A Study On The Practical Application Of Repair Development Methods For Aerospace Components

by

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ABSTRACT

In the industry of manufacturing, each gas turbine engine component begins in a raw state such as bar stock and is routed through manufacturing processes to define its final form before being installed on the engine. What is the follow-up to this part? What happens when over time and usage it wears? Several factors have created a section of the manufacturing industry known as aftermarket to support the customer in their need for restoration and repair of their original product. Once a product has reached a wear factor or cycle limit that cannot be ignored, one of the options is to have it repaired to maintain use of the core.

This research investigated the study into the creation and application of repair development methodology that can be utilized by current and new manufacturing engineers of the world. Those who have been in this field for some time will find the process thought provoking while the engineering students can develop a foundation of thinking to prepare for the common engineering problems they will be tasked to resolve. The examples, figures and tables are true issues of the industry though the data will have been changed due to proprietary factors.

The results of the study reveals, under most scenarios, a solid process can be followed to proceed with the best options for repair based on the initial discrepancy. However, this methodology will not be a “catch-all” process but a guidance that will develop the proper thinking in evaluation of the repair options and the possible failure modes of each choice. As with any continuous improvement tool, further research is needed to test the applicability of this process in other fields.

ACKNOWLEDGMENTS

First of all I would like to thank my mother, Bertha, for the lifetime of encouragement in my academic and engineering career. To my daughter, Jessika, whose birth made me pursue excellence at a previously unimaginable level through the experience of fatherhood. The writer’s gratitude is also expressed to the entire faculty of the Department of Engineering Technology for their guidance during his study in Arizona State University. In regards to the thesis itself, there are three individuals who deserve special appreciation: Dr. Sharon Lewis for her superior mentoring throughout this journey, Dr. Robert Meitz for his vast mechanical engineering expertise; and Mr. Trian Georgeou for his manufacturing excellence, thank you all for patiently guiding me on my path.

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INTRODUCTION

Since the creation of the gas turbine engine for the aerospace industry, there has been a need to repair the components of these engines. The transition from new components to repaired condition was under limited visibility as manufacturing technology advanced from manual machines to CNC machines along with the inclusion of special processes. The original design engineers of today's products have limited involvement with the aftermarket process. The repair engineer will be dealing with a finished component that has been in service for some time.

Statement of Purpose

The principal objective of this document is to create a methodology which describes the practice of repair development of aerospace components. Both proactively and reactively, this document should inform the reader about the diagnosis of discrepancy in an aerospace component. This is accomplished by reviewing the environment in which these components function. This work's intended audience is those who have or will have involvement in the aftermarket industry. This includes non-engineers as this provides an overview of the process of aerospace repairs in the aftermarket.

Research Objectives

1. What is repair development and why is it needed for the aerospace industry?
2. What are the common drivers which can drive a component of an aerospace engine to be repaired?
3. What common manufacturing practices are benchmarked in the practice of aftermarket repairs and what processes have been developed for repairs only?
4. How is a repair process validated while in process and upon completion of all repair steps?
5. How do a customer and a repair facility review the cost factors associated with the repair of a component?

The ambiguous starting point of these repairs presents the need for the following study. The manufacturing engineers and design engineers have collaborated to produce products that have been designed for manufacturability but the repair process is unique. The collaboration with design engineers is still needed as repair development engineers will be addressing the repairs needed for components and can provide feedback to the design group for future improvement. A typical manufacturing engineer will not have the same thought process as a remanufacturing engineer because they address two different life stages of the same products. A manufacturing engineer can have a product that starts as bar stock or as a casting, while a remanufacturing engineer will deal with a product in its finished state which has been in service for some time. The separatist mentality must change in order to provide value and reduce cost from the overall process of repairs.

The scope of this thesis is limited to aerospace components while the practice of repair development can be benchmarked in some fashion to other industry practices. This thesis does not address every single component that exists in aerospace engines as different models have a substantial variety of components but gives an overview of the areas of interest. Though some specification are listed in the document, there is a vast quantity of process equivalent specification to review for application, as some are noted to be industry standard.

Repair Development Introduction

Repair Development Engineers (RDE) review aerospace engine components that have been in service as part of the assembly of the engine. One of the goals of this engineering group is to produce and substantiate viable repairs to be performed at a repair facility that will restore the part to airworthy condition. These engineers must have knowledge of current manufacturing standards, including the variety of the basic machining practices used when a component is made new to benchmark. This includes such as lathes, mills, and CNC machines. The differentiation comes in the fact that they will be preparing an FAA approved document with step-by-step instructions on how to fix a discrepancy found on the component.

The RDE will need to use mechanical analysis while choosing a manufacturing practice to ensure that the very nature of the process chosen does not cause further discrepancies or invalidate the intended repair. The end result of the repairs made will be a process that returns the part the same fit, form and function originally intended by design. The validation of any repair will be a pass/fail test on the repair performed. In some cases, non-destructive test can evaluate the integrity of the repair, while other methods can include a functional test, such as balance for rotating components of the engine.

The RDE evaluates several factors of a component to develop a sound repair that will be approved for aftermarket products. All engineers face this enigmatic baseline since there are several starting points one can take. What is needed for consistency is a standard procedure. There is no one true fit-all methodology for every single component in existence but there is a common thought process that will save the time wasted in an uncoordinated repair. The cost of engineering in a project is ~$125 per hour so outlining a process plan can assist in reduction of the overall repair project cost.

The Design of Repair Development

The Design of Repair Development (DRD) reviews three factors of the component. In the simplest form, the three factors are:

1. Discrepancy
2. Material
3. Function in engine

The Design of Repair Development is conceived as a tool which yields an acceptable resolution to the components' discrepancy. Because these aerospace components are in extremely high demand from the airlines, this tool is designed to reach the feasible repair as quickly as possible. Every repair option will ultimately need further evaluation based on factors of each scenario to reach a methodical decision. As the document progresses, it reviews the industry practices based on specifications known to the aftermarket. The tools and information in this document should provide both new and experienced minds in manufacturing with a conclusive understanding of the methodology behind repair development. In the interest of continuous improvement, the practices to create the tools and provide order to the ambiguity are the same as used in six sigma methodologies for lean manufacturing (Heizer, Render, 2011).

Anticipated Results

As part of the primary investigation, it was expected that the experiment would yield at least a documented methodology of the repair development process. In some examples, there were preliminary finite element analyses which demonstrated justification for the limits of the repair intention. This takes into account safety factors mandated in the repair of aerospace components. A number of specifications noted in the literature review provide background which must be understood before a repair may begin. These results minimize new engineers' efforts to understand the thought process required to repair aerospace components. To describe the intent of this thesis with a quote, from Dