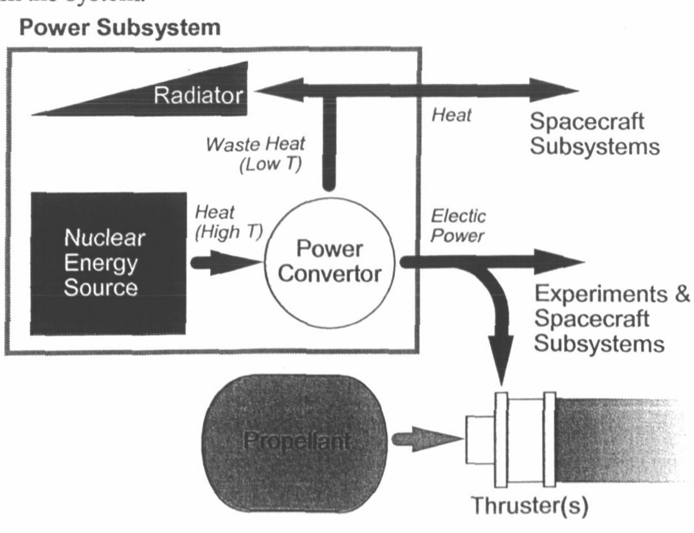


Figure 1: Role of radiators and heat rejection in nuclear space power systems (Patton, 2003).

The transfer of waste heat from the power conversion cycle to its ultimate rejection to space via thermal radiation involves a number of steps. Each step has inefficiencies associated with it that manifest as a decrease in the heat rejection temperature at the radiating surface. These steps are summarized below:

1) Heat transfer between the power generation system and a heat transport fluid, which is done by conduction to the fluid interface, and then convection to the fluid.
2) Transport of the working fluid to the radiator manifold.
3) Convection heat transfer from the working fluid to the radiator manifold, and then convection to the manifold walls.
4) Heat transfer from the manifold walls to the radiating surfaces.
5) Radiation heat transfer to space.

For a given amount of waste heat, the lower the rejection temperature, the larger the required radiating surface. For radiation heat transfer, the quantity of heat rejected is proportional to the fourth power of temperature; therefore, the area requirements increase rapidly as the temperature decreases. This paper presents the development of an analytical tool which predicts an optimal design that minimizes the inefficiencies associated with steps 4) and 5) above while simultaneously minimizing the radiator mass by making the most efficient use of the available radiator area.

Importance of Radiator Mass Reduction in Space Systems

Typical heat radiator masses for NEP space missions range from 30-50% of the total vehicle mass, not including payload and fuel. Therefore, heat rejection technology is a key driver in the high energy systems needed to fulfill the Exploration vision. Radiator technology in the U.S. to date has been essentially limited to the relatively low heat rejection needs of the International Space Station.

The problem with radiator design has always been that the area nearest the heat source is at the highest temperature and therefore radiates the most efficiently. The designer has had to make the tradeoff between radiator thickness and the area of the radiating surface, often using constraints that have nothing to do with the radiator performance. Previously, this may have resulted in small mass overages, but since the amount of heat rejection was typically small, the radiator was small. Therefore, the radiator mass was a minor percentage of the overall mass. With the nuclear electric propulsion now strongly considered for long duration space missions, the heat rejection requirements have increased a thousand fold and the radiator mass is now a significant portion of the overall mass. The designer can no longer afford to SWAG radiator layouts but needs to optimize the design to minimize mass.

Heat rejection radiators have a striking impact on the total system mass for space vehicles, for example Jupiter Icy Moons Orbiter (JIMO) studies. Demonstrated in Figure 2 is the mass distribution for the JIMO study. It reveals that the heat rejection system comprises a significant portion of the total vehicle mass and is one of the most massive components for the higher power vehicles. It is vital that a mass reduction in radiator design accompany new vehicle configurations.

