Mitigating the Impact of a Time-Dependent Production Process

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Submitted to the Sloan School of Management and the Engineering Systems Division in partial fulfillment of the requirements for the degrees of

Master of Business Administration
and
Master of Science in Engineering Systems

In conjunction with the Leaders for Manufacturing Program at the

Massachusetts Institute of Technology
June 2007

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Abstract
Value-added processes that bear associated wait times occur frequently during production manufacturing and increase cycle time. Since the wait time is integral to the value created by the process, it can be difficult to reduce the cycle time impact. The use of adhesives and the impact of their associated cure times is an example of such a time-dependent process and one that appears frequently on products made at Raytheon Space and Airborne Systems (SAS). Using a typical Raytheon pod system (RPS) as a case study, this thesis examines various ways to mitigate the impact of these value-added associated wait times (VAAWT) on cycle time. Adhesives with long cure and/or set times are used extensively throughout the design of this RPS in both structural and non-structural applications. Now that the RPS is well into full-rate production, the cycle time impact of these adhesives' VAAWT has become a burden, accounting for over 60% of the cycle time on the three assemblies studied on during the case study.

Both short-term and long-term solutions were developed as a result of this project, which enabled a 23% reduction in cycle time exclusive of changes in design. Based upon the lessons learned during this case study, a set of guidelines is presented for application to other time-dependent processes and Raytheon products. This thesis also discusses some of the barriers encountered during the implementation of this project and suggestions for overcoming them. These guidelines and lessons have already been applied successfully to reducing the impact of adhesive cure times on a second SAS product line, resulting in a cycle time reduction of 80%.

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Acknowledgements

This project could not have been completed without the support and assistance of many people.

I would like to thank everyone I met and worked with at Raytheon Space and Airborne Systems; it was a wonderful learning experience for me. In particular I am grateful for all the assistance I received from my supervisors at both sites - Pete Freeland and Alison Howlett. I would also like acknowledge the support of Jeff Bayorgeon, Dennis Coyner, David Shih, Clay Cooley, Don Magnuson, and the entire McKinney team.

I would like to thank the Leaders for Manufacturing program for providing me with the opportunity to expand my horizons and the environment in which to learn the skills to do so. It has been a rewarding two-year journey. I would also like to thank Professors David Hardt and Roy Welsch for their invaluable knowledge and feedback as I prepared this thesis.

Finally, I would never have made it this far without the support of my family. To my parents: Thank you for teaching me to believe in myself and my abilities and to always strive for the best. To my sister: From the admissions essay to the thesis, you've been an excellent advisor during LFM and a great role-model always.

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1 Introduction

This thesis builds upon lessons learned during a six-month internship in the Advanced Manufacturing Department at Raytheon Space and Airborne Systems in El Segundo, California. The project focuses on the effect that time-intensive processes, specifically the curing of adhesives, can have on production cycle time and examines ways to minimize that impact in both the short and long terms. This chapter will explain the importance of this investigation as a whole within the arena of manufacturing and provide some specifics regarding the particular case study conducted at Raytheon.

1.1 Thesis Motivation

The interests of manufacturing efficiency necessitate the constant pursuit of cycle time reduction. These cycle time gains can be achieved by following the primary principle of Lean Manufacturing – remove waste. Under the Lean methodology, process steps are typically divided into two categories – *value-added* and *non-value-added*. The latter category is associated with waste; thus, cycle time reduction usually entails identifying non-value-added process steps and determining ways to remove them from the assembly sequence.

With a straightforward assembly sequence, the "blocks" of non-value-added time occur as independent entities, e.g. time spent accumulating batches of product to move between operations instead of utilizing single-piece flow. A schematic of this process is shown in Figure 1, where the solid green blocks are value-added operations and the red-striped blocks are non-value-added wait times.

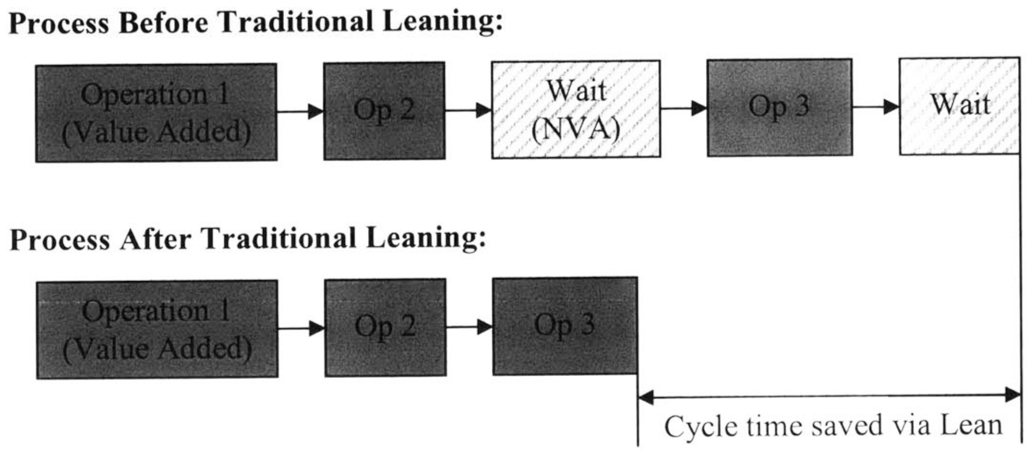

Figure 1 - Cycle Time Savings Acheived through Typical Lean Efforts

Occasionally a third category, *non-valued-added but required*, is used to describe those activities which do not directly add value to the product but cannot be removed from the system. For example, at an automobile manufacturer which utilizes a main assembly shop and a separate paint shop, each vehicle must be transferred between the two shops, and while the application of paint adds value to final vehicle, the transfer time does not. One way to remove this non-value-added transfer time would be to paint each car as it moved down the line in the main assembly shop. However, for environmental reasons and to achieve economies of scale, it is more operationally efficient to keep the paint process in the separate plant and move the cars back and forth. Therefore, the transfer time would be classified as *non-value-added but required.*

The difficulty faced by Raytheon and the motivation for this thesis is dealing with a fourth variation, which will be called *value-added associated wait time (VAAWT).* VAAWT is a process that only adds value when directly tied to another value-added process and is comprised primarily of wait time. Again consider the application of paint to a car. The customer desires a blue vehicle, so the physical application of blue paint is a value-added process. The associated drying time for that same paint, however, is VAAWT. The value "added" by the paint is only achieved by allowing it to dry (the car is not protected from rust until the paint cures), but the act of drying necessitates waiting and prevents further assembly from being performed on the vehicle. This scenario is represented in Figure 2, where Operations 2 and 4 consist of both a value-added portion and a VAAWT cure component. Since the VAAWT combines traits associated with both value-added (transforming the paint to its useful state) and non-value-added (waiting) processes, its duality is represented by the use of red and green shading.

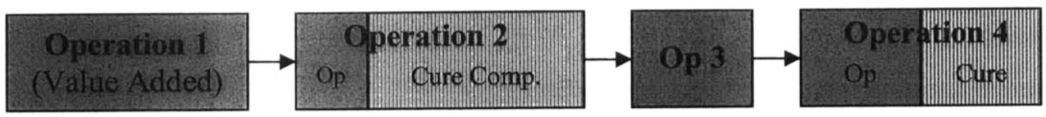

Figure 2 - Process with Value-Added Associated Wait Time

Ordinarily under Lean, wait time and assembly delays would be classified as *non-value-added* and ways would be sought to remove them. In this case, however, it is not possible to remove the wait time without also eliminating the associated process' value. The best-case scenario, therefore, is to minimize the impact this VAAWT has on the product's overall cycle time. This thesis explores ways to achieve this impact minimization via a case study performed at Raytheon SAS in which adhesives and their associated cure times represent the VAAWT. The lessons learned from the short and long-term solutions developed during that study are then generalized to create guidelines for dealing with any VAAWT processes. As these guidelines have already been applied to another SAS product, a second case study is also presented in Section 7.2.

1.2 Thesis Structure

This thesis is organized into 8 chapters:

Chapter 1 explains the motivation for this thesis. It also contains background information regarding Raytheon and the product line used for the primary case study.

Chapter 2 describes the military's configuration management requirements and the unique constraints they presented to this investigation.

Chapter 3 focuses upon the use of adhesives and both defines terminology specific to Raytheon and provides technical background relevant to the case study.

Chapter 4 evaluates the impact of adhesives on the product line being studied and the goals for the project.

Chapter 5 explains the improvement options uncovered over the course of this investigation.

Chapter 6 describes the changes made during the project and the cycle time savings achieved.

Chapter 7 discusses the relevancy and applicability of the lessons learned on this project to future projects and product lines at Raytheon.

Chapter 8 summarizes the project and thesis.

1.3 Company Background

Raytheon Company is "an industry leader in defense and government electronics, space, information technology, technical services, and business aviation and special mission aircraft."[1] With over 80,000 employees worldwide, Raytheon is comprised of seven major businesses and produces a diverse portfolio of products.

Raytheon Space and Airborne Systems (SAS) grew, in part, out of the former Hughes Aircraft Company and is based in El Segundo, California. The division develops advanced sensor technology for a variety of civil and military applications and reported sales of $4.3 billion in 2006.[2] Radar technologies developed and built at SAS are used primarily for avionics, surveillance, and fire control in military planes, but are also applied to programs in missile defense and space exploration.

The internship that served as the basis for this thesis was conducted primarily from the main El Segundo plant, but significant data collection and site work also occurred at the manufacturing facility in McKinney, Texas. The latter site, an acquisition from Texas Instruments, performs some of the full-rate production for SAS.

[1] http://www.raytheon.com/about/

[2] Raytheon Company 2006 Annual Report

1.4 Case Study Background

This section describes the product line studied and some operational practices and terminology that are specific to Raytheon and applicable to this case study.

1.4.1 Raytheon Pod Systems and the Electro-Optical Sensing Unit

Some of the primary product lines built by SAS are navigation systems for military aircraft. Each of these products, which henceforth will be described as a Raytheon Pod System (RPS), typically integrates multiple capabilities for weapon targeting and flight navigation into a single unit.

The typical RPS embodies a standard structure with three main components: the Electro-Optical Sensing Unit (EOSU), the electronics housing, and the structural housing (Figure 3). The EOSU contains most of the mechanical and optical components essential to the functionality of the RPS. Accordingly, the EOSU assembly drives the critical path, which made it a logical choice to serve as the basis for the case study. This narrowed focus made short-term improvements manageable in scope, but still allowed for long-term, wide-spread applicability to other RPS lines and other types of Raytheon products.

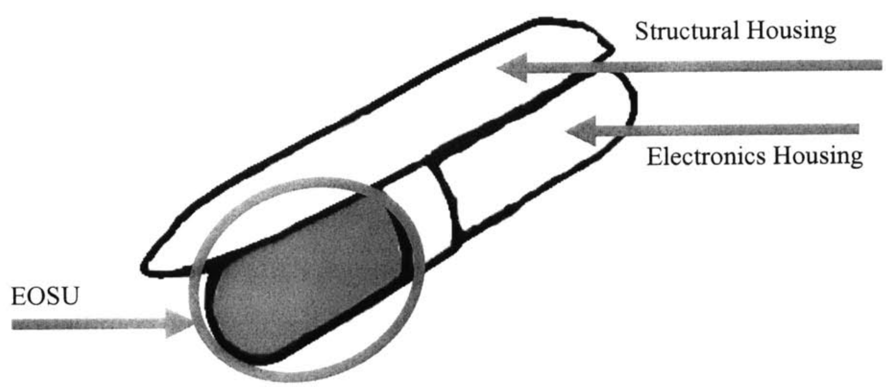

Figure 3 - Schematic of a Typical RPS

The EOSU chosen for this study exemplifies a typical system built by Raytheon. Initially developed as a prototype system for several new technologies, this RPS has now been in full-rate production for several years. During this time improvements have been made to reduce the cycle time and cost, but there is continued pressure to make further gains.

1.4.2 Production Timeline

The development cycle for SAS products begins with a design and prototype process. Once the prototypes have reached a satisfactory level of manufacturability, the product is launched into low-rate production. Over time, this production rate is increased, while incorporating process and design improvements, to achieve full-rate production (FRP). For this RPS, FRP was simultaneously ramped up at the McKinney plant and ramped down in El Segundo. By ultimately manufacturing the mature product line solely in McKinney, Raytheon is able to maintain a high level of product quality at a lower overall production cost.

Due to a change in customer needs for the RPS studied, the entire design and prototype process was compressed to roughly one-third of the intended schedule time. As will be discussed later on, this altered timetable is thought to be a primary factor for much of the VAAWT present on this RPS.

1.4.3 Raytheon Documentation Methods

The EOSU is a five-tier indentured structure made up of nearly 100 sub-assemblies, each of which has its own print drawing. These lowest-level assemblies are combined into upper-level sub-assemblies through additional drawings. Parts are thereby combined through new drawings into larger and larger sub-assemblies until the complete EOSU is achieved. Each drawing is converted into a single, revision-controlled work instruction which is made up of numbered line items called operations. An operation groups a task or set of tasks together into logical build steps for the technician. In the case of adhesives, their use is typically achieved through notes and references on the drawings, and these notes are then converted into separate operations in the work instructions. Work instructions combine both text and visual imagery, thereby standardizing the step-by-step assembly process and allowing production work to be transferred between the El Segundo and McKinney facilities with ease.

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2 Initiating Change on Government Products

One unique characteristic of this case study is the constraint imposed by the government's configuration management practices, which are used to maintain consistency across a product line. An overview of these policies is provided in this chapter and their direct impact on the case study will be discussed in Chapter 4.

2.1 Configuration Management Policies

Military Handbook 61A, *Configuration Management Guidance*, contains the guidelines that the military institutions follow in order to maintain consistent configuration management (CM) for their products. As explained by this document:

> Configuration management is defined as a process for establishing and maintaining consistency of a product's performance, functional and physical attributes with its requirements, design and operational information throughout its life.[3]

Under proper CM practices a baseline configuration is established for a given product and defined in configuration documentation. All "configuration items" are then uniquely identified and verified for conformance against these documents. In order to make any changes to the configuration of any product, therefore, the appropriate changes must also be made to the configuration documentation. As described in the handbook, the change process is as follows:

> Whenever a change is contemplated to an item, the effect of that change on other items and associated documents is evaluated. Changes are systematically processed and are approved by the appropriate change control authority.
>
> Change implementation involves update and verification of all affected items and documentation. Information about item configuration, document identification and status, and change status is collected as activities associated with the CM process occur. This configuration status accounting information is correlated, maintained, and provided in useable form, as required.

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[3] MIL-HDBK-61A, 1-3.

> The responsibility for the CM process and supporting activities is shared between the Government and the contractor and will usually vary according to the acquisition philosophy (performance or design-based) and according to the phase of the life cycle.[4]

As would be expected, the changes being made to the production processes of Raytheon-built products for military use often fall under the province of this CM change process. Predominantly the changes fall into the category of Engineering Change (EC), which is a "change to the current approved configuration documentation of a configuration item [or any] alteration to a product or its released configuration documentation."[5] Engineering changes are further classified into either Class I or II changes, where the former covers more significant changes that impact form, fit, or function. The official definitions can be seen in Figure 4. An Engineering Change Proposal (ECP) is used by the contractor to suggest an EC and it initiates the change process.

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[4] MIL-HDBK-61A, 1-5.
[5] MIL-HDBK-61A, 3-6.

Class I Criteria:
An ECP proposing a change to approved configuration documentation for which the Government is the CDCA or that has been included in the contract or statement of work by the tasking activity, **and**:

(1) affects any physical or functional requirement in approved functional or allocated configuration documentation, **or**
(2) affects any approved functional, allocated or product configuration documentation, **and** cost, warranties or contract milestones, **or**
(3) affects approved product configuration documentation **and** one or more of the following:

(a) Government furnished equipment,
(b) safety,
(c) compatibility, interoperability, or logistic support,
(d) delivered technical manuals for which changes are not funded,
(e) will require retrofit of delivered units,
(f) preset adjustments or schedules affecting operating limits or performance to the extent that a new identification number is required,
(g) interchangeability, substitutability, or replaceability of any item down to non-repairable subassemblies,
(h) sources on a source control drawing,
(i) skills, manning, training, biomedical factors or human engineering design.

Class II Criteria:
An ECP proposing a change to approved configuration documentation for which the Government is the CDCA **or** that has been included in the contract or statement of work by the tasking activity, **and** which is not class I.

Figure 4 - Definitions of Class I and II Engineering Changes[6]

2.2 Impact of Configuration Management on Manufacturing

The complexity and length of the CM process, while assuring consistency of government products, often has an adverse effect upon contractors. The stringency of these guidelines often causes contractors to avoid initiating changes that would initiate the official engineering change process. Essential engineering changes are always submitted, but changes that might improve manufacturability are often overlooked if the burden of the Class I change process outweighs the immediate benefits to production.

[6] MIL-HDBK-61A, 6-16 ff. The CDCA is the Current Document Change Authority, or the agency that is responsible for the content of the configuration documentation and the only authority that can make changes to those documents. In this case, Raytheon's customer for the RPS.

Not surprisingly this drawback of the CM process impacted this pilot project as well. As process changes were proposed and evaluated for implementation on the RPS, it was always necessary to determine if the change would alter the "form, fit, or function." If it did, the change was classified as Class I and implementing it would necessitate invoking the EC process. Given the length of the EC process relative to the timeframe for conducting the case study, the classification of proposed process changes into either Class I or II ultimately became a classification of a long-term vs. short-term implementation horizon. Therefore, the changes explored and implemented on this RPS will be discussed in keeping with this secondary classification.

One strategy that Raytheon has developed for overcoming the burden of the EC process is to aggregate non-critical changes. Instead of initiating an ECP each time a manufacturing process improvement is discovered, the opportunities are submitted to a centralized review board. They are then evaluated with respect to their feasibility of implementation and savings potential. Eventually, at a convenient point in time (such as a when the contract for a new model is being negotiated), a consolidated list of changes is presented to the government for consideration. In this way, Raytheon has succeeded in making improvements to manufacturability while still honoring the CM guidelines.

3 Technical Background on Adhesive Usage and Fasteners

Adhesives with long cure and/or set times are used throughout the construction of an RPS, and in keeping with Raytheon convention, their usage is described as either "bonding" or "staking" depending upon the application. This chapter defines these two terms and explains their importance to the RPS studied.

3.1 Bonding

Bonding refers to the situation in which two materials are joined together with adhesive (Figure 5). An adhesive might be used in lieu of a mechanical fastener in this situation due to physical constraints or difficulty of assembly. In addition, additives to the adhesive, such as glass beads, can provide electrical insulation – conductivity between parts being of particular concern in most electrical products. In some cases, this use of a structural adhesive occurs in addition to the use of a mechanical fastener for the purpose of design redundancy on a functionality-critical or an alignment-critical component.

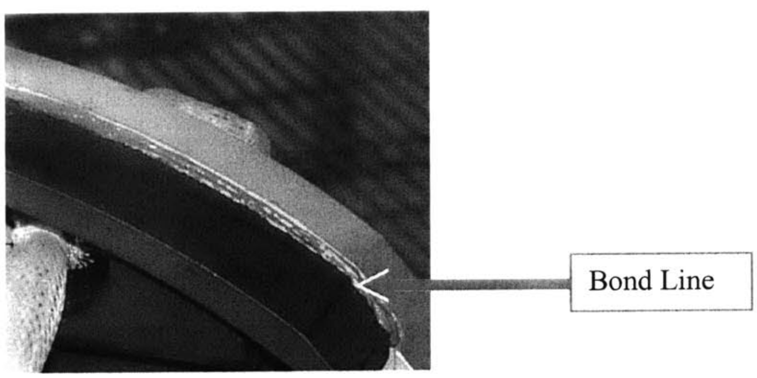

Figure 5 - Representative Bonding Application

The strength of a bonded joint is dependant upon two things: "(1) the bonding strength between the adhesive and the substrate, *adhesion*, and (2) the strength within the adhesive, *cohesion.*"[7] Improper substrate preparation and poor adhesive selection are the most common causes for bonded joint failure and lead to "adhesion failure" or "cohesion failure" respectively.[8] In order to avoid the latter failure, a number of material properties, such as strength and durability, must be checked when selecting an adhesive. Also, the RPS is subjected to a variety of cyclical loads due to operational vibration, temperature variations (both during operation and due to thermal expansion stresses when bonding dissimilar materials), and load-stress cycles. Unfortunately, "cyclical stresses, particularly slow ones, are much more damaging to an adhesive joint than a steady stress,"[9] which reinforces the use of a redundant mechanical fastener system on a bonded joint.

3.2 Staking

The term staking is used on the RPS to describe two different processes – an adhesive being used to secure alignment-critical parts or (more frequently) a specific fastener locking feature wherein an epoxy locking compound is applied over the head of the fastener (Figure 6). The latter application is termed "screw staking" and has the benefit of providing a quick visual reference to see if fasteners have moved.

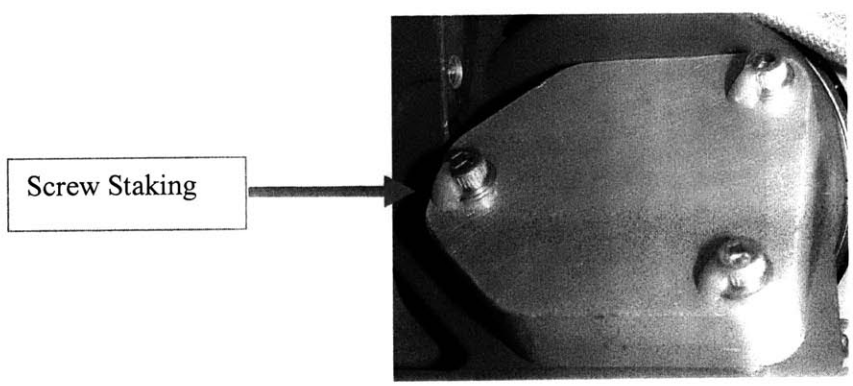

Figure 6 - Representative Screw Staking Application

[7] John Cocco, "Adhesives and Sealants for Bolting," in Handbook of Bolts and Bolted Joints, eds. John H. Bickford and Sayed Nassar, 57.
[8] Ibid., 57.
[9] Ibid., 61.

In the past at SAS, screw staking was used as a locking feature and therefore appears frequently on this RPS (the full history follows in Section 3.2.1). While screw staking does provide a quick visual reference to see if fasteners have moved, it does not provide a reliable locking feature (the technical need for locking features is discussed in Section 3.3). In 2005, a study performed at Raytheon Missile Systems (RMS) demonstrated that screw staking typically sheared off at a fraction of the fastener's installation torque. Building upon this evidence, it has been decided that screw staking does not reliably prevent fastener loosening and an effort has been made to prohibit its future use as a locking feature. In the meantime, screw staking has two deleterious effects on production – adding considerable amounts of assembly and cure time to overall cycle time and providing the opportunity for foreign object debris (FOD) should the adhesive come loose. Clearly, the former disadvantage provides the impetus for this investigation. The latter drawback, however, is particularly serious on an RPS, which contains a number of sensitive optics systems and is assembled under cleanroom conditions. Even if properly applied, as the RMS study showed, there is the possibility that the adhesive staking could come loose. Should one of these pieces of FOD adhere to an optical part or become wedged between moving parts it could compromise the functionality of the system. For the time being, however, screw staking represents an integral part of the RPS design and a burden on production cycle time.

3.2.1 The Usage of Screw Staking on RPS

Screw staking has been used in manufacturing at Raytheon for at least 20 years. The precise technical basis that motivated its initial use has largely been lost over time, and instead it has been adopted as a common engineering practice. Within the last few years, however, more formal fastener design guidelines have been developed. Through efforts driven largely by the Electro-Optical Sensor Subsystems Department in El Segundo, two fastener design reference manuals – one for space applications and one for tactical applications – have been released for use across Raytheon. While both of these documents encourage the use of at least two locking features per fastener, they also both clearly state that screw staking is not a preferred secondary locking feature. These statements helped provide the necessary technical justification for the long-term changes initiated during this project and discussed in Section 6.2.

On this particular RPS, there is only anecdotal evidence for the abundance of screw staking and it is rooted in the cultural and political situation that surrounded the design of this pod. Through the technical expertise of its highly-regarded engineers, Raytheon has continually developed cutting-edge technologies over the years. Often the products start as prototypes, which are assembled by hand in the shop as a way of testing out several advanced capabilities. As the story is told for this RPS, "The good news was that it worked. The bad news was that it worked." Once Raytheon demonstrated via the first prototype that the technology they proposed was viable, the customer wanted production to begin immediately. This request led to a dramatically shortened design and prototyping timeframe, as mentioned in Section 1.4.2.

It is purported that screw staking was used as a locking feature during initial prototyping of this RPS because it provided a visual reference and was more easily removed. By using screw staking the engineers could quickly determine which fasteners had been torqued into place and could also more easily disassemble the product than if threadlocking compounds were used. Once the design schedule was reduced, it was necessary to develop manufacturing drawings and work instructions more quickly than normal. Every last detail from that first working pod was recorded and incorporated into the final design because no one was entirely sure which details were responsible for the product's initial success and there was no longer time to investigate. There also wasn't time to develop more appropriate locking features, and screw staking became integrated into this RPS.

While this story might be a bit of an exaggeration, there is at least a fair bit of truth behind it. Design for Manufacturing is not fully-integrated into the company culture, so it's not unreasonable that the practices followed during prototyping would not be questioned when applied to the final design. Unfortunately, the process to undo these practices is made more difficult by the issues of configuration management discussed in

Chapter 2. At the end of the day, staking remains well-ingrained into the design of the RPS and continues to burden production years later.

3.3 Technical Background on Fastener Retention

3.3.1 The Mechanisms of Self-Loosening

Threaded fasteners are commonly used in production because they are easily removable, but this advantage also engenders their primary disadvantage – self-loosening.[10] The assembly is able to loosen itself when sliding movements occur between the contact surfaces which overcome the frictional forces of the threads. This process is described with the following equation:

$$M_L = F_V \frac{d_2}{2} \tan \rho + F_V = \mu_A r_A - F_V \frac{d_2}{2} \tan \phi \qquad (1)$$

where

M_L = self-loosening torque

F_V = available prestress force

d_2 = pitch diameter of thread

ϕ = helix angle of thread

ρ = angle of friction of thread

μ_A = coefficient of friction of bearing surfaces

r_A = lever arm of frictional force at the bearing surfaces

If the binding force of the threaded assembly cannot prevent relative movements between the parts under stress, then the threads are able to slide over one another and the loosening torque reduces to

$$M_i = F_V \frac{d_2}{2} \tan \phi \qquad (2)$$

[10] Much research has been done examining the phenomenon of self-loosening, but the basic force components involved are generally the same from study to study. Thus, the technical discussion that follows is taken (nearly verbatim) from Cocco, 61ff as a representative explanation.

This loosening moment, M_i, is dependent only on the prestress force, the pitch diameter, and the helix angle of the thread, and it acts against the direction of tightening causing the assembly to loosen. Sliding movements between the contact surfaces can be caused by

1. Dynamic load in the direction of the axis. A pulsating axial overload leads to a relative movement at the flanks of the thread.
2. Dynamic load at right angles to the direction of the axis. If the materials of the assembled parts have different thermal expansion rates this can occur. Bending, repeated impacts, or vibrations can also overcome the forces of friction between the bearing parts.

In the case of the RPS, thermal expansion and vibration are present under normal operating conditions, so fastener self-loosening is quite likely. By design all fasteners on the RPS have an applied torque, which is used to create the prestress necessary by Equation (2).

However, there are two drawbacks to relying upon torque to prevent self-loosening. First of all, "torque is not the most precise method of controlling clamping load, although it is the most common. When bolt and nut manufacturing is closely controlled, the tension produced in a bolt for a given torque varies up or down by 15 percent."[11] Secondly, in a threaded assembly "about 85 percent of the torque and effort of tightening a bolt is absorbed by the friction in the threads and under the head. Only 15 percent produces clamping load. Therefore, high torque may be absorbed by high friction and not produce tension."[12] As a consequence prestress alone is not enough to prevent self-loosening, and additional assurances are necessary. The self-loosening situation is summarized in Figure 7.

[11] Robert A. Valitsky, "Keeping Threaded Fasteners in Their Place," http://www.mt-online.com/articles/10-99log.cfm.
[12] Ibid.

