

Implications of Advanced Thermal Control Architecture for Modular Spacecraft

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ABSTRACT: The combined knowledge-bases of architecture theory, thermal design, and advanced technologies have been used to develop a modular approach to thermal control. This new approach was designed specifically for the requirements of a modular spacecraft, reducing or eliminating the system-level coupling and interdependencies of traditional thermal designs. The decoupling of the thermal subsystem allows improved control methods using advanced technologies that control the heat leaving the spacecraft. These control methods eliminate the need for survival heaters, reducing mass and power as well as simplifying the analysis effort required for verification and validation of the design. In addition, the modular approach allows fundamentally different designs to be incorporated into the spacecraft architecture and structure. The modular thermal approach, structural implications, and system implications are explained with illustrations and examples.

INTRODUCTION

Research has recently been completed in methods of thermal control for modular spacecraft^{1,2}. This research provides new methods for implementing thermal control within a modular architecture. The Air Force Research Laboratory (AFRL) sponsored research combining architecture theory, thermal design, and advanced technologies to provide the framework for the development of modular thermal control architectures.

The need for a new architecture is driven by the system-level coupling that is prevalent in a traditional thermal control approach. Modular architecture requires independence of functionality, well-defined interfaces, standardization, and flexibility. The traditional approach to thermal control results in a fixed, customized design that is highly coupled rather than independent.

ADVANCED THERMAL ARCHITECTURES

The roles and functions of the thermal control subsystem were evaluated and divided into five principle areas: heat generation, heat transportation, heat storage, heat rejection, and adjustment of the thermal energy balance. These five functions, shown graphically in Figure 1, were then assembled in such a way that they could each be functionally independent except through a well defined thermal interface, allowing the functions to be modularized. The way in which the functions are separated and the way they interface with each other defines the thermal architecture. A number of architectures were developed and compared, each providing varying levels of modularity, performance, and unique characteristics. A subset of the architectures that are most relevant to discussions of system-level design changes are presented here.

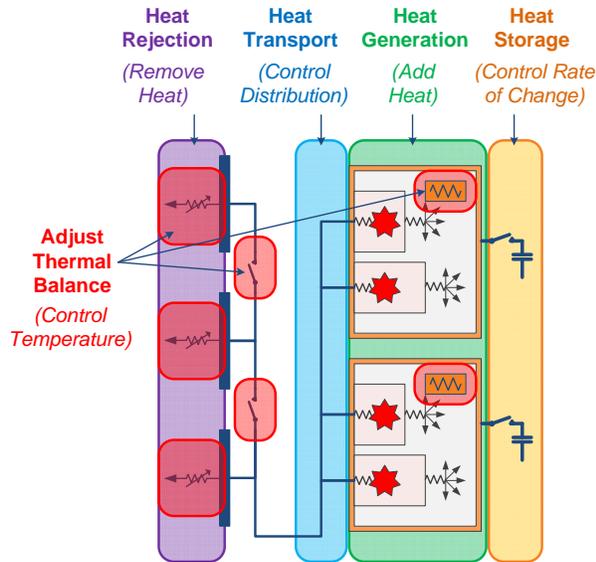


Figure 1: Representation of the five functions identified for the thermal control subsystem.

Traditional Thermal Control Architecture

Traditional thermal control architecture, shown schematically in Figure 2, is included here for comparison against the advanced thermal control architectures. Traditional thermal control uses a cold-biased/heater safety net approach. The radiator is designed to ensure the hot end of the allowable temperature range is not exceeded (the cold bias). Heaters are used as a safety net to prevent temperatures from dropping below the allowable temperature range. The design approach is to customize the thermal links, paths, heaters, and radiators. The design is then analyzed to ensure the allowable temperature range is maintained in all cases. The design approach is well understood, uses low risk components, and has been very effective in fulfilling the purposes for which it has been developed.