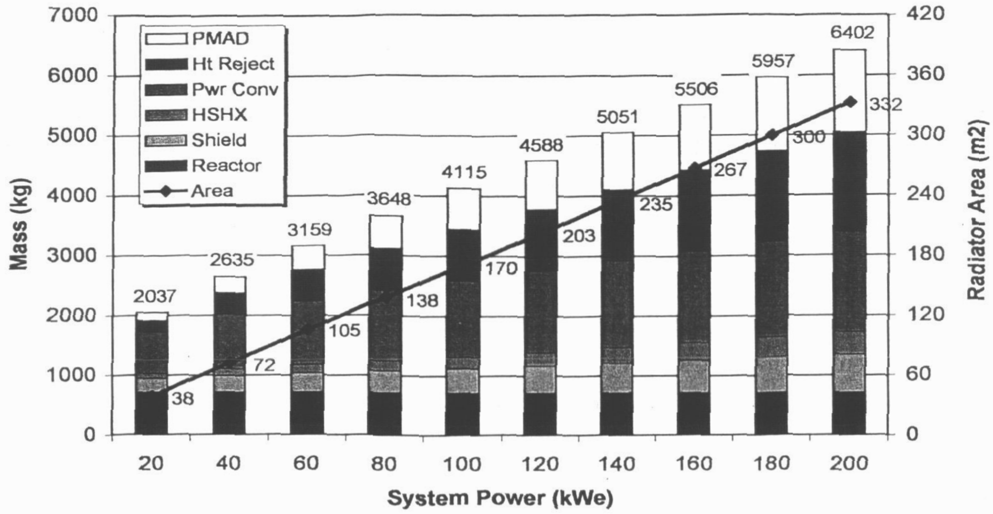


Figure 2: Impact of heat rejection system (radiator) mass on total vehicle mass, for early JIMO study (Mason, 2004).

Presented here are two examples of heat rejection radiators, a variable deployable area radiator and a rotating belt radiator. Research and development has been performed on moving belt radiators (Teagan, 1994); however, it has never been flown.

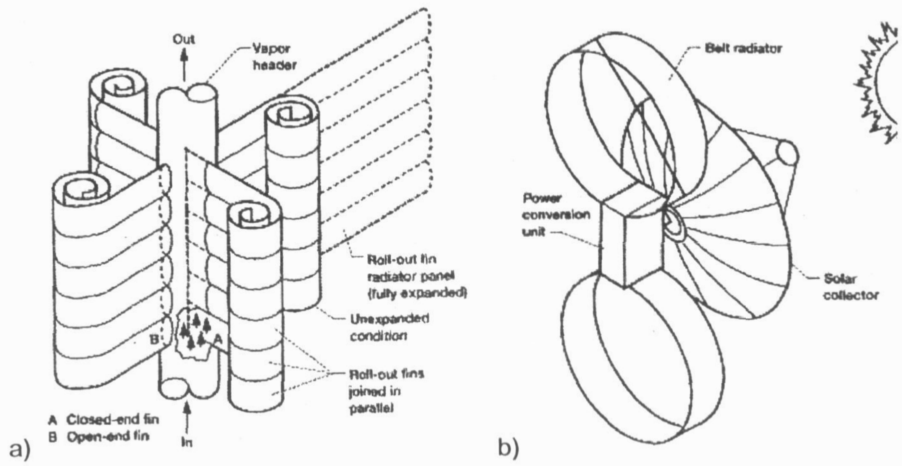


Figure 3: Advanced radiator concepts: a) roll-out panel and b) rotating belt (Juhasz, 1994)

Presented in this paper is a novel method to reduce overall radiator mass.

Paper Objective

There is a recognized need for highly efficient heat rejection radiators for space applications. The objective of the presented work is to develop and apply genetic algorithm shape optimization coupled with radiation heat loss thermal analysis for in-space radiator designs. There are two methods to approach the radiator mass reduction problem, either reduce the radiator material density (development of lightweight, high temperature materials) or provide a possible reduction of the total volume of the radiator (innovative ways to increase the surface area, A, with mass penalty). This paper will focus on reducing the overall radiator volume in 2-dimensions while maintaining a constant density throughout the material. A design tool is presented here that is capable of designing minimal mass space radiators for a variety of heat loads. Two different methods are used in this optimization technique, variable thickness and spline curve boundary. A simple example problem using both mentioned methods is presented to clearly demonstrate the author's optimal radiator design tool development.