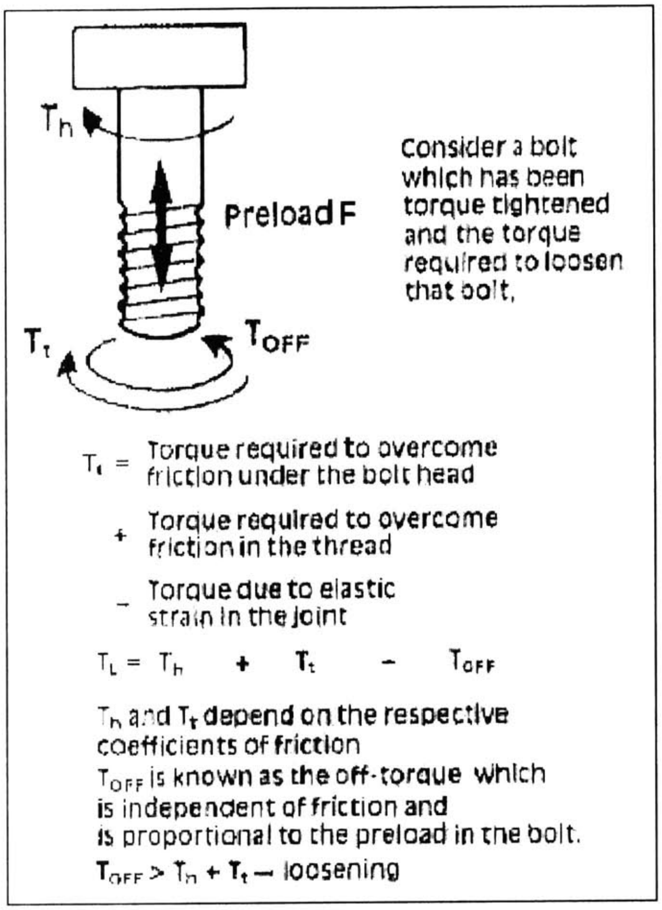

Figure 7 - Diagram of Self-Loosening Forces[13]

3.3.2 Common Methods for Preventing Self-Loosening

Since self-loosening can be caused by common operating conditions, many methods have been developed over time to lock the fastener into place. These locking features can be divided into four main categories: "(1) free running preload-independent locking fasteners, (2) free running preload-dependent locking fasteners, (3) prevailing torque locking fasteners, and (4) chemical locking."[14]

The first two categories of free running fasteners are installed normally and then an additional locking feature is added that may or may not depend upon the fastener's

[13] D. J. Light, "Vibration Loosening of Threaded Fasteners," Chartered Mechanical Engineer, v 30, n 5, May 1983, 58.
[14] Daniel P. Hess, "Vibration- and Shock-Induced Loosening," in Handbook of Bolts and Bolted Joints, eds. John H. Bickford and Sayed Nassar, 806-807.

preload. Some examples of preload-independent locking features are cotter pins, lock wire, and tack welding of the fastener head. Screw staking would also fit into this category. For the most part, preload-independent features can be difficult (if not impossible) to remove and can require precise alignment for installation. These drawbacks make them a poor choice on the RPS studied, which demands fastener removability and has many fasteners located in difficult to reach locations. The most common preload-dependent feature is the lock washer, which compresses when the fastener is tightened and then adds to the fastener tension. Lock washers are used extensively on the RPS because they allow for easy removal and can be inexpensively replaced if necessary after use.

Prevailing torque locking fasteners require additional torque to assemble and disassemble because they use thread interference to provide locking. Examples in this category are metallic fasteners with modified threads and fasteners with a non-metallic insert. The former fastener provides thread interface through the shape of the fastener itself (i.e. non-circular cross-section) or the design of the threads. The latter example uses a second material, usually nylon, to provide thread interference through friction.

The final category, chemical locking, encompasses anaerobic adhesive compounds that are applied directly to the threads. Fasteners that have been locked in this way can generally be removed, but do require proper cleaning in order to be reused. In the case of the RPS, anaerobic compounds are used extensively because they are easily installed in even the tightest spaces, lock the fastener reliably, and do not require additional parts. However, there have been concerns raised at Raytheon in the past regarding the generation of FOD when removing fasteners installed with these adhesives.

Overall, preventing fastener self-loosening is an important design consideration and one that is not always reliably achieved. Because the fastener can begin to loosen due to loads along more than one axis and many locking features operate against a single axis, it is often necessary to use multiple locking features to achieve reliability.

4 Evaluating the Impact of Bonding and Staking on the EOSU

As discussed above, a single EOSU was chosen for this study since it represented the critical component of the RPS studied. Although it was known that adhesives posed a significant bottleneck in the EOSU's assembly, their true impact was largely unknown. The first step in this investigation, therefore, was to determine the extent to which adhesives were impacting cycle time.

4.1 Prioritization of Operations

In order to collect the necessary qualitative and quantitative information around adhesives use on the EOSU, the following process was followed:

1. **Created database of all bonding/staking operations on the EOSU**

   The first step in the process ultimately proved the most critical one, as it dictated the rest of the prioritization process for this assembly. During this stage, the work instructions for the entire EOSU were systematically studied and a database of all the adhesive-related operations was created. This activity generated a list of roughly 100 operations spread throughout the build process from the smallest component assembly through the final EOSU closure.

2. **Created database of all materials used in these operations**

   Working from the database created in Step 1, a comprehensive material list was developed. It categorized all the adhesives used during the assembly of the EOSU by type, class, and style.[15]

[15] This exercise also revealed several typos on the work instructions, the removal of which eliminated the remote chance of material misuse.

3. **Mapped and walked the process to better understand critical path**

   The first two steps helped create a picture of when and where bonding and staking were occurring during assembly. On paper, however, it was difficult to understand the whole picture. Instead, this was best achieved by watching production, so FRP in McKinney was observed over a period of several days. This process not only enabled the author to quickly understand the production flow that was not evident from studying the assembly tree, but also provided the ideal opportunity for conversations with the technicians. Overall, these discussions provided some of the most useful insights into the use of adhesives on the EOSU. Because production has been on-going and evolving for years, the technicians have an excellent sense for what does and does not work for them during assembly. Their familiarity with the product allowed them to notice opportunities that spanned assemblies and drawings; changes that would not typically be obvious by studying the documentation alone.

   From these conversations, it also became obvious that some assemblies and bonding/staking steps posed a much larger obstacle than others, and it was possible to narrow the focus of the project to the most critical assemblies. By taking a closer look at the operations highlighted by the technicians and comparing them back to the database created in Step 1, it was discovered that five key assemblies accounted for over 40% of all the adhesives' operations on the EOSU. In addition, these five assemblies were built in series, dictated the cycle time to completion, and were the only assemblies to contain at least three separate bonding and staking operations.

4. **Collected cycle time data for critical assemblies**

   The next step was to collect cycle time data for the EOSU. General cycle time metrics were being tracked for each sub-assembly and the EOSU, but this data did not provide enough information regarding the specific bonding and staking processes being studied. Instead, more detailed data was culled from the electronic work tracking software, which could be used to assign times to each operation in the work instructions for the five key assemblies. This data set was validated against several other sources, including time-motion studies, material specifications for the cure cycles, and the operators.

Shortly after developing the cycle time data for the five assemblies, the list of study was shortened to only three assemblies. The work instructions for two of the assemblies were undergoing radical revision at the time of this study, so it was deemed counter-productive to modify a production process that would no longer exist in a few months' time. The remaining three assemblies, however, still accounted for 25% of all adhesive operations on the EOSU.

Based upon the knowledge gained from this process, the final scope for improvements was narrowed to three key assemblies, which will henceforth be referred to as Assemblies A, B, and C. These assemblies accounted for a significant portion of the VAAWT (value-added associated wait time) and effort related to adhesive curing during EOSU assembly.

A generalized form of the process described above should be applied during future time-mitigation efforts, as it outlines a simple but thorough methodology for collecting all the quantitative and qualitative data necessary in order to successfully modify the production processes on an existing product. Performing Steps 1 and 2 made it possible to understand the nature and impact of each operation that included VAAWT. When aggregated into a single database, the operations' impact on the entire production process was more readily observed as well. Progressing into Step 3, the information from the first two steps could be physically observed in the plant and confirmed with the practical knowledge of the technicians. Finally, Step 4 quantified what had been learned from the previous three steps, which could ultimately be used to calculate project improvements. Overall, each of the four steps provided knowledge and data essential during the rest of the project. It is a methodology that is applicable to products at any point during their lifecycle – from design to many years into production – and to any type of time-dependent process.

4.2 Cycle Time Impact of Bonding and Staking on the EOSU

The data collected during the prioritization process quantified the amount of time being lost to material cures. Up until this point, bonding and staking had been identified as bottlenecks in the build process, but the true extent had been unknown. As can be seen in Table 1 - Table 3, the impact on each assembly was significant.

	mins.	hrs.
Mechanical Assembly Steps	1077	17.9
Adhesive Application Steps	160	2.7
Total Mechanical Assembly Time	**1236**	**20.6**
Total Cure Time	540	9.0
	43.7%	**Percentage of time spent curing vs. assembling**

Table 1 - Cycle Time Data for Assembly A

	mins.	hrs.
Mechanical Assembly Steps	710	11.8
Adhesive Application Steps	30	0.5
Total Mechanical Assembly Time	**740**	**12.3**
Total Cure Time	1200	20.0
	162%	**Percentage of time spent curing vs. assembling**

Table 2 - Cycle Time Data for Assembly B

	mins.	hrs.
Mechanical Assembly Steps	405	6.8
Adhesive Application Steps	101	1.7
Total Mechanical Assembly Time	**506**	**8.4**
Total Cure Time	2160	36.0
	427%	**Percentage of time spent curing vs. assembling**

Table 3 - Cycle Time Data for Assembly C

Between these three assemblies, 65 hours of time was being lost to the curing of adhesives (Table 4). This amounts to over 1.5 times the value-added labor overall and a staggering 13.5 times the amount of value-added labor for adhesive application. Even considering just 25% of the total instances, the use of time-dependent adhesives was increasing the cycle time of the EOSU significantly.

	mins.	hrs.
Mechanical Assembly Steps	2192	36.5
Adhesive Application Steps	290	4.8
Total Mechanical Assembly Time	**2482**	**41.4**
Total Cure time	3900	65.0

157%	**Percentage of time spent curing vs. assembling**
1343%	**Percentage of time spent curing vs. applying adhesives only**

Table 4 - Cycle Time Data Summary for Assemblies A-C

4.3 Goal of Project and RPS Program

Having recognized the impact that the VAAWT was having on the EOSU, the goal of this project fell in line with the overall RPS program goal – to reduce production cycle time. The data collected during the project-scoping process corroborated the "hunches" had by the production staff.

Prior to this project, the RPS program was aware of time being lost due to adhesives, but did not understand the overall impact to cycle time. There were numerous cases of production flow being stalled due to an assembly curing in an alignment fixture, and the bottleneck presented by adhesives was a problem that had been attacked in the past. Strategies tried up until this point included the following:

- **Judicious use of alternate materials:** The adhesives used on the EOSU are clearly specified and governed by Raytheon process specifications. In many cases, however, these documents permit the use of a few approved alternate materials. The production team was, therefore, able to remove some non-value-added cycle time by choosing the alternate adhesives with the shortest cure times.

- **Flexible application of cure schedules:** The Raytheon material specifications also present multiple methods for achieving full cure of an adhesive. Typically these methods range from performing the entire curing process at room temperature (the longest method) to conducting it through a high temperature oven cure (the shortest). It can also be possible to apply a combination of room and oven cures to achieve the full material strength. Rather than dictate that a single process should always be used, the technicians were given the freedom to apply an appropriate cure for each situation. For example, if the cure step was reached near the end of the day, it was more appropriate to use a room temperature cure since, unlike an oven cure, it could be performed between shifts and without delaying production. On the other hand, a quick (relatively-speaking) oven cure might make more sense on an assembly already behind schedule. This flexibility in production enabled some cycle time savings that might have been lost by blindly using the theoretically shortest cure schedule (i.e. oven curing at all times).
- **Reducing the number of adhesive operations:** Work instructions are typically generated using the most logical build sequence. Unfortunately, this sequence is not always the most efficient one from a cycle time standpoint. For example, on a two-sided product it would seem reasonable to assemble the left side fully before moving to the right side. If there was an adhesive cure associated with each side, however, that would result in an instruction sequence of build left, cure left, build right, cure right. By reordering the work instructions, the sequence could become: build left, build right, cure completed assembly. Under this paradigm, the production team combined and rearranged operations where practical in order to reduce the number of cure cycles necessary.

Using these types of strategies, reductions to cycle time as caused by adhesives had been made (over 30 hours had already been removed from Assembly A's cycle time prior to this investigation), but it continued to plague production. The overall hope was that through this investigation new methods might be found for mitigation of these processes' impact.

4.4 Impact of Configuration Management on Cycle Time Reduction of the RPS

As discussed in Chapter 2, the government's configuration management policies classify production changes into Class I or II depending upon their impact to form, fit, or function. During this case study, categorizing proposed changes to bonding and staking operations into one of these classes ultimately became a classification of a long-term or short-term implementation horizon. The impact of this classification system upon the two main categories of adhesive use is as follows:

Screw Staking

As discussed earlier, screw staking is one of the primary uses of adhesives on this RPS. On the three assemblies studied on this RPS, screw staking accounts for 58% of all adhesive operations (Table 5) and a blanket solution would offer a significant impact to the overall cycle time of the product. Since the usage of screw staking has already been shown to be technically unjustified on this product (Section 3.2), it could theoretically be removed from the RPS without impacting functionality. Its removal, however, presents a particular problem in the context of CM. From an engineering perspective, all instances of screw staking could be removed from the RPS under one of two possible rationales:

1) The staking exists in the presence of two locking features already, thereby making it redundant, or
2) the staking can be replaced with a more suitable secondary locking feature.

However, any changes that would be made under these situations would necessitate a drawing change, and therefore, fit into the realm of a Class I engineering change. For this reason, the outright removal of screw staking from the RPS could not be completed during this case-study. Instead various short-term solutions were implemented (Section 6.1) that immediately reduce the cycle time associated with screw staking. In the long-term, a Class I change is being pursued that could eliminate all the associated cycle time (Section 6.2).

Assembly	Screw Staking	Structural Adhesion
A	60%	40%
B	50%	50%
C	60%	40%
Total	**58%**	**42%**

Table 5 - Breakdown of Adhesive Operations by Category as a Percentage of All Adhesive Operations

Structural Adhesion

The remainder of the adhesive operations can be classified as structural adhesion. These operations include bonding of parts to one another (with or without additional mechanical fasteners) and permanently staking parts into alignment-critical positions. Unlike the screw staking, these types of operations are typically immutable with respect to the design. Cycle time savings to be garnered from these operations, therefore, require more creativity. A reasonable amount of time can be saved without necessitating a Class I change, and these activities were implemented for immediate gains on this RPS (Section 6.1). More significant savings could be had with long-term, Class I-type efforts, which will be discussed in Section 6.2 but could not be pursued in the time-frame of this study.

5 Available Improvement Options

Over the course of this project several options were considered as means to mitigate the impact of value-added associated wait time (VAAWT). They will be discussed in detail in this chapter.

5.1 Materials Changes

5.1.1 Modifying the Cure Process

For many epoxies there are multiple ways to reach the final, cured state. For example, an oven-only cure vs. a short air cure plus an oven cure vs. a very long air cure. By taking into account the configuration of the assembly at the time of bonding or staking, it is often possible to find a cure procedure that combines several curing methods so as to minimize cycle time and maximize the quality of the adhesion. Optimizing cure time for the application is a short-term strategy with immediate benefit and no CM impact. It does require input from the Materials Department to ensure compliance with all material specifications, as those documents sometimes specify the only acceptable cure procedures. As mentioned earlier (Section 4.3) some flexibility in cure schedule application can also help remove non-value-added cycle time.

5.1.2 Streamlining the Materials List

As part of the project-scoping process a database of all adhesives in use on the EOSU was developed (Section 4.1). In the case of this EOSU that list was fairly lengthy. Throughout the entire assembly (i.e. not solely the three assemblies of primary concern) 28 different types of adhesives were referenced. Many of these adhesives come from the same family, which means that their material properties are generally similar. Take for example the material family 16-103. Nine unique material references are used on the EOSU and the relationship between them can be seen in Figure 8. The distinctions between many of these nine materials vary from differences in cure times, maximum operating temperatures, or even color. When considering the insignificance of some of these variations, it seems reasonable to expect that not all of the 28 unique materials are necessary.

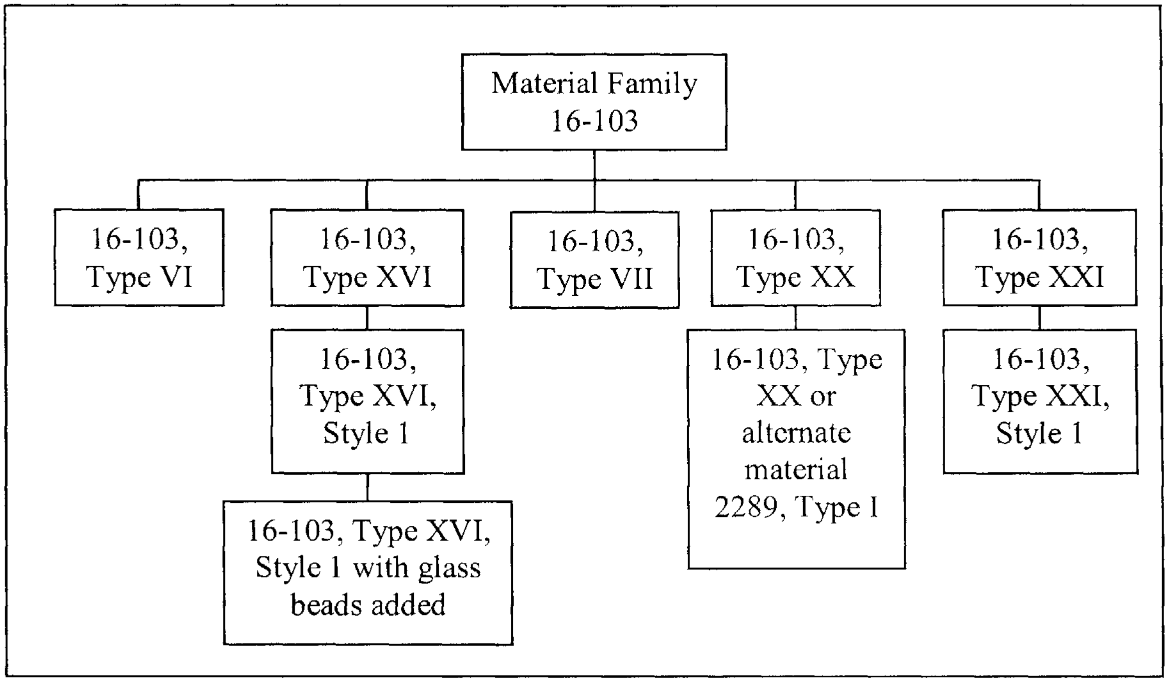

Figure 8 - Example of a Material Family Hierarchy

Although there are 28 adhesive materials called-out on this EOSU, in actuality only 15 are being used. As can be seen in Figure 8, the references sometimes allow for the use of alternate materials. Also, one material might be valid for multiple references as is shown in Table 6, where the same material can be used for all three references.

Reference Number	Material Specified	Material Used
1	16-25, Type XVII, Class A or Class B	16-25, Type XVII, Class A, Style 1
2	16-25, Type XVII, Class A only	
3	16-25, Type XVII, Class A, Style 1	

Table 6 - Example of Material Overlap

The use of so many different materials on a single product provides a significant opportunity in the context of this study. By choosing the alternate materials with the shortest cure schedules, it is possible to reduce the overall cycle time. Using the previous example of material 16-25, Type XVII, if the cure time for the Class A, Style 1 adhesive was considerably shorter than that of the Class B adhesive, there would be cycle time savings gained by only using the former material. If the substitute material is an approved alternate, there is no change to the CM of the EOSU, proving it to be an effective short-term option for cycle time reduction.

A different methodology could also be used as a long-term strategy. In that case, the materials list could be shortened by considering the mechanical properties necessary for each adhesive application. For example, if four different bond lines must withstand varying amounts of forces, the material suitable for the largest load could be used in all four locations instead of using four materials of adequate strength for each location. By paying close attention to the cure times, it would be possible to create the smallest set of materials that minimizes cycle time while still meeting the design needs of the product. However, this sort of effort would be classified as a Class I engineering change under the CM guidelines, which makes it a long-term option.

Streamlining the materials list using either the short or long-term methods provides several added benefits to production.