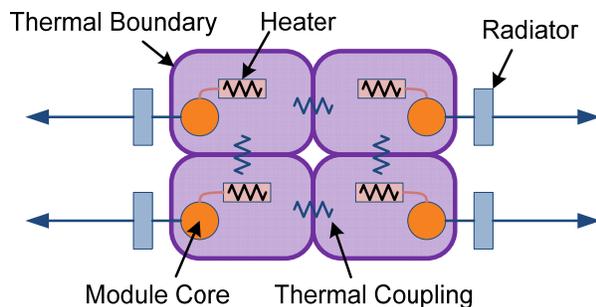


Figure 2: Schematic of a traditional thermal control architecture.

Isothermal Bus

The isothermal bus architecture adds a high conductivity thermal link, or thermal bus, between modules. This link transfers heat so that all modules are essentially isothermal. The thermal boundary is drawn at the system level because individual modules effectively share the same thermal zone. The rest of the design is similar to traditional thermal architecture. This architecture is illustrated in Figure 3 with a variable radiator that can adjust the thermal balance using new technologies that can change either the emissivity or effective radiator area.

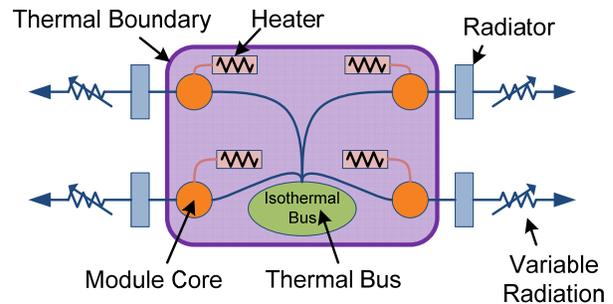


Figure 3: Schematic of an isothermal bus thermal control architecture, shown with optional variable radiative heat transfer.

The isothermal bus architecture maintains survival heaters and individual radiators from the traditional architecture, but significantly improves heat transfer, thereby reducing temperature gradients and increasing the effectiveness of the radiator (via lower temperature drop and thus higher resulting radiator temperature, increasing the output of the radiator, which is proportional to the temperature raised to the fourth power). The addition of variable radiative heat rejection, as shown in the figure, can further improve the design performance. This architecture is not fully decoupled, but retains cross-boundary interactions and localized heaters and radiators.

Modular Isothermal Bus

The modular thermal bus, shown in Figure 4, separates the heater and radiator from the modules, removing the last major interdependency. The radiator can be modular and scalable with a clear interface for heat input and heat output. The centralized heater is not necessary because of radiator control, but is shown here as it would be if a modularized heater safety net were desired. Both the heater and radiator can be changed or scaled without affecting the physical design of the other modules. It can be noted that an increasing amount of thermal control infrastructure, such as the heater and isothermal bus, is required for this architecture. The hardware complexity has increased, but the system-level interfaces and dependencies have been greatly

simplified. The thermal analysis effort may be reduced to simply adjusting the heater and radiator sizes to ensure positive thermal control over the range of operating conditions, thus eliminating the need for detailed thermal analysis of every variation in hot and cold cases.

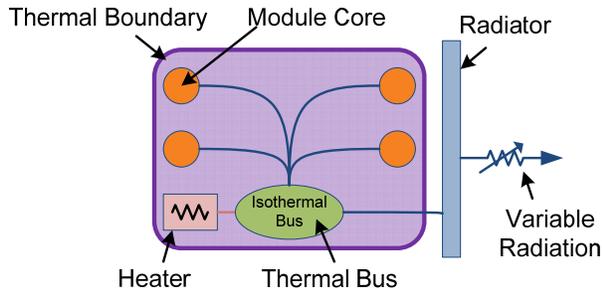


Figure 4: Schematic of a modular isothermal bus thermal control architecture with variable radiative heat transfer.

Dual Thermal Bus

The dual thermal bus architecture, illustrated in Figure 5, duplicates the modularized isothermal bus with two thermal buses. There are several different ways to use the dual thermal bus. The two buses can be switchable, with different control temperature ranges. This type would introduce thermal coupling between modules if not isolated but would prove useful for spacecraft that required different operating ranges. If radiators are instead individually sized to manage the entire heat load the thermal control could be a fully redundant system.