BACKGROUND

Typical radiators include pumped loop, heat pipe, and photovoltaic. An example of the radiators used on the Space Shuttle is shown in Fig. 4. This system includes over 250 small, parallel tubes embedded within a honeycomb structure with warm, single-phase Freon circulated through the tubes. Unfortunately, this system is heavy, and any MMOD penetrations would cause a failure of the entire heat rejection system.

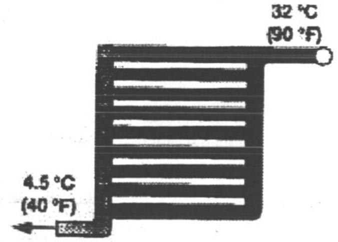


Figure 4: Space Shuttle radiator (Juhasz, 1994).

One application that has been receiving much attention lately is the JIMO mission. This project is studying the potential of using nuclear electric propulsion to deliver scientific payloads to Callisto, Ganymede, and Europa. The propulsion system will consist of a 100 kW_e reactor power system and ion thrusters. The most likely power conversion system for the JIMO mission is a closed cycle Brayton system, because it has a high efficiency and is suitable for the required power level (Mason, 2004). The proposed heat rejection system for the power conversion consists of heat pipes with carbon-carbon facesheets (Siamidis, 2005) and is shown in Fig. 5. The heat rejection system dominates the vehicle layout, because of the large amount of surface area required by the radiator panels (Mason, 2004).

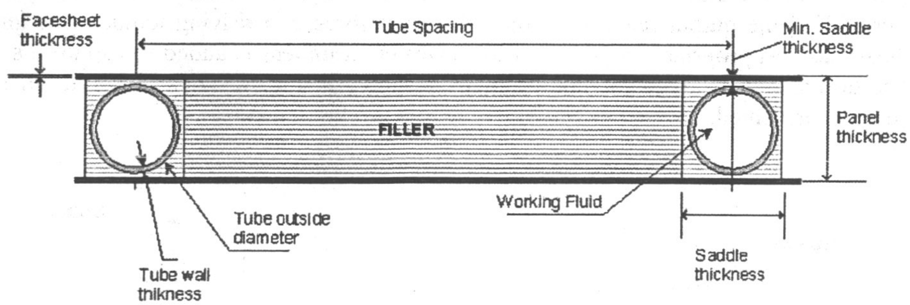


Figure 5: JIMO radiator panel cross-section (Siamidis, 2005).

Clear benefits of lightweight, high-temperature heat radiators have been described in terms of the nation's Space Exploration Vision. Future space vehicles, surface power bases, and space platforms can be made more mass and volume efficient through development of the technologies described in this paper. Figure 2 clearly shows that radiator mass can be a large fraction of the total vehicle mass. Therefore, reductions in radiator mass of even a few percent can yield substantial improvements in overall system mass.

DESIGN TOOL DEVELOPMENT

A design tool has been developed to genetically design an optimal in-space radiator. The optimality criterion is defined as a 2-dimensional radiator with a shape demonstrating the smallest mass for the greatest overall heat rejection. The evolutionary computing design approach primarily depends on the fitness function to be minimized and from which every design is measured. A diagram of the general form of the current procedure used for the evolutionary design of radiators is shown in Fig. 6. The proposed process consists of the following steps; design parameterization based on the exterior boundary of the radiator, objective function definition, objective function evaluation via finite element analysis, and optimization based on evolutionary algorithms.