- **Risk of Misapplication:** A shortened set of adhesive options reduces the risk for misapplication during assembly. When the list is lengthy and multiple materials are sometimes used during a single work instruction step there is room for error by the technician.
- **Less Wasted Material:** The majority of the adhesives come in pre-mixed, frozen syringes. Once thawed, the contents must be applied within a certain time-frame, and any material not used during this time must be thrown away. If the same adhesive were being applied to multiple locations on an assembly, a single syringe could be used for more applications and less adhesive would be wasted.
- **Reduced Materials Management Costs:** The frozen syringes also have a limited shelf-life. The assembly shop must maintain an inventory of all materials in use and continually check for expired products, a process whose length increases in direct

proportion to the number of materials in stock. Also, freezer space requirements increase with more materials, which can necessitate capital investments as shop output increases. Thirdly, since it is easier to predict demand for fewer items, a smaller set of materials could result in less waste of adhesives due to over-ordering and less lost production time due to shortfalls. Finally, it's not unreasonable to expect that cost savings could be had by purchasing fewer materials in larger batches.

5.1.3 Upgrading the Materials List

Another area for improvement in the materials space is through a wholesale upgrade of adhesives. While any changes made to the material list would again involve a Class I change, cure time savings might be available from newer, advanced adhesives. A true discussion around recent adhesives technology is outside the scope of this project, but there are undoubtedly more advanced materials available than are currently in use on this EOSU. An example would be to use materials that cure under ultra-violet light in a matter of minutes, materials that are already often used in other industries. Developing an upgraded set of available adhesives is a long-term effort that would require significant effort on the part of the Materials Department at Raytheon. Substitution of these new materials into existing products would also require time and coordination among the engineering, materials, and manufacturing departments.

5.2 Process Changes

The majority of the improvements considered and implemented on this EOSU fall into the process change category. Very few of them necessitate Class I changes, which made them viable in the time available for this study. All of these improvements do, however, require familiarity with the assembly sequence. On this EOSU, it was the expertise of the technicians (Section 4.1) that brought many of these opportunities to light.

5.2.1 Combining Adhesive Operations within an Assembly

As mentioned earlier, bonding and staking references on the drawing become separate bonding or staking operations on the work instructions. Depending upon the build sequence established in the work instruction and consolidation efforts performed at other points in time, there might be a single bonding operation with multiple sub-steps or numerous operations each with a single adhesive application therein. Often, there were more blocks of VAAWT than truly necessary. By examining the assembly sequence from the perspective of cure time minimization, the applications of adhesives can be combined into fewer operations thereby eliminating whole cure cycles. So long as the final assembly has all the adhesions required by design, the order in which they are applied is immaterial and does not invoke any CM concerns, making this a good short-term strategy.

It should be noted that when combining the cures of multiple materials the longest cure schedule must be used. So, for example, when putting an adhesive with a 4-hour, 200°F cure into an operation that previously required a 2-hour, 150°F cure, the modified operation will default to the 4-hour, 200°F cure. However, the combined cure will still eliminate two hours of cure time, in addition to the addition warm-up and cool-down periods for the oven.

One immediate outcome of this project was to highlight the importance of deliberate work instruction creation. The best work instructions optimize several factors, including the ease of assembly for the technician, cycle time, material costs, etc. This project showed the need to consider the wait time as added specifically by other value-added processes. As the methods explained in this document are already being applied on other products at Raytheon (Section 7.2), an awareness regarding VAAWT is slowly being spread throughout SAS. As more and more projects are worked from a standpoint of VAAWT minimization, the practice of developing optimized work instructions from the beginning will become the norm.

5.2.2 Rearranging Operations within an Assembly

If the operations cannot be combined any further within a given assembly, rearranging their order can sometimes be beneficial. Under this scenario, cycle time savings can be achieved in two ways:

- Delaying the cures of earlier operations until a later operation has been completed allows for the elimination of whole cure cycles. Unfortunately, delaying cures is only a valid option under certain circumstances. Often the adhesives are being used to secure alignment critical parts, so while the adhesive is un-cured the assembly cannot be moved or touched. However, for less critical applications, such as a fastener staking, it is possible to apply the adhesive, continue work on the assembly, and then formally cure the adhesive during a later bonding operation.
- Installing a particular part earlier in the assembly sequence could allow for cures to be combined. This is similar to the discussion from Section 5.2.1 in that cure cycles are combined, the distinction being under that scenario the same number of staking applications occur but as the result of fewer work instruction operations and using fewer cure cycles. In this case, fewer cure cycles might be possible by modifying the order of the mechanical assembly process. An example of this will be shown in Section 6.1.3.

5.2.3 Rearranging Operations between Assemblies

A final alternative is to rearrange operations between multiple assemblies. This type of change is harder to accomplish, however, because of drawing requirements. For the most part, individual assemblies are built and then connected together modularly. In some cases, it is necessary to partially disassemble one of the completed assemblies in order to combine it with another. If this disassembly requires the removal of staked hardware it would be preferable to postpone the original staking operation from the one assembly's work instruction to that of the final, combined assembly. Since some sub-assemblies are built as spare parts, however, they need to reach a certain level of completion from their own work instructions. Thus, it is not always possible to eliminate a staking operation that's redundant under initial production but essential in a replacement part. At Raytheon there are procedures to work around this type of CM complication, but it is an important consideration when looking at transferring operations between assemblies.

5.3 Procedural Changes

As has already been discussed, adhesive use as a fastener locking feature could be eliminated. Removing it from Raytheon products is a long-term effort that ultimately requires a culture change. Although a difficult undertaking, the benefits would be great and applicable to all products and it should not be overlooked as a means of cycle time improvement.

One possible means for initiating such a cultural change would be a successful implementation on one assembly or product line. Achieving a marked improvement in cycle time on a test case would provide some initial leverage within the company to begin looking for similar opportunities on other products. In the case of SAS, the Advanced Manufacturing Department, which functions as a bridge between engineering, design, and manufacturing, is in an ideal position to initiate these sorts of projects. This department is typically brought in to assess manufacturing difficulties on existing products and implement improvements. Removing screw staking and/or minimizing the impact of the VAAWT processes on that product could easily be incorporated into the final implementation plan by the Advanced Manufacturing Team no matter what the reason for their initial involvement with the product.

Implementing improvements to existing product lines and driving cultural change via final production is only half of the battle. If the possible ramifications of screw staking are never considered during the design phase, the problem will continue to exist in final production. Therefore, a cultural change must also be initiated at the front end through the engineering and design phases of production. The two Raytheon fastener guidelines discussed in Section 3.2.1 are the first step towards achieving this change. Those two guidelines are a means for altering the culture that has adopted screw staking as the norm. The strong support these documents already receive from upper management are important for their success in the long run, but it will still likely take some time for the change to propagate throughout SAS and Raytheon. Overall, this two-pronged approach seems to be a sound strategy both for changing the culture that continues to use screw staking and systematically eliminating the procedure from existing products.

6 Improvement Implementation

This chapter will cover the improvements implemented during this case study in both the short and long terms. Where applicable the impact on cycle time will be discussed as well.

6.1 Short-Term Changes

The changes described in this section were discovered and assessed for feasibility during a several week period, which included two site visits to the McKinney production facility. The changes were then made to the production methods. The end result was cycle time savings in excess of 14 hours of cure time and 45 minutes of touch labor (Table 7). Over the remainder of this particular contract, this will result in estimated savings of over $1 million.

	BEFORE		AFTER	
	mins.	**hrs.**	**mins.**	**hrs.**
Mechanical Assembly Steps	2192	36.5	2142	35.7
Adhesive Application Steps	290	4.8	290	4.8
Total Mechanical Assembly Time	**2482**	**41.4**	**2432**	**40.5**
Total Cure time	3900	65.0	3060	51.0
Percentage of time spent curing vs. assembling	**157%**		**126%**	
Percentage of time spent curing vs. applying adhesives only	**1343%**		**1054%**	

Table 7 - Cycle Time Metrics Before and After Implementation

6.1.1 Assembly A

Of the six adhesive-related operations on this assembly, it was possible to make changes to only two in the short term.

- **Change 1: Move an operation between assemblies**
  Assembly A is a high-level assembly that is comprised of many other sub-assemblies. Many of the operations on its work instruction require the attachment of small parts to

the larger assembly. In one particular case, a single part (Item 3 in Figure 9) was being bonded to a structural housing (Item 2) that was completed prior to Assembly A. Since the part was in no way reliant upon work performed subsequent to the housing's completion, it was not necessary to wait until Assembly A to install it. Instead the part could be bonded during assembly of the housing, at which point it could cure with other bonding steps occurring at that time, thereby eliminating a 2 hour oven cure from Assembly A (Figure 10).

Original Configuration: All three components are connected on Assembly A's work instruction.

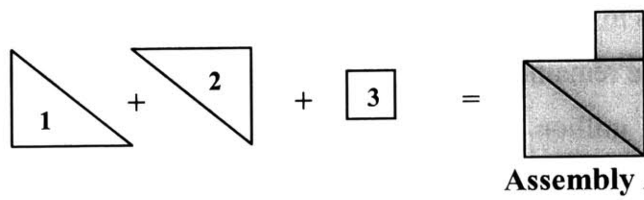

Figure 9 - Original Manufacturing Process for Assembly A

Modified Configuration: Items 2 and 3 are bonded during construction of Assembly 2. The new Assembly 2 (i.e. Assembly 2') is then combined with Item 1 to form Assembly A.

