Cost Savings & Predictable Performance Benefits of Carbon Nanotube Satellite Thermal Interface Solutions

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Abstract **– We present an analysis of the cost savings and performance benefits delivered by a predictable carbon-nanotube-based thermal gasket – Carbice® Space Pad™, for spacecraft builds. We show a >60% net savings in the Assembly Integration & Test (AI&T) and Thermal cost in a typical satellite build, supported by an independent analysis performed by a large space prime. Based on this analysis, a projected $1.13 billion in cost savings for Department of Defense's Satcom budget may be extracted by using carbon nanotube-based gaskets for all satellite assembly interfaces. This carbon-nanotube-based thermal gasket delivers valuable labor cost savings and performance improvement by taking advantage of a unique combination of excellent thermal properties and mechanical properties as a result of its structure – vertically aligned carbon nanotube forests bonded to both sides of an Aluminum core. The aligned carbon nanotubes not only provide high through-plan thermal conductivity, but their elasticity also allow reliable thermal contact during cycling, providing low thermal resistance in application. The Aluminum core keeps nanotubes intact, enables a form factor that is easy-to-use and fully reworkable, while contributing to in-plane thermal conductivity. The resulted thermal gasket is operable over a wide range of interface pressures, ranging from very low pressure up to over 1000 psi. This combination of thermal and mechanical properties allows satellite designers to incorporate full functionality into the system payload without the limitation of existing thermal solutions.**

There are two classes of materials that dominate spacecraft interfaces today: liquid solutions like particle laden silicone RTV and gap pads like graphite or particle laden gap fillers. RTV has a low thermal conductivity, limiting its ability to remove heat from on board electronics. Furthermore, their application process is time consuming (and therefore costly) when accounting for the time needed to prep surfaces, mix, precisely apply and cure the material. After curing, RTV is not reworkable, so when components must be removed from after initial testing it must be scraped manually from the flight vehicle and the underlying surfaces often need to be re-polished. Furthermore, this scraping process can generate conductive foreign object debris hazards. Gap pads like graphite or particle laden gap fillers come in the form of gaskets that can be cut to size reducing some of the installation burden. However, these materials suffer from irreversible compression set after installation. As a result, the gap pads can lose preload or in some cases dewet entirely from the interface as it expands and contracts thermally. This three-factor combination of component deformation, inelastic gasket compression and thermal cycling can transfer stress to the fasteners resulting in gradual pull out of the inserts that mount the components to panel structures in the spacecraft.

Considering the strengths and weaknesses of the thermal interface materials available in the market today, predictable carbon-nanotube-based thermal gasket represents a unique solution that accelerates thermal design optimization and mission timeline while enabling significant AI&T savings.

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1. INTRODUCTION

One of the limiting factors to involvement in space related activities has been the high cost associated with traditional missions. In the early years of space exploration, this was not a particular problem as the majority of missions were run by space agencies and the military, which were directly funded by their associated governments. Though involvement in space exploitation began to grow considerably in the 1970s, the costs involved still tended to favor governments and large commercial corporations.

The goal of opening up space to more diverse organizations could only be achieved if lower cost alternatives were sought.

The result today is that numerous missions have been created to stimulate alternative markets, mission types, and objectives by providing much lower cost access to space.

Indeed, the desire for cost-effective missions across all areas of space technologies and mission types is even more important in today's global financial environment. Commercial organizations need robust business plans to gain funding, and even government funded missions are seeking more cost-effective missions when their budgets are cut.

The question remains: How can you enable more cost-effective space missions?

When referring to the cost of a space mission, it is the total cost required to fund the mission from its earliest concept design right through to in-orbit operations and eventual disposal. It includes all design, manufacturing, management, testing and operational aspects of the space and ground segments.

To minimize mission cost, it is then important not only to focus on the technical aspects but also on programmatic elements, like keeping the overall schedule as short as possible without increasing risk beyond an acceptable level.

This is for several reasons. Firstly, if the mission is not ready it may miss its launch. In addition, the longer the schedule, the longer the team of engineers and managers will be working on the project, increasing cost. However, if the schedule is shorter than some optimal point, there may be little time to allow for additional testing. The result could be that late-breaking problems arise in Assembly, Integration and Testing (AI&T). These are typically very costly to fix that late in the project and again will drive up mission costs considerably [1].