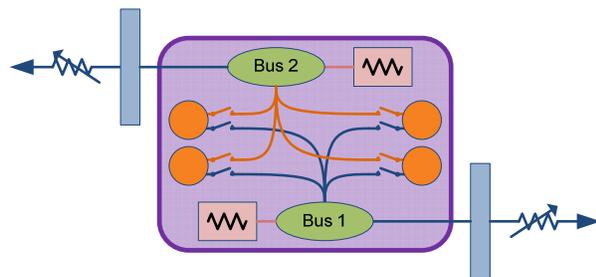


Figure 5: Schematic of a dual thermal bus thermal control architecture with variable radiative heat transfer.

WHAT IS DIFFERENT

The advanced thermal control architectures presented in the previous section introduce principles of modularity to the thermal control subsystem. In the process, changes to the thermal control system are introduced. The use of an isothermal bus to transport heat is for the purpose of separating that functionality from the structure and from radiative heat transport, each of which cause thermal coupling between modules. An

independent, removable radiator also provides functional separation. The addition of variable emissivity or variable area radiators, both possible with technologies under development, simplifies the control system and further enhances the modular characteristics of the thermal control architecture.

These advanced thermal control architectures are designed to reduce recurring costs, simplify analysis, and reduce assembly, integration, and test efforts. Increased complexity in the development and first unit design are traded for reductions in cost and schedule for follow-on units.

In addition to the characteristics designed into the thermal control subsystem, as described above, there are changes that are the byproduct of the new design. The isothermal bus significantly decreases the temperature variation across the spacecraft. Even without a variable radiator control, the system will experience decreased diurnal temperature variations because the entire thermal mass of the spacecraft is utilized as opposed to localized cooling that occurs in a traditional spacecraft design.

With variable radiator control the spacecraft can maintain constant temperatures, something very difficult to do with a traditional spacecraft and very power intensive. Rather than add heat, the variable radiator control reduces heat loss. This method is more akin to bundling up a coat on a cold winter day – a more efficient method for regulating temperature.

Another added benefit is the possibility of extending radiators beyond the spacecraft panels. This is possible because the radiator is now separate from the structure, a modularity requirement. Extended radiators can be more effective than body mounted radiators if, as is also required of the modular system, the heat can be transported effectively.

IMPLICATIONS TO SPACECRAFT

The thermal considerations discussed above have indicated several significant implications to the design of the spacecraft. These include the possible elimination of survival heaters, system implications of improved temperature stability, extended radiators with lower mass, and a reduced need for external structure. Each of these areas is discussed in more detail here.

Elimination of Survival Heaters

One of the most significant changes to the thermal subsystem is the ability to control the thermal energy balance without the need for survival heaters. The use of advanced control methods described earlier provides effective control without the need for additional power. Initial implementations of these advanced thermal control architectures may continue to implement a

backup survival heater system until the primary control method is proven to be as reliable as a traditional survival heater system then there would be no need for the additional hardware. For some missions, the elimination of heater power during eclipse would provide significant reductions in battery size, saving both mass and power.

Temperature Stability

The advanced thermal control architecture also provides significant advantages in temperature stability. By controlling heat rejection, the temperature of the thermal bus can be held constant. This allows the components to be held at a constant temperature, adapting to changes in the environment and internal heat dissipation. Given a sufficient dynamic range and response in the control system, the temperature stability of the spacecraft can be excellent, as shown in Figure 6. For simulations using an isothermal bus, the variation in temperature from one module to another is caused by the amount of power dissipated in the module, creating a temperature difference between the equipment and the interface to the thermal bus. Thermal stability can improve the performance or life of temperature sensitive components, such as clocks, inertial reference units, focal planes, and batteries.