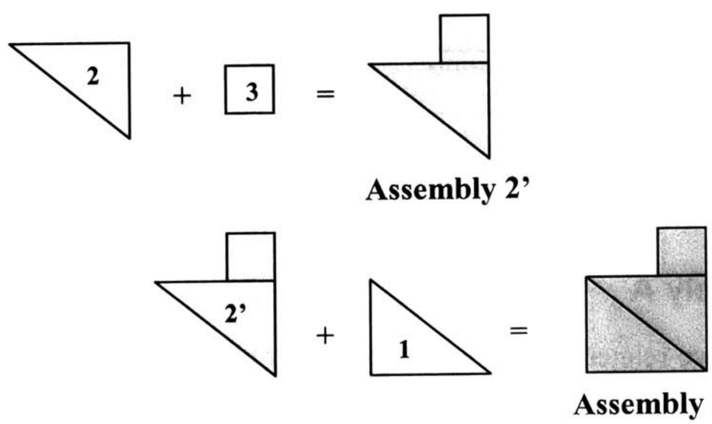

Figure 10 - Modified Manufacturing Process for Assembly A

- **Change 2: Delay an operation until a later assembly**

  This change actually eliminated a redundant application of thread-locking compound. In this case, a component was installed and sealed into position on a sub-assembly. At Assembly A, however, it was necessary to remove that same component in order to complete other work and reinstall it afterwards. Since the component was installed with thread-locker, it was tedious to remove and also presented the possibility of FOD generation. Initial discussions suggested moving the entire installation to Assembly A. However, the component is required to perform functional tests on the sub-assembly so that option was not possible. Instead, it was determined that the thread-locker was not essential for the functionality of the sub-assembly. Rather the thread-locker ultimately serves a fastener locking feature to ensure longevity in the field, so the part could be installed without the threadlocker the first time. Following the reinstallation during Assembly A, the fasteners would be sealed into place per design.

  Although not technically a time-dependent process (since thread-locking compounds cure in only a few minutes), removing this redundant step did eliminate 25 minutes of touch labor from Assembly A and reduced the possibility of FOD. The latter issue brought this redundancy to light during team discussions because FOD is of concern to the customer.

Overall, the changes made to Assembly A resulted in cycle time savings of 25 minutes of touch labor and 2 hours of cure time.

6.1.2 Assembly B

The changes to Assembly B are all the result of delaying cures and operations to more logical times in the production process.

- **Change 1: Combine cures from multiple operations**

  There are three screw staking operations that occur at roughly equal intervals during the build of Assembly B. While the installation of the components whose hardware was being staked needed to remain in the same relative positions, the actual curing of the staking material did not have to occur at the time of installation. Using the consideration discussed in Section 5.2.2, the work instructions were changed in the following way:

  - All parts were installed per the original instructions at Staking Operation 1, 2, or 3 with the associated screw staking adhesive.
  - All the screw staking material was cured with a single oven cure after Staking Operation 3.

  By combining these three cures into a single one, over 8 hours of VAAWT was eliminated from Assembly B.

- **Change 2: Delay an operation until a later assembly**

  A nearly identical situation to that discussed in Change 2 of Assembly A existed on Assembly B. In this case a component installed and thread-locked into place on Assembly B was then removed and reinstalled on Assembly A. By eliminating the thread-locking step on Assembly B, another 25 minutes of touch labor could be eliminated from the production of Assembly A without detriment to functionality.

Combined these two changes resulted in cycle time savings of 25 minutes of touch labor and 8 hours of cure time for this assembly.

6.1.3 Assembly C

A single change was made to Assembly C by rearranging operations within the work instruction. A bonding operation was moved from the assembly's final operation to a much earlier one that already necessitated an oven cure. Prior to this study, all reasonable operation modifications and cure combinations had been implemented on this assembly. The particular change implemented in this case was the result of engineering creativity and cooperation among departments.

In order to bond the part on early, new tooling fixtures had to be developed to hold the components in place. At the start of production, Assembly C is positioned face-up. When this particular part is bonded on at the end, however, the assembly is positioned face-down. In order to bond the part on early, the assembly would need to be flipped. Unfortunately, at the early stages of the work instruction, Assembly C is not sufficiently self-contained to permit flipping without the aid of fixturing. Once the proper tool was developed, the part bonding could be accomplished earlier in the sequence. In the end, a 4-hour oven cure was eliminated from this assembly.

6.2 Long-Term Changes

Two long-term changes were initiated as a result of this study.

- **Change 1: Material Substitution**

  During the analysis of Assembly C, it was noted that it would be possible to make a material substitution in one operation. The bonding adhesive in use during that step did not appear to be the most efficient choice possible. An alternate material was proposed that would shorten the oven cure time by 6 hours on that operation. However, as discussed in Section 5.1, since this new material was not already an approved alternate, its use would be considered a Class I change. The possibility of making the substitution in the future is still being pursued by the Materials Department.

- **Change 2: Eliminate Screw Staking**

  Based upon the data collected during this study and the efforts underway company-wide, it was determined that the elimination of screw staking on this RPS was a real possibility. Using Assembly A as an example, a change request was submitted for review, the details of which cannot be discussed here due to proprietary concerns. If this initiative is approved and implemented, it is estimated that over 50% of the adhesive application touch labor and roughly 80% of the cure time would be eliminated from that assembly. In addition to these significant cycle time savings, the modified design would be more in keeping with the current approved practices for fastener locking mechanisms. If similar changes were made to all three assemblies studied during this project, approximately 27 of the 65 cure hours could be eliminated.

7 Relevancy and Applicability beyond the RPS

As discussed initially, the internship-based work performed for this study and the recommendations implemented were intended as a case study. The ultimate end goal was a set of lessons learned that could be applied to other Raytheon products in order to address any processes that necessitated VAAWT and to mitigate the cycle time impact on production. This chapter will discuss applications beyond the original RPS studied.

7.1 Guidelines for Mitigating the Cycle Time Impact of Staking

The process followed during this investigation was transformed into a set of guidelines for future use at Raytheon entitled "Guidelines for Mitigating the Cycle Time Impact of Staking." This document, which can be found in Appendix A, was added to the "toolbox" of the Advanced Manufacturing Team at SAS. These guidelines were not written with the intention of providing an all-inclusive set of "rules" for eliminating cycle time related to VAAWT. Instead, they focus solely on instances of screw staking and provide a basic strategy for looking at situations and usages of staking. For this reason, the guidelines are presented at a reasonably high level and do not offer detailed suggestions, e.g. alternate materials, ways in which specific cure schedules can be modified, etc.

The document centers around a decision tree with four main decision nodes. These four nodes are the primary ways in which staking can be dealt with (based on the options discussed in Section 5) and funnel down from the greatest cycle time reduction possible to the smallest. Associated with each decision node is also a section of text which suggests some of the questions that need to be answered in order to affect change and also sub-options available for each decision. For example, the fourth decision node asks the user to question the order of operations and then offers three possible options for how to rearrange workflow around the staking step.

Overall, the document is intended to be a conversation starter. Ideally the guidelines will spark ideas among those involved in the manufacturing process, be it design engineers, manufacturing engineers, or shop floor technicians, regarding the pitfalls around staking (or any time-intensive process) and some ways to avoid those traps. The appropriate subject matter experts can then be engaged in discussions so as to either reduce the cycle times on existing products via redesign or prevent inflated cycle times on products still in design. In short, the relevant parties should discuss Design for Manufacturing and Assembly as it relates to the VAAWT in question. For more detailed specifications regarding staking in particular, the guidelines refer the reader to the two internal Raytheon fastener guides, which provide more concrete and quantitative rules surrounding proper staking usage and replacement.

7.2 Applications to Other Product Lines

Using the "Guidelines for Mitigating the Cycle Time Impact of Staking" as a starting point, a second SAS product line was examined with regards to cycle time reduction as caused by adhesive application. This project was conducted following the conclusion of the internship by members of the Advanced Manufacturing Department and demonstrates both that the lessons learned are applicable outside of the RPS studied and that knowledge transfer was achieved successfully.

The second case study was conducted on a satellite component that is still in the design phase. This component has roughly a three-year cycle time from contract award through hardware delivery. Of that time period, hardware construction was allocated a six-month block of time, but once assembly planning began, it seemed that construction would exceed the allotted time frame. In order to shorten the expected construction schedule, a team of manufacturing engineers examined the usage of adhesives on the component. They discovered the existing design to be as follows:

- The satellite component contained a set of 5 lenses.
- Each lens required a number of adhesive operations with lengthy cures in order to be properly aligned.
- The lenses were being assembled in series.

Under the initial design, the assembly and alignment of each lens required at least 7 days. When performed serially (and accounting for some additional intermediate assembly steps), all five lenses accounted for 42 days of cycle time. In other words, these five lenses were consuming more than 20% of the cycle time needed for the entire component.

Using the guidelines and flow chart discussed in Section 7.1, the team looked for ways to reduce the cycle time impact of these lenses. By making two changes to the design, they were able to eliminate more than thirty days from the cycle time. First, they changed the adhesive being used to align the lenses. This substitution immediately reduced each lens' cycle time contribution from 7+ days to 3 days. Secondly, they altered the order of assembly. Instead of working serially, they found that they could build the first two lenses in parallel, then the next two lenses in parallel, and finally the fifth lens. By switching to this 2-2-1 assembly sequence, another six days were removed from the process. Overall, these two changes reduced the cycle time from 42 to 9 days, or nearly an 80% reduction.

In addition to the significant savings achieved on this satellite component, the Advanced Manufacturing team is now looking at applying the same methodology to the latest design of the Global Hawk unmanned aircraft. They have found that the guidelines present a simple and easily replicated tool that is applicable to a variety of the products and processes they work with daily at SAS.

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8 Thesis Summary

This thesis presented the concept of *value-added associated wait time (VAAWT),* which was defined as any process that would be deemed *non-value-added* if not for its connection to another *value-added* process. For example, the drying time in a paint-application process might ordinarily be classified as non-value-added wait time, but because that time is necessary for the paint's value-creation, it falls into the category of VAAWT.

The bulk of this thesis focused on the tactics applicable when attempting to mitigate the cycle time impact of VAAWT. All potential strategies were described for the general case, and then specific implementations of these strategies were presented in the form of two case studies. The first case study was derived from a six-month internship conducted at Raytheon Space and Airborne Systems. The internship focused on unburdening a specific Raytheon Pod System (RPS) from the sizeable cycle time impact being caused by the use of adhesives. Short-term gains on the order of 15 hours of cycle time per RPS were achieved by looking at only the three primary assemblies. Cost savings of over $1 million are estimated based on these changes. Plans for additional long-term savings in excess of 26 hours were proposed and transitioned to a permanent team for further investigation and implementation. The second case study implemented the mitigation strategies to achieve a VAAWT reduction of over 80%.