In fact, rigorous AI&T is required to increase the operational reliability of any satellite in a space environment. To assure that a satellite will survive a launch and perform to the desired specifications, it must undergo extensive space qualification and verification on the ground. Highly specialized AI&T technologies are required, together with environmental testing facilities, during assembly, integration and testing of engineering and proto-flight versions of space hardware, which is also the case for small satellites.

For instance, current government and industry standards in spacecraft testing result in an AI&T timeline of greater than six months [2]. To get a sense of the relative size of the various costs in the typical spacecraft program, Younossi et al showed the average percent share of total spacecraft cost by subsystem or program-level cost and mission type, where AI&T and Thermal together accounted for 20% of Communication Spacecraft Cost driven by assembly process and labor [3].

This status-quo does not support the vision of Industry Primes and New Space leaders who now need to deploy a satellite within days to fill an urgent need, not months or years.

As the global satellite industry begins to transition to mass development and deployment of constellations, emphasis on streamlined AI&T is increasingly necessary for mission assurance and risk reduction.

2. LIMITATIONS OF CURRENT SPACECRAFT THERMAL DESIGN

Today, the performance of a spacecraft's thermal design is typically verified during expensive and time-consuming thermal balance testing in vacuum. Component level testing and validation may occur prior to full assembly of the spacecraft, but even then, this is typically done through physical testing in vacuum. The need to do such extensive testing is driven in part by the inability to truly predict performance of assembled interfaces between components.

Consequently, any thermal design can provide only a limited assurance that the predicted temperatures encompass all the events and conditions of the spacecraft lifetime.

To minimize this uncertainty, thermal engineers apply analysis techniques involving the simulation of the satellite by a thermal mathematical model which is usually 'tuned' by a series of ground tests to a specific level of accuracy before being adapted for predicting in-orbit performance.

For conventional thermal interface material (TIM), the translation from datasheet to real-application performance leaves a lot of gaps. As high as 50% of mismatch is often seen between simulated results and real-world test results.

For Thermal Engineers: the process of embedding thermal interface materials into a spacecraft thermal model and cross-correlating analysis results with thermal vacuum (TVAC) test campaigns' outputs is a very laborious, costly and overall frustrating task.

In the analytical process of temperature prediction with a thermal mathematical model, a number of inaccuracies due to the depth of modelling, available physical data and lack of precise definition of the item and its environment are present. And when a test is performed, additional inaccuracies due to test set-up, and test instrumentation are to be considered. In many cases these uncertainties are out of the control of the thermal engineer, for example workmanship variations.

Furthermore, the transfer of thermal models between parties is a task that occurs many times during the course of a typical space project. For example, models of equipment or subsystems are regularly provided by sub-contractors to customers for integration into a higher level model. Prime contractors also regularly provide system level models to customers or reduced models to launch authorities for coupled analysis. And unfortunately, every time a model transfer occurs there is the potential for problems to arise, e.g.

corruption, or even loss, of electronic data; incomplete or incorrect deliveries meaning that the model cannot be executed; incomplete or inadequate documentation describing the model and how to execute it; portability problems such as the use of different operating systems.

For Structural Engineers: insert pull out is a critical issue.

Potted inserts can pull out when using traditional thermal interface materials and the incumbent liquid silicon rubber (LSR) process. Bolts have to be torqued slowly with LSR to avoid overstressing because the LSR needs to pump down and thin out until bottoming out on a metal shim– this is hard to control with technicians in practice. The thickness of the LSR drives extra stress.

Traditional thermal pads require a lot of force to deform them because the entire pad must deform from any locally applied pressure point. Then the compression set of the pads later adds risk in loosing contact at the fasteners and stressing potted inserts.

For AI&T Engineers: the pain of working with liquid thermal interface materials is well-known:

- Long curing times
- Difficult to install and thus prone to failure
- Prone to damaging the spacecraft if the adhesive needs to be removed
- When reworking interface, LSR will need to be re-dispensed and re-cured, a time-consuming process
- Void formation in the interface from shrinking during curing
- Inconsistent bond lines and various optical inspections are required to verify quality parameters.

Furthermore, liquid TIM dispense tooling takes up significant space in facility driving more space needs. Process development and implementation is required for each dispense pattern and interface, and filler separation is common in dispensers when machine is not constantly on, limiting flexibility.