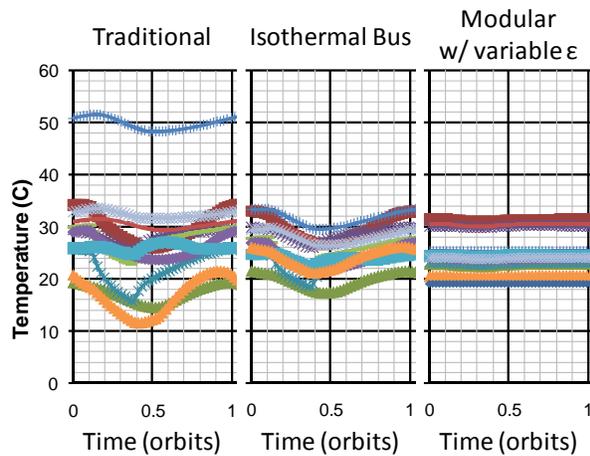


Figure 6: Comparison of orbital simulation results of three architectures: traditional, isothermal bus and modular isothermal bus with variable emissivity control radiators. The module temperatures plotted illustrate the temperature stability achievable with advanced controls methods.

Advanced Radiators

The architectures presented here are easily adapted to a deployed (e.g. mechanically unfolded) or extended (e.g. fixed position, but extending beyond the body of the spacecraft). This type of radiator presents several advantages that are applicable to advanced thermal architecture or a traditional thermal architecture.

A radiator that extends out from the body of the spacecraft requires less surface area to dissipate the same amount of heat, reducing radiator mass. For a given radiator size, in the worst case orientation (normal to sun), using a typical radiator coating ($\alpha_{\text{solar}} = 0.20$ $\epsilon_{\text{IR}} = 0.85$), a deployed radiator requires less than 20% of the size of a body-mounted radiator. This is caused in part to the doubling of the radiator area (front and back sides) and in part to the reduction in the amount of solar heat load that the smaller radiator absorbs (smaller frontal area). An actual design would be somewhat less efficient because of the view of the spacecraft that blocks portions of the view to space and some inefficiency that is bound to be caused by the added thermal distance between the extended radiator and the heat source. Figure 7 illustrates the difference between a one-sided (i.e. body mounted) radiator and a two-sided (i.e. extended) radiator.

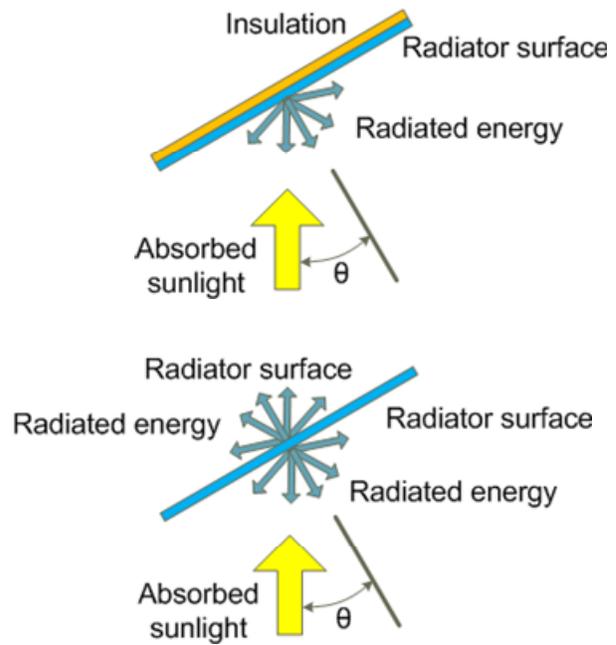


Figure 7: Illustration of a one sided radiator (top) and a two sided, extended radiator (bottom).

An extended radiator that is one fifth the size would also reduce heat loss during an eclipse. The combined surface area of the extended radiator is 40% of the area of the traditional radiator, which reduces the heat loss proportionally given a constant temperature or reduces the temperature drop of the spacecraft if the temperature is allowed to drift.

An extended, two-sided radiator would present additional challenges such as structural integrity during launch, efficient transport of heat to the radiator, volume constraints or the need for a deployment mechanism; however, this type of radiator has clear

thermal advantages for both sunlit and eclipse periods. Table 1 summarizes the differences in design for an example radiator.