It should be noted that the strategies for mitigating VAAWT that were presented in this thesis are ones discovered, tried (both successfully and unsuccessfully), and implemented during the course of the internship. Many of them are situation-specific to the product, the company, and the processes that were being studied. In all likelihood there are many more, similar strategies that could be found and successfully used for efforts of this type with respect to different processes or products.

The overall lessons to be learned from this investigation and thesis are not the specific tactical maneuvers and implementations, but rather the conceptual framework around them. The very act of considering cure times when adding a bonding step to an assembly is not one that often occurs during the design or engineering process, but it is an essential step towards avoiding unnecessarily inflated cycle times. Taking the time upfront to consider the possible impact of VAAWT and to gather the necessary subject matter experts into a discussion are the primary means for achieving success on a project such as this one. In the long run, implementing company-wide policies that support these types of efforts (e.g. streamlining the allowable materials list, discouraging the use of unnecessary screw staking) are all essential components for mitigating the impact of VAAWT on both a single product and throughout an entire organization.

Acronyms

CM – Configuration Management

EC – Engineering Change

ECP – Engineering Change Proposal

EOSU – Electro-Optical Sensing Unit

FOD – Foreign Object Debris

FRP – Full-Rate Production

RPS – Raytheon Pod System

RMS – Raytheon Missile Systems

SAS – Space and Airborne Systems

VAAWT – Value-Added Associated Wait Time

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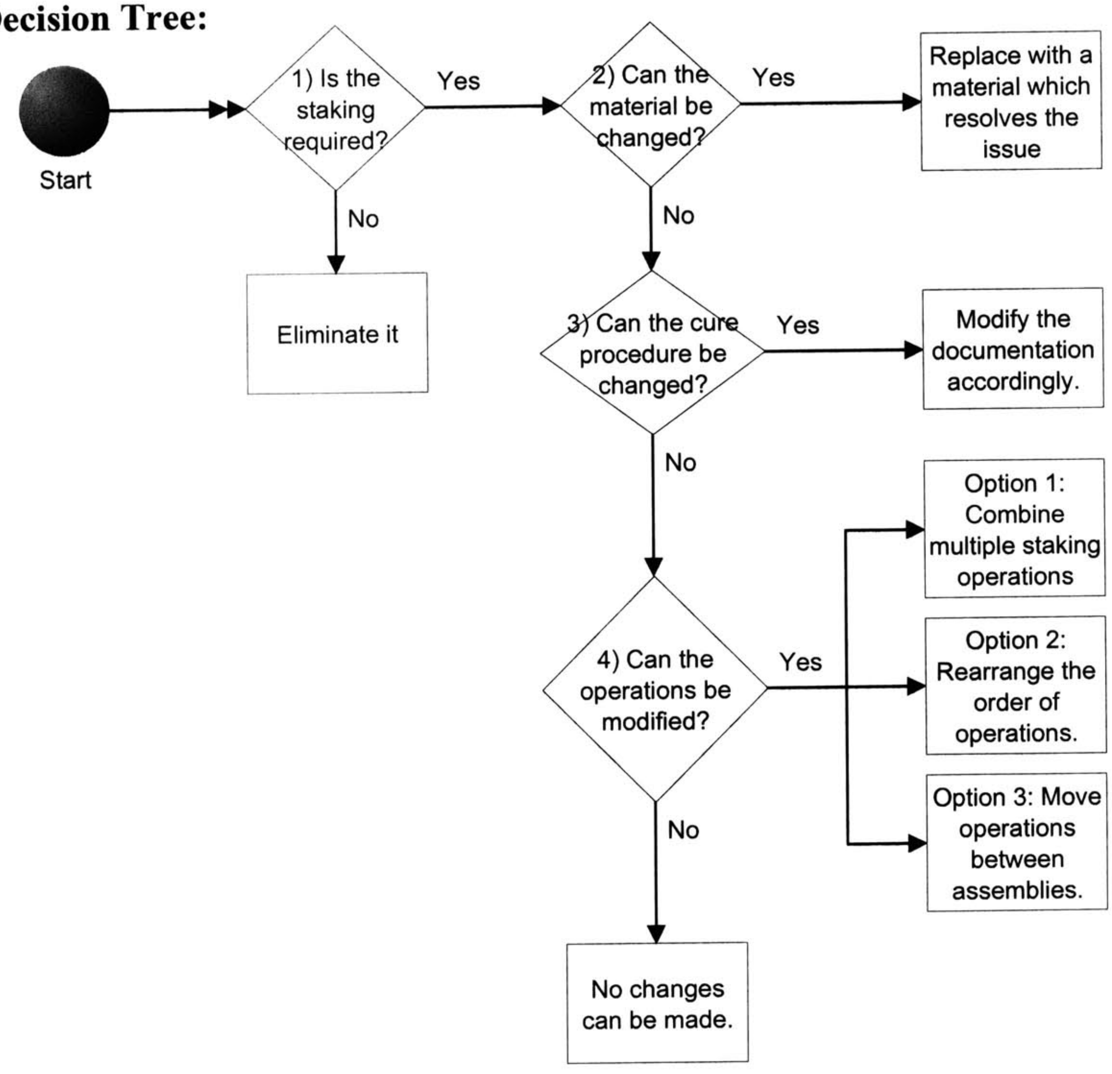
Appendix A: Guidelines for Mitigating the Cycle Time Impact of Staking

Background:

These guidelines are based upon process improvements made to a single Raytheon pod. They represent the lessons learned from that project and are meant to provide a starting point for future, similar analyses. Bonding and staking operations with long cure times were targeted during this study, but these lessons can be applied to other time-dependent processes. The steps and options outlined below represent the types of questions and considerations that should be discussed when attempting to minimize the cycle-time impact of cure times. They should be mixed and matched as appropriate to achieve the optimal results for the situation and are by no means all-inclusive. This type of investigation is best performed by launching a discussion with members from throughout the production process, such as M&P, manufacturing, engineering, etc.

Decision Tree:



Step 1: Is the staking required?

There are two primary uses for staking – as a fastener locking feature or to hold alignment-critical parts in position. When used as a locking feature, an epoxy locking compound is applied over the head of the fastener. This "screw staking" application has the benefit of providing a quick visual reference to see if fasteners have moved, but it does not provide a reliable locking feature. It also adds assembly and cure times to overall cycle time and the opportunity for FOD should the adhesive come loose. In most instances, head staking *is not* the preferred locking feature during design. Preferable methods are outlined in *Fastener Design Guide for Tactical Applications (EN-03-26-26)* or *Fastener Design Guide for Space Applications (EN-03-26-21 Rev. A)*. Wherever practical, screw staking should be removed, which will immediately eliminate the associated time delays. Bonding and alignment staking usually have technical bases, so the actual design driver must be known to determine if they can be replaced.

Step 2: Can the material be changed?

In some instances, staking is the most practical design option, in which case the usage should be optimized. There are numerous materials available for use as staking compounds, all of which have varying material properties and set/cure times. Two things to take into consideration when selecting a material:

1) What other staking materials are being used on the assembly and/or product? Material maintenance costs increase in direct proportion to the number of materials being used. Also, having many different materials increases the risk for misapplication.
2) What are the trade-offs associated with each material? Strength, cure time, propensity for generating FOD, etc. all vary by material, and caution should be taken not to focus on optimizing a single trait to the detriment of other manufacturing concerns.

Step 3: Can the cure procedure be changed?

For many epoxies there are many ways to reach the final, cured state. For example, an oven-only cure vs. a short air cure plus an oven cure vs. a very long air cure. By taking into account the configuration of the assembly at the time of staking, it is often possible to find a cure procedure that combines several curing methods so as to minimize cycle time and maximize the quality of the staking. As a caveat, for some materials the only acceptable cure procedures are specified in the associated HMS or HP document. Work with M&P to develop the appropriate case-specific solution.

Step 4: Can the operations be modified?

The final opportunity for mitigating the impact of staking is at the work instruction level. The following three options are viable ways to minimize cycle time impact due to cure times.

- ***Option 1: Combine multiple staking operations***
  Many assemblies have several bonding and/or staking steps throughout the build process. For example, each time a piece of hardware is installed the screws are staked immediately thereafter. However, unless the hardware installation is alignment critical, all fasteners could be staked at once near the end of the build. By combining steps, where appropriate and feasible, cures times can be overlapped. Generally, the longest cure schedule will apply if multiple materials are being used, but this option can still shave hours off the entire assembly's cycle time. Be careful to ensure that the fasteners are still accessible at the time of final staking. For example, if the installation on Operation 100 covers up the fasteners from Operation 020, then attempting to stake both sets of fasteners at OP 100 is impossible and staking must occur separately for the OP 020.

- ***Option 2: Rearrange the order of operations***
  Another way to combine cure steps is by changing the order of work. Perhaps moving the installation of a particular part from OP 150 to OP 070 makes it possible to combine some cure times. These sorts of changes require a thorough understanding of the build process for a given assembly and close cooperation between engineering and manufacturing, but can be a great way to eliminate cure time and improve overall manufacturability.

- ***Option 3: Move operations between assemblies***
  Similar to Option 2, this option changes work-flow between assemblies. By moving a part's installation from Assembly A to Assembly B, cure times again might be combined or manufacturability improved. An important concern for this option, however, is configuration management. Moving a part between assemblies can prevent a completed assembly from matching the final drawing. Since some parts are sold as spares, it's important to follow the correct documentation and planning procedures that permit deviating from the drawing configuration.

Conclusions:

Again, this is not an exhaustive list of all the possible questions and pitfalls that need to be examined when attempting to minimize cure-time impact, but it should provide an overall picture of the process to be followed. Many of these options can be used in parallel or applied in an order other than one outlined here. The key is to engage all the relevant parties in a discussion.

Finally, many of these changes (particularly Steps 1 and 2) will result in Class I changes. Depending upon the timing (early in the design process vs. full-rate production) and impact making a Class I change is not always a viable option. However, changes should not be ruled out solely because they are Class I, but rather examined more thoroughly with respect to potential savings (both cost and time).