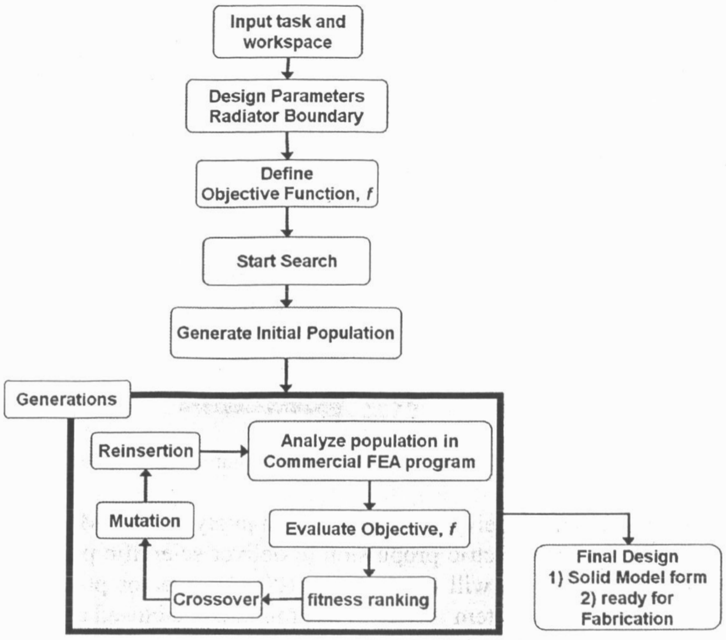


Figure 6: Current approach for shape optimization of in-space radiators.

Following the usual shape optimization approach used in structural optimization, a general continuum representing the maximum allowable material for the desired in-space radiator is acted on by an input force in order to provide some output reaction. Here, the input force is a driving temperature and the output reaction is heat loss. Appropriate modeling of the space environment is added to capture its effect on the radiator. The design region given for this problem is shown in Fig. 7. Next a definition of the design parameters used is presented.

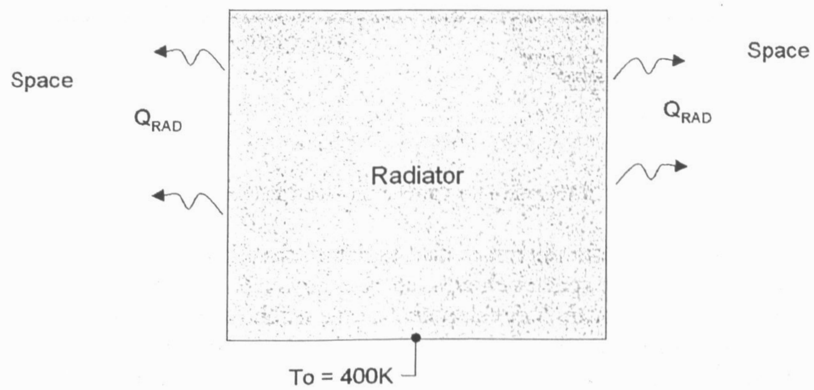


Figure 7: Design domain and problem parameters.

Design Parameters

The design parameters chosen for this radiator shape optimization problem fall into two classes, variable thicknesses along the width of the radiator and a spline curve defining the upper material boundary of the radiator. Each design parameterization method has merit and will both be demonstrated using a common example.

The sample problems simulate a homogeneous 2-dimensional radiator interfacing with the condensing side of a two-phase cooling loop. One edge is exposed to a constant temperature and both sides are radiating to a 0K heat sink. The length on the constant temperature edge is fixed and the thickness and profile are allowed to vary within predefined constraints. Optimal solutions are derived that maximize the heat rejection per unit mass.

Height Parameterization

The variable height parameterization for this shape optimization problem changes the vertical dimensions at equal positions throughout the width of the radiator. This parameterization is readily adaptable to differing design regions and an increased number of design parameters (more divisions). As shown below in Fig. 8, this design method can lead to jagged shapes for the radiator. A simple solution is to increase the number of design parameters, thus permitting the optimal design to have a more recursive shape. However, the objective function is largely dependant on mass and a very thin spike can have little mass and, therefore, not affect the objective function and end up in the final design.

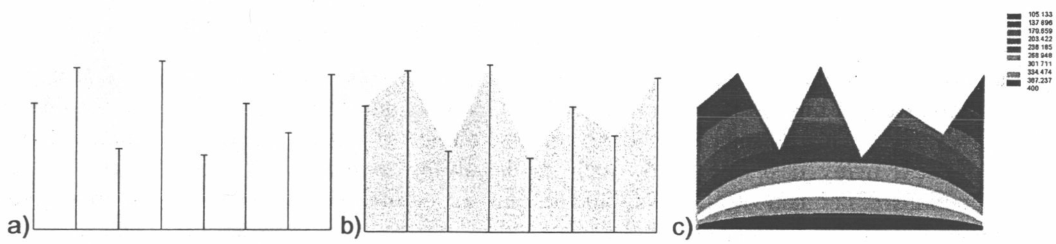


Figure 8: Randomly generated heights: a) Equally spaced variable height design parameters, b) Radiator shape based on variable heights, c) Thermal radiation analysis of radiator.