Overall, liquid TIM dispense tooling can drive $2M in CAPEX along with maintenance cost.

For M&P (Materials & Processes) engineers: graphite-based solutions' contamination risks are critical.

Contamination, if not adequately anticipated and controlled, can result in loss of spacecraft, performance degradation, mission degradation, and/or loss or injury of flight crew.

Particulate and molecular contamination from both ground processing and on-orbit migration may degrade the performance of optical devices, thermal control surfaces, and solar arrays.

Particulate contamination accumulated during ground processing or generated during operations may interfere with mechanisms, bearings, and seals; may plug or restrict fluid orifices or filters; and may pose a hazard to the crew.

For these reasons, graphite use is low and not desired because of a known source of on orbit failure due to Foreign Object Debris (FOD) contamination.

Graphite is used in less than 5% of applications due to FOD and complex extra engineering labor costs that make it a pain for programs.

For Project Managers:

1) A lack of clear understanding of the effort involved in each project task makes analysis of the critical path very difficult and time consuming. Especially during project phases like Thermal Analysis/Modeling and Thermal Analysis and Control where early assumptions and iterations are significant.

2) The cumulative AI&T costs and schedule due to impossibility to rework/disassemble satellite build are big burn to the overall project budget and schedule.

3) The current global supply chain shortage further compounds the issue with project schedule due to the need to replace damaged components as a result of the aggressive process to rework incumbent TIMs.

3. PREDICTABLE CARBON NANOTUBE THERMAL INTERFACE MATERIAL

At its core, the relationship between excessive AI&T costs and thermal interface solutions is an inability to predict performance in real application, and as a corollary to this, an inability to predict cost. While liquid solutions can provide a semi-form fit to an undefined interface, they often contain voids sometimes 50% or more of the total interface area [4]. This has to be accommodated by excessive and expensive testing and rework, or overdesign to build in margin to account for uncertainty. Often times, the only quality checks that can feasibly be done are simple composition checks of the LSR mixture, because in situ inspections like ultrasound imaging are too time consuming, expensive and sometimes simply not practical. Even when thermal performance of liquid solutions like LSR meet expectations, rework brings additional uncertainty in the way of scheduling impacts due to long rework times, damaged components after dismount that need to be replaced, and the need to reorient the spacecraft to a mounting position for replacement.

Dry gaskets have the potential to solve many of the challenges posed by liquid TIMs, however their adoption has

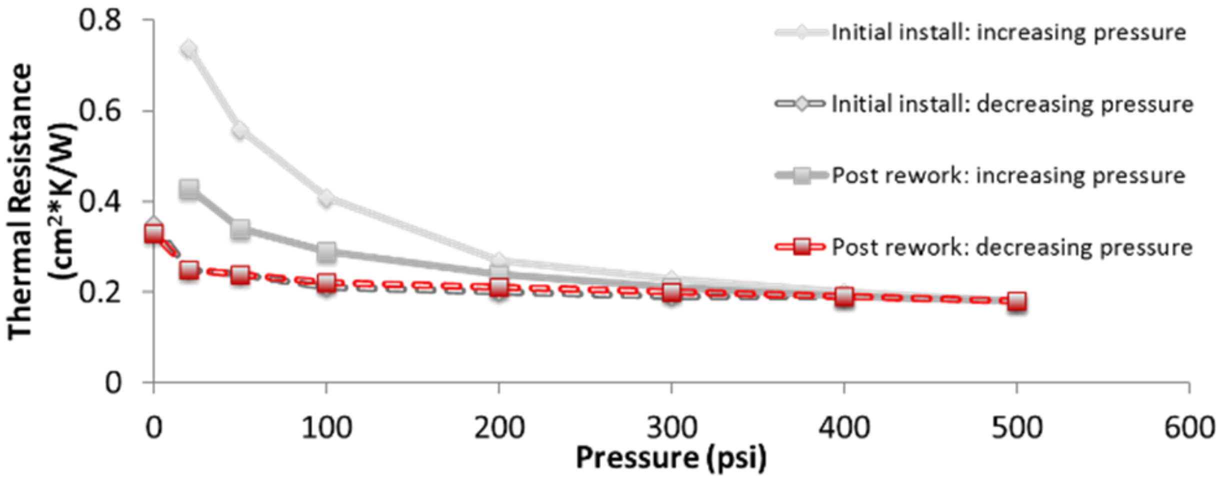

Figure 2 Thermal resistance hysteresis of a Carbon Nanotube thermal interface material subjected to increasing and decreasing pressure