Table 1: Comparison of extended, two-sided radiators and traditional, one-sided radiators.

Performance Parameter	Extended Radiator	Traditional Radiator
Design Load	100 W	100 W
Size	0.23 m ²	1.22 m ²
Full sun heat loss (293K)	100 W	100 W
Eclipse heater power (required to hold 293K)	81 W	434 W
Eclipse steady state temperature drop (no heaters)	33 K	90 K
Designed for 293K maximum temperature (hot case), $\alpha_{\text{solar}} = 0.2$, $\epsilon_{\text{IR}} = 0.85$, $Q_{\text{solar}} = 1367 \text{ W/m}^2$		

Reduced need for external structure

The traditional approach to spacecraft design, with equipment panels forming the outside skin, has been developed over time to optimize the design within a number of constraints. The need for strength and stiffness, radiator space, and radiation shielding are among the most prominent drivers. The advanced thermal architecture eliminates one of these drivers by separating the heat source from the heat sink. Without the need to have electrical equipment mounted directly to the radiator, new structural designs are possible. Some of the other structural drivers will still apply, which will require system trade analysis to determine the best approach for a specific mission, but the trade space can be larger with the possibilities opened up by removing the thermal constraints.

Several concepts for new structural configurations have been developed to investigate and illustrate the possibilities. These concepts are designed for modular spacecraft with the ability to be scalable and expandable, as well as having standardized interfaces. The AFRL Space Plug-and-play Avionics (SPA) architecture³ is used as the electrical and data infrastructure, with centrally located connections to reduce harness lengths.

The first concept design also illustrates the product architecture theory process adopted for the development of a new product. The module “chunks,” or discrete physical units, are made up of equipment bays and the SPA infrastructure units. These “chunks,” shown in Figure 8, are then configured to form the basic structure of the spacecraft, as shown in Figure 9. The structure is patterned after the thrust-tube spacecraft architecture, which provides a strong central tube to handle launch loads with additional surface area for electronics to

mount to. Adding additional layers above or below, the “stack” of units becomes a scalable spacecraft.

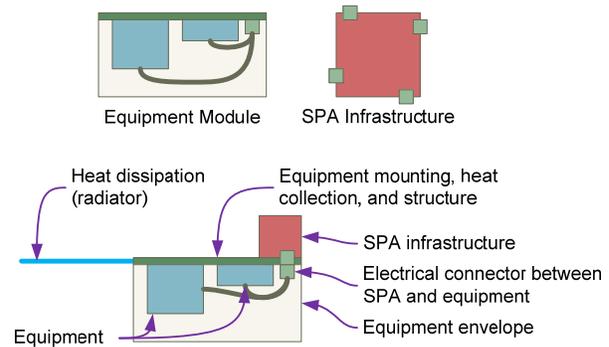


Figure 8: The module building blocks (top) are combined with thermal components (bottom).

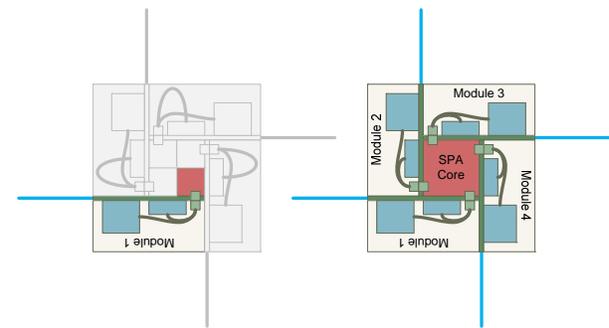


Figure 9: Individual modules, thermal components, and SPA infrastructure form the building blocks of the modular structure (left) which combined form a complete spacecraft layer (right).