Spline Curve Parameterization

The design formulation defined by a spline curve is the second design parameter formulation used in this optimization. Initially left-side and right-side radiator heights are defined, and then the multipoint spline curve is created to bridge the gap between the boundary heights. The spline curve is defined through a series of heights created over the width of the design region. The varying heights and temperature distribution of the subsequent design are shown in figure 9.

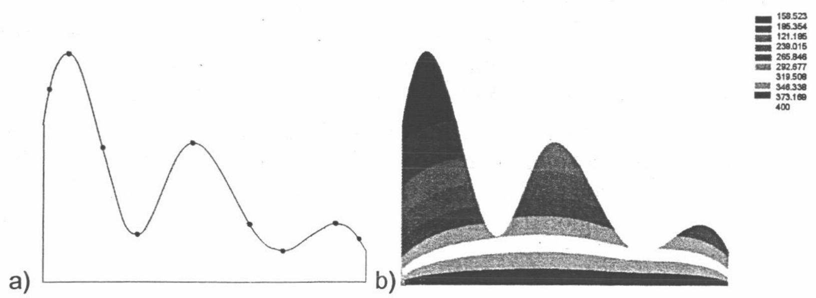


Figure 9: Randomly generated curve: a) Spline curve defining upper boundary b) Thermal radiation analysis of spline curve radiator.

Objective Function Definition

The fitness function for the proposed analytical radiator design tool is subsequently defined as,

$$fitness = \frac{m(kg)}{Q(W)}$$

where m is the total mass and Q is total heat loss for the radiator. Each design within the defined evolutionary precedent is ranked according to this fitness function.

Objective Function Evaluation

The objective function is evaluated as the solution to a radiation thermal analysis problem performed using commercial finite element analysis software (ANSYS 8.0). ANSYS is called as part of the optimization routine and is sent the blueprint information (either variable heights or spline curve) for a given design. The design is modeled and analyzed in solid form with designer selected material properties, heat loads and boundary conditions. Upon conclusion of the FEA thermal analysis, ANSYS returns precise solution data in the form of nodal temperatures and heat fluxes. Based on this information a fitness function is evaluated. This process of FEA analysis and fitness function evaluation, while short in overall time, is merely a single step in the global genetic algorithm optimization (as described in the following section), therefore the computational costs for this design method are high. However this high computation cost is easily remedied by performing parallel processing and using multiple seats of the FEA program.

Evolutionary Algorithms Optimization

Genetic algorithm optimization is a highly suitable method for the optimal design of heat rejection radiators. Algorithms of this nature are guided random searches, and therefore remove the requirement for gradient derivations. This permits a decidedly diverse choice of possible objective functions. Genetic algorithms possess many desirable traits, such as the ability to handle both convex and non-convex objective functions (Chapman et al, 1994) and finding an optimal family of solutions, thus giving the designer greater freedom to select the final design Also, genetic algorithms are proficient at performing multi-objective optimization (Parsons and Canfield, 2002). Genetic algorithms do have certain restrictions such as high computation time, convergence performance that is complicated to predict, and are non-deterministic in nature.

Instigating the genetic algorithm search is executed by defining each possible radiator design as a real valued blueprint of the geometric features. For example the height design parameterization blueprint consists of a series of heights that define the current design region for the radiator. The spline curve parameterization blueprint involves all the point locations defining the design region. Following the evolutionary pattern, the fittest design blueprints will be carried to future generations, and the weaker designs will be removed. Mutation of the design parameters follows to ensure diversity in the genetic population. The genetic algorithm cycle continues through the steps of breeding, mutation, and recombination of designs for the number of generations chosen by the user. Finally as mentioned previously the final design is presented as a group or family of *good* solutions rather than a single *optimal* solution. Due to the difficulty of guaranteeing that a global solution to the radiator mass problem has been found; the final decision to choose from the solution set rests with the designer.

In this work, a combination of large population, sufficient mutation rate and stochastically selected initial states were used to help guarantee a solution near the global optimum. If a more globally optimal solution is desired beyond that selected by the GA, a hybrid GA could be used. Dozier et al (1998) presents a GA to obtain a solution in the region of a global optimum, and then switches to a gradient-based technique to hill climb and find that optimum.