lagged in critical interfaces, again due to the difficulty in truly predicting the performance of the material in application. It is well known that the correlation between data sheet values and conductance in an application, in vacuum, is very weak [5]. For dry gaskets, the variance from data sheet to in application conductance can be more than an order of magnitude difference [6]. This is not primarily, due to lack of transparency on the part of gasket manufacturers. Instead, it is driven the physical reality that conductance in application is a complex problem, dictated by the mechanical –structural dynamics of the interface, as well as the thermal properties of the filler material. To understand the gap that must be filled in a real spacecraft interface, one must consider the as-built planarity of the components being assembled, as well as the distortion in the assembled parts that is induced by the loading of the fasteners on the components [7]. Critical to this structural mechanical understanding is the role of the interface material itself, as it creates a reaction force on the assembled components that impacts the distribution of stresses in the interface as well as the deformation of the as assembled components.

An understanding of the stress distribution in the interface is critical for predicting and preventing pull out of potted inserts. Insert pull out has been a significant roadblock to the adoption of dry gaskets in spaceflight applications, especially those involving bolting large nonplanar boxes to honeycomb panels. Because the large boxes are not flat, the inserts can be stressed while the gap between gasket and component is closed. Furthermore, if the dry gasket is irreversibly compressed during assembly (beyond its elastic range due to over torquing) the fasteners can be loaded during flight due to thermal expansion of the joint that the gasket cannot follow.

To address these challenges, a new thermal interface solution has been developed, based on a polymer encapsulated platform of vertically aligned carbon nanotubes (VACNTs), grown on both sides of a 50 µm thick aluminum substrate (Fig. 1). The VACNT forest platform at the core of the thermal interface solution solves the problem of over compression at bolt locations due to its high elasticity and ability to rebound back after compression, even at high loading [8]. Unlike other dry gaskets, VACNTs can maintain their elasticity up to extremely high pressures, like those seen close to bolts in typical interfaces. At the same time, the individual nanofibers enable billions of contact points in an interface, even at low pressures like one would find far away from a bolt or fastener.

Figure 1 A 3D rendering of the cross sectional view of the vertically aligned carbon nanotubes on both sides of an Al substrate

As an example of the reversible elastic mechanics of VACNT gaskets, as well as their performance across a wide pressure range, a 6 mil gasket was placed in an ASTM 5470 thermal test apparatus described in [9]. After assembly, pressure is increased, up to 500 psi. It is then slowly decreased, until the interface is completely separated. This represents a typical rework cycle (Fig. 2). The interface is then re assembled and pressure is increased again following the same cycle with no loss in performance due to exposure to high pressure or the make/break action.

Even in vacuum, this VACNT based thermal gasket has demonstrated the ability to maintain consistent contact and even improve in thermal performance after four thermal cycles and over 1,000 mechanical cycles in a test application [10]. Through thermal-mechanical cycling, the nanostructures continue to create additional contact points at the mating surfaces.

What predictable mechanics has enabled is the ability to develop a first principles suite of modeling tools that can inform the satellite build team of how the interface will perform, both mechanically and thermally, even in complex non planar interfaces. As an example, we examine the stress on a potted insert during assembly of a simulated spacecraft using a calibrated modeling suite developed to predict performance of carbon nanotube thermal interfaces in real applications. We consider a large 6 bolt, 8"x 8" box with 20 mils of out of flatness along the bolted side of the plate, with a 125-micron thick gasket installed beneath the plate. During fastening, the box is deformed due to the torquing of the bolts, until it contacts the gasket at slightly over 200 lbs. of fastener load (Fig 3). After this, the gasket is deformed an additional almost 20 microns during torquing to the final preload of the joint. In this case, the pull-out load of the fastener is the force required to close the gap, plus the force stored in the gasket compression. Because a relatively low compression gasket was selected for this application, the additional gasket compression load is low. However, the true power of the modeling capability is not the characteristics of this particular solution, but the ability to know before beginning of assembly if the final loads will meet the design window of the inserts without the risk of pulling any inserts out that would result in substantial setbacks and cost to the overall build. Predictability enables the assembly team to know and decide up front if the interface is safe to torque, or if compensatory measures such as a thicker gasket shim, or other mitigation factors are needed to safely complete the build.