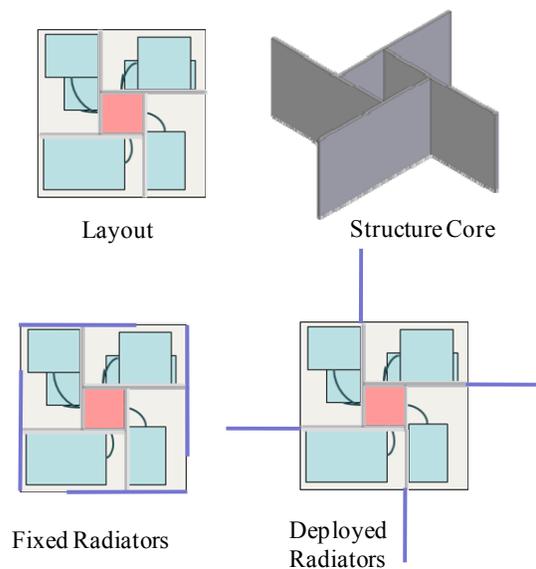


Figure 10: The modular square thrust-tube design illustrated here can be assembled from simple building blocks

The design can adapt well to deployed or traditional radiators, as shown in Figure 10. The same basic design can be adapted to other forms, such as hexagonal or octagonal versions, as illustrated in Figure 11.

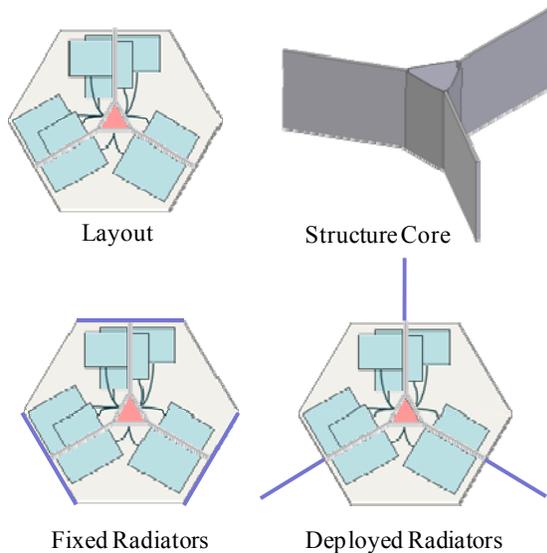


Figure 11: The same layout can be used in hexagonal (top) or octagonal designs (bottom).

Increased Complexity

The added benefits of the advanced thermal architectures come at a cost. The most obvious is the added complexity of the thermal components. The use of heat pipes or other high conductivity component for the thermal bus, the use of technologies to alter the rejected heat from the radiator, and the possible mechanisms that would be required for a deployable radiator each add complexity. For programs that require modular architecture, the complexity will be offset in part by the simplified system design and system testing and in part by reductions in development times and costs (at least for follow-on units).

Additional costs include several difficult design issues. One such issue is the contradictory design goals of removable, modular radiators and efficient heat transport from the modules to the radiators. This issue, illustrated in Figure 12, requires something like a bolted joint between the radiator and module. A bolted joint between two standard heat pipes, for example, is likely to produce the largest temperature drop in the heat path (other bolted joints tend to be at locations where less power is concentrated). Using a fluid coupling, which is possible with advanced heat pipes, eliminates this temperature drop, but may introduce additional risks or performance issues.

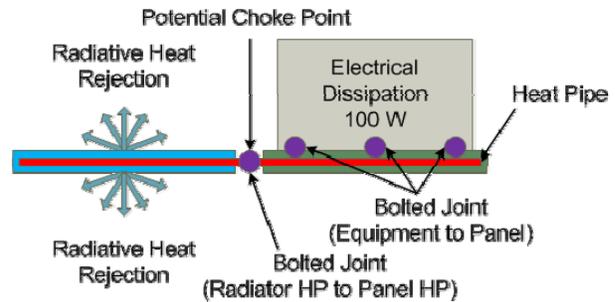


Figure 12: Illustration of a potential “choke” point that could represent a design challenge.

CONCLUSIONS

Research into modular thermal control architecture has produced effective modular thermal control architectures. These architectures represent a trade between modularity, and the potential cost and schedule savings that would follow, and increased levels of thermal subsystem complexity. Additional system-level benefits are possible, including elimination of survival heaters, increased temperature stability, improved radiators, and changes in the way spacecraft structures are designed.

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