Example Problems

This section demonstrates the implementation of the presented design method for both the height and spline curve design parameterization methods. As part of the GA-based optimization routine, a population of solutions results at the end of the optimization process. The solution with the best objective function value from this final family is shown for each example.

The initial design region is defined in Fig. 10 as a 15m constant width and 15m variable height. The design parameters given for this problem are a) the variable thicknesses for the first example, and b) spline curve points for the second example. The radiator is at an initial uniform temperature of 0K, the bottom side is held fixed at 400K. The radiator is 0.005m thick and constructed of aluminum. The objective of this problem is to *minimize* the radiator mass and maximize the heat loss. The following two examples demonstrate possible solutions to this problem. The better solution is given in Fig. 11.

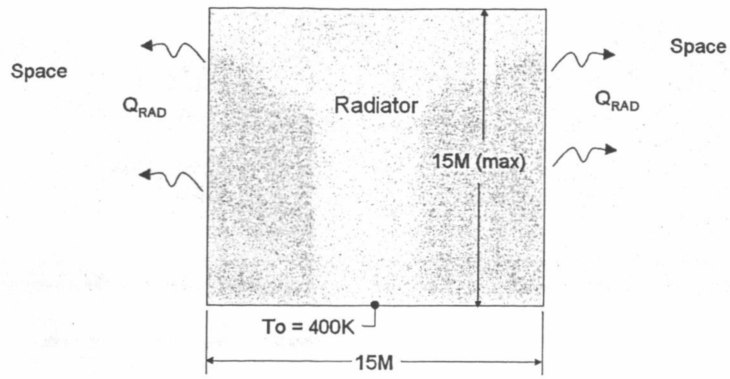


Figure 10: Design region for the height and spline curve parameterization example problems

Height Parameterization

Demonstrated in Fig. 11a is the FEA mesh for the design boundary given. Figure 11b displays the steady state temperature distribution for the variable height parameter radiator design. The overall heat loss for this plate using height parameterization is 7.88796e+05W and the mass is 4239.79kg. The objective formulation is given below:

$$fitness = \frac{m(kg)}{Q(W)} = \frac{4239.79\text{kg}}{7.88796\text{e}+05\text{W}} = 5.375e-03(\text{W/kg})$$

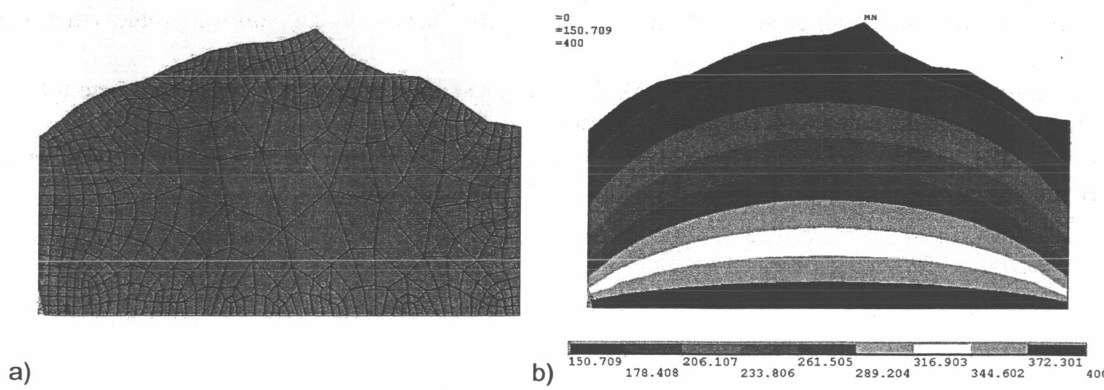
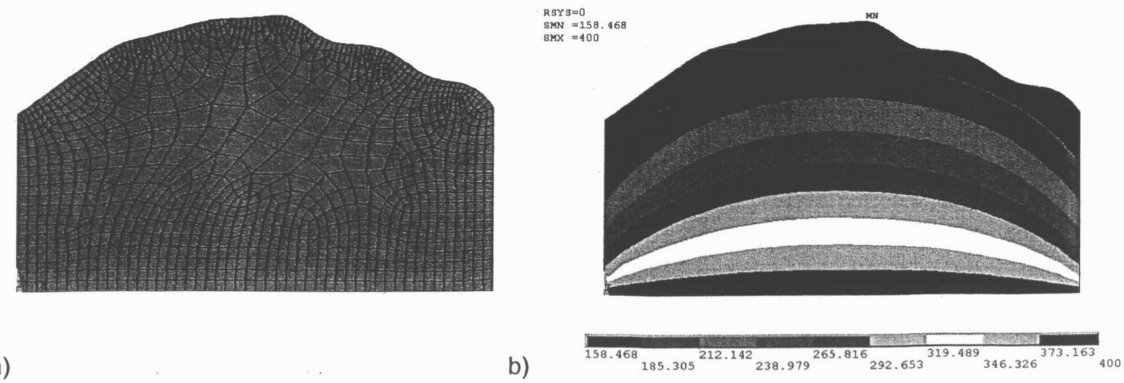