Beyond assembly guidance, the predictable mechanics of this carbon-nanotube based thermal also allow modeling tools to inform the design team of the expected thermal performance of the gasket, in vacuum, without having to resort to expensive and time consuming TVAC testing. This simulation tool solves not only the mechanical problem but also the thermal problem that is coupled to the distribution of contact pressure in the interface. As an example, a 11" x9" aluminum box with 16 bolts heated with 4 cartridge heaters (Fig. 4) was tested with a 125 um thick carbon nanotube gasket, and the average conductance was compared to that predicted by this simulation. The average conductance is determined by computing a local conductance in discretized regions of the interface, captured by thermocouples both in the 11"x 9" box and in corresponding locations in the baseplate that the box was bolted to. Average conductance is then computed by area weighted average of the local conductances across the interface. The interface had a measured in application conductance of 6390 W/m^2-°C, which was within 3% of the 6200 W/m^2-°C conductance predicted by the model.

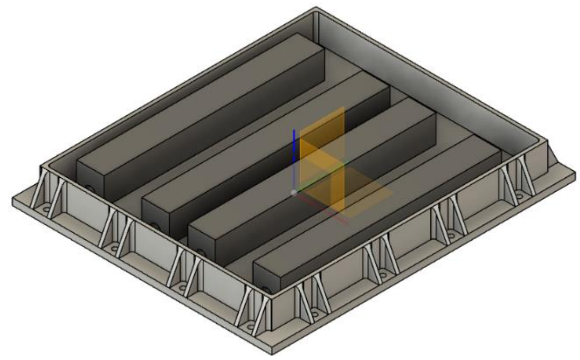

Figure 4 Schematic of the 11" x9" aluminum box used for validation testing

Furthermore, the interface was disassembled and reassembled 12 times, and even after 12 simulated rework cycles, including the typical sliding wear that might be seen in the field, the conductance was within 5% of the time zero conductance (Fig. 5). In general, performance tended to improve with use, which aligns with observations noted in other studies [10]. This ability to not only easily rework the interface when needed, but to also re-use the same interface is a game changing ability that is only available due to the rugged, low compression set nature of carbon nanotubes in carbon nanotube thermal gaskets.

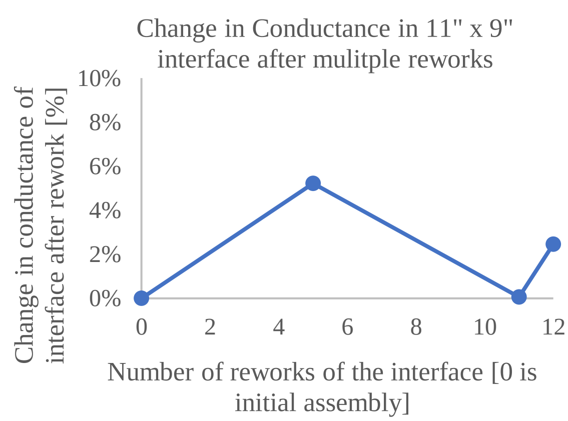

Figure 5 Change in conductance of 11" x 9" joint after 12 reworks

4. AI&T COST SAVING ANALYSIS

OVERVIEW

This section will cover the significant time and cost advantages the VACNT based gaskets can provide during the AI&T processes of spacecraft manufacturing versus LSR. LSR is the main incumbent solution used today in spacecraft manufacturing. These interface sizes can vary from the area of a playing card to many square feet. These interfaces may only have 4 corner bolt holes in a rectangular interface to very large, complex structures with random bolt hole patterns.

The manufacturing steps for interfaces requiring TIM include:

- Thermal Material and Interface Preparation
- Assembly
- Removal and Rework
- Reassemble

THERMAL MATERIAL AND INTERFACE PREPARATION

Thermal Material Preparation

LSR requires a weigh and mix process which is vendor and part-number specific. "Processing" is the euphemism for mixing to produce a "homogenous blend". De-airing or degassing is required to assure the mixture is bubble-free. These processes are time consuming and require experienced personnel. Furthermore, spacecraft manufacturers have operation procedures outlined by vendor and part-number and the amount of LSR needed at time of application.