Figure 11: Variable Thickness: a)FEA mesh of radiator design, b)temperature distribution of radiator

Spline Curve Parameterization

Figure 12a shows the FEA mesh for the spline curve design boundary given. Demonstrated in Fig. 12b is the steady state temperature distribution radiator design. The overall heat loss for this plate using spline curve parameterization 3.26726e+06W and the mass is 4246.57kg. The objective formulation for the spline curve design parameter problem is given below:

$$fitness = \frac{m(kg)}{Q(W)} = \frac{4246.57\text{kg}}{3.26726\text{e}+06\text{W}} = 1.299e-03(\text{W/kg})$$



a) b)

Figure 12: Spline Curve: a)FEA mesh of radiator design, b)temperature distribution of radiator

CONCLUSION

Clear benefits of lightweight, high-temperature heat radiators have presented in this paper. Future space vehicles, surface power bases, and space platforms can be made more mass- and volume- efficient through development of the technologies described in this proposal. It was shown by reference to an early JIMO study that radiator mass can be a large fraction of the total vehicle mass. Therefore, reductions in radiator mass of even a few percent can yield substantial improvements in overall system mass.

This paper has presented a design method to create minimal mass highly efficient heat rejection radiators. The design problem formulation includes several steps as described in this paper, FEA thermal analysis, genetic algorithm search and two novel shape change methods for the radiators. This design procedure was then demonstrated using both presented design parameterization schemes on a common problem in radiator design.

A general discussion of the utility and applicability of this modified approach is considered here followed by concluding remarks on the process implementation.

The presented solid-model design provides a standardized description of the design that is readily acceptable by commercial engineering software and CNC fabrication software.

ACKNOWLEDGEMENTS

REFERENCES

Juhasz, A. J., and Peterson, G. P., "Review of Advanced Radiator Technologies for Spacecraft Power Systems and Space Thermal Control," NASA-TM-4555, June 1994.

Chapman, C. D., Saitou, K. and Jakiela, M. J., 1994, "Genetic Algorithms as an Approach to Configuration and Topology Design," Journal of Mechanical Design, 116, pp. 1005-1012.

Dozier, G.; Bowen, J., and Homaifar, A., 1998, "Solving constraint satisfaction problems using hybrid evolutionary search," IEEE Transactions on Evolutionary Computation, Vol. 2(1), pp. 23-33

Parsons, R. and Canfield, S., 2002 "Developing Genetic Programming Techniques for the Design of Compliant Mechanisms," Journal of the International Society for Structural and Multidisciplinary Optimization, 24(1), pp. 78-86.

Mason, L.S., "A Power Conversion Concept for the Jupiter Icy Moons Orbiter," Journal of Propulsion and Power **20** [5] 902-910 (2004).

Patton, B., "In-space Propulsion: Power Conversion Cycles and Radiators", presented at NASA Advanced Space Propulsion Workshop, Huntsville, AL, May 2003.

Teagan, W.P. and Aguilar, J.L., "Investigation of Moving Belt Radiator Technology Issues," NASA CR 195340 (1994).Siamidis, J., Mason, L., Beach, D., and Yuko, J., "Heat Rejection Concepts for Brayton Power Conversion Systems," NASA TM 213337 (2005).