The carbon-nanotube based Space Pad is a dry solution requires no processing or setup time. It can be pulled from inventory and moved directly to the Assembly area.

ASSEMBLY

Spacecraft assembly and integration is a complicated endeavor involving several subsystems. This section will focus on a subassembly requiring TIM to attach the subassembly to a subsystem henceforth called the "Interface".

Assembly using a legacy liquid TIM like LSR mandates careful planning because of workable time or "pot life". Assemblies are staged because not all sub-assemblies are ready at the same time. Assembly process includes the following steps after the mixing and de-airing process described above.

- Experts carefully dispense and apply LSR on the subassembly and/or subsystem per guidelines. The experts try to maintain a constant bond line thickness while carefully navigating bolt holes or other opening, edges, corners, and other called out areas. Experts must work within the LSR timeframe, which means multiple experts working in parallel to build multiple units or single expert mixing and assembling multiple units in series.
- Excess LSR must be removed and LSR in the working area must be cleaned before the next step.
- Assembly Experts then carefully assemble the Interface in the still wet environment. A further cleaning step maybe required if excess LSR appears at the edges or in bolt holes.
- The assembled interface now moves to the curing stage. LSR manufacturers specified an oven curing temperature and time (i.e., 4 hours at 60 ℃) and recommended increasing the cure temperature slowly or utilize a multistep curing process to allow the solvent to evaporate prior to the silicone curing. Most interfaces are cured at room temperature because they will not fit inside a curing oven. Spacecraft manufacturers opt for a multi-day room temperature cure step today to allow all solvents to evaporate and the silicone to cure. Some manufacturers attempt to monitor room-temperature curing.
- The cured interface then moves to inspection. The inspection process checking the integrity of the interface will be specific to the subassembly and subsystem. Some inspections are rigorous and require more than visual inspection. Experts using tools will check for voids, cracking, and other imperfections associated with LSR post-curing that might affect the thermal integrity of the system. Interfaces failing inspection are set aside for rework.

The carbon nanotube interface shortens the entire assembly process saving time and expenses by eliminating the Dispense, Curing, and Cleaning steps and reducing the inspection and validation time.

- Assembly technician fetches the pre-cut part that matches the interface from inventory.
- Assembly technician pulls of the top-side liner and aligns the pre-cut carbon nanotube gasket to specified surface. Technician can easily peel off and realign during pre-assembly even when the VACNT gasket has a pressure sensitive adhesive coating.
- Technician assembles the Interface.
- The assembled interface moves to inspection. The inspection process checking the integrity of the interface will be specific to the subassembly and subsystem. Some inspections are rigorous and require more than visual inspection, though the carbon nanotube gasket does not crack, void, or pit. Rigorous inspections will determine misalignment- or assembly- related issues. Interfaces failing inspection are set aside for rework.

REMOVAL AND REWORK

Removal and Rework of subsystems and subassemblies in spacecraft is a complicated endeavor. This paper will focus on removing and reworking interfaces as defined above. Interface removal and rework is a common practice built into the overall manufacturing and test process and plan. Most interfaces will be removed at least once during the overall process. Reworking interfaces requires spacecraft manufacturers to decide which part of the interface to rework and/or discard. As will be discussed below, handling during

Table 1: Case 1 - Total Cost analysis of Space Pad vs LSR with 2 reworks

	Assemble	Rework	Assemble	Rework	Assemble	Total
LSR Material	**$117,855**	**$131,241**	**$117,855**	**$131,241**	**$117,855**	
Carbice Space Pad	**$14,392**	**$11,879**	**$14,392**	**$11,879**	**$14,392**	
Delta LSR - Space Pad	**$103,463**	**$119,361**	**$103,463**	**$119,361**	**$103,463**	
Net Cost Savings (%)	87.8%	90.9%	87.8%	90.9%	87.8%	60.5%

removal process contributes to more subsystems being discarded.

Removal and Rework using a legacy liquid TIM like LSR requires the following steps:

- The entire Interface must be removed from the build because additional force required to separate the cured LSR.
- The next step is to disassemble the interface. The removed interface is usually placed on a flat surface. What type of force, how much force, how the force, and who applies the force can be interface specific. This is a time and resource consuming effort performed by experts. Special attention and time are required if one or both parts of the Interface will be reworked.
- The next step after disassembly is Rework. Reworking includes 1) removing critical components, 2) scraping cured LSR, 3) replacing perishable and damaged items, 4) re-purposing surfaces to within tolerances, and 5) finally cleaning and preparing surface for re-assembly.
    - Critical components that survived the disassembly process will need removing before rework begins.
    - Scraping is a manual process whose time and effort depends on the size of the interface. Sharp metal tools can expedite the scraping process at the expense of increasing surface damage to the Interface. Otherwise, less-abrasive tools like piano wire take significantly more time and manual exertion.
    - The forces associated with interface removal and disassembly and LSR scraping increase the number of damaged items needing replacement in addition to perishables consumed with all assembly builds.
    - Forces associated with LSR removal, disassembly, and scraping alter surfaces. At a minimum, the surfaces will need close inspection to ensure tolerances are met. Otherwise, surfaces need repurposing to meet tolerances.
    - Lastly, the reworked surfaces need cleaning and preparation for re-assembly.

The calculations do not include technician and engineer idle time when waiting for reworked subassemblies. However, it's worthwhile to point out how idle times due to LSR Removal, Rework, Re-install, and Reassemble will increase program cost. Assume one subassembly critical to system testing needs to be reworked and re-installed at spacecraft level. Furthermore, if the subassembly is mounted upside down or in a challenging orientation for LSR, then more assembly resources and time will be needed.

Carbon nanotube interfaces reduce the Removal and Rework time process by eliminating time and resource consuming removal steps resulting in significant time and cost savings.

- Options exist to disassemble the interface with the build because of the carbon nanotube gasket's peel-off capability. This capability allows non-essential parts of the Interface to remain in the build reducing handling costs and mitigating risk to subsystems. With the carbon nanotube gasket, interfaces can be disassembled in any orientation. The gasket can be removed with same exertion required to remove adhesive cello tape [11] significantly reducing time, energy, and resources. Lastly, no special attention and time is required. Manufacturers choosing to remove the entire interface from the build will be driven by build needs, not by forces required to separate Space Pad at the Interface.
- The next step after disassembly is Rework, if required. Reworking Interfaces using this carbon-nanotube based thermal gasket includes 1) Removing critical components and replacing perishable items and 2) inspecting, cleaning, and preparing surface for re-assembly.
    - Removal and disassembly of interfaces using carbon nanotube gaskets will result in reusability of more critical components and less damaged items.
    - The surfaces will need inspection to ensure tolerances are met if the assembly process alters the surfaces. Otherwise, the surfaces need cleaning and preparation for re-assembly.

EXAMPLE COST SAVING MODEL

The tables in this section summarize the cost savings realized by multiple spacecraft manufacturers. They independently shared the sum savings and could not share input conditions.

Here are the inputs for Case 1.

- 5 subassemblies totaling 144 in^2 interface area with complex bolt holes across multiple panels.

- 5 interfaces assembled, removed, and reworked **twice**, and reassembled **twice at the same time** onto the spacecraft.

Material cost can vary significantly depending on features and requirements of the interface. In practice, material costs for LSR and Space Pad carbon nanotube gaskets are comparable, but for the exercise of this comparison, it is assumed that the Space Pad solution was approximately 40% more expensive in up front material cost, to enable an examination of how this impacts total costs, including assembly and rework. We calculated inputs such as technician rate and floor space cost because they're confidential to our partners. We generated times for mixing, dispensing, applying, curing, inspecting LSR from our experience. Similarly, our in-house engineering experience was used to calculate LSR removal and rework times. Table 1 shows Space Pad net savings for Case 1.

Table 2 shows 57% net savings for Case 1 if the 5 interfaces were assembled, removed, and reworked **once**, and reassembled **once** onto the spacecraft.

Here are the inputs for Case 2.

- 5 subassemblies totaling 1000 in^2 interface area with complex bolt holes across multiple panels.
- 5 interfaces assembled, removed, and reworked **once**, and reassembled **once at different times** onto the spacecraft.

Table 3 shows Space Pad net savings of 69% for Case 2 with just 1 rework. The ~60% overall AI&T cost savings has not been refuted by other spacecraft manufacturers who have replaced LSR or similar legacy liquid TIM in their manufacturing process. In fact, independent evaluation performed by a large space prime for Case 1 resulted in a 62% cost savings using Space Pad.

Potential Cost Saving Impact of Space Pad

To envision the impact this predictable carbon nanotube based thermal gasket can have on an enterprise budget, one can look at the US Department of Defense. Over the next five years, the Pentagon plans to spend approximately $13 billion on military communications satellites [12]. As detailed in the published budget, this spend includes funding for the Pentagon's first low Earth orbit broadband constellation and a smaller number of communications satellites to either supplement the constellation or replace existing systems in orbit. When you combine this with the understanding that approximately 70% ($9.1B) of this projected spend is on the build of the satellite with the remaining on launch [3]. In addition, 20% of this build cost ($1.82B) is AI&T and Thermal budget. When you apply the 62% net AI&T savings enabled by implementing this predictable thermal gasket solution, the Department of Defense can save $1.13 billion of the 5-year planned total budget. This will be billions of taxpayer money saved by the US Government.

A practical example of the savings delivered by implementation of Space Pad both from thermal performance as well as its ability to be easily reworked was shared by a US satellite manufacturer. In this build, Space Pad was used under a software defined radio component for a high watt density microsat, which conducted more heat dissipation during transmit of the radio board and the electronics box housing. Interface temperatures improved with Space Pad, enabling the satellite to use less heater power in eclipse. In addition, the reworkability saved the satellite manufacturer

Table 2: Case 1 - Total Cost analysis of Space Pad vs LSR with 1 rework

	Assemble	Rework	Assemble	**Total**
LSR Material	**$117,855**	**$131,241**	**$117,855**	
Carbice Space Pad	**$14,392**	**$11,879**	**$14,392**	
Delta LSR - Space Pad	**$103,463**	**$119,361**	**$103,463**	
Net Cost Savings (%)	87.8%	90.9%	87.8%	57.7%

Table 3: Case 2 - Net Savings of Carbice Space Pad vs LSR with 1 rework

	Assemble	Rework	Assemble	**Total**
LSR Material	**$207,578**	**$231,162**	**$207,578**	
Carbice Space Pad	**$25,290**	**$23,416**	**$25,290**	
Delta LSR - Space Pad	**$182,288**	**$207,745**	**$182,288**	
Net Cost Savings (%)	87.8%	89.9%	87.8%	69.3%

money in development phases by saving components that were a struggle to purchase due to supply chain challenges. The effectiveness was further demonstrated during flight, and the customer is now flying higher power dissipation electronics and thrusters in small satellites with this predictable carbon-nanotube-based thermal gasket.

5. CONCLUSION

Getting the right thermal gasket is a critical, but often underappreciated aspect in building spacecraft. Incumbent thermal gaskets take a long time to cure, are difficult to install and thus prone to fail, and are prone to damaging the spacecraft if they need to be removed due to such failure. All of these problems happen on what is called “spacecraft serial time” – that is, time when the whole assembly team must wait until a single event is accomplished. Spacecraft famously take a long time to build - usually 3 or more years from an inked contract to a functioning mission. As with everything in society, there is a need to accelerate the DoD’s mission timeline to respond faster to fill urgent needs and stay ahead of competitors.

Additionally, spacecraft manufacturers have all experienced the 30+ years of pain dealing with the incumbent technology. Thus, various R&D programs have been conducted to find alternatives but with little progress, until now. We demonstrated that a predictable carbon-nanotube-based Space Pad successfully solves these problems by offering a thermal gasket that requires no curing, is easily reworkable, even reusable, and provides good performance.

This side-by-side comparison of the process of building a spacecraft with an incumbent thermal gasket (LSR) and with Space Pad showed significant simplification and timeline reduction. Our example cost saving model in a specific use case showed a >60% savings on AI&T can be achieved by switching from LSR to the predictable Space Pad. This finding agrees with spacecraft manufacturer’s independent evaluation from one of the largest space primes in the industry.

When scaled to every spacecraft interface in the DoD’s 5-year plan, over $1 billion of the DoD’s budget can be saved as a result of the benefits this predictable thermal solution provides. Additionally, critical components that would be damaged and need replacement as a frequent consequence of using and reworking incumbent thermal gaskets can be saved. This not only contributes to additional savings in taxpayer’s money, but also minimizes the risk of mission timeline delay due to the current global shortage of critical components.

Ultimately, the value of Space Pad in terms of cost savings should not only be viewed at book value because the acceleration of project timelines provides a competitive edge and opens up new opportunities to the space industry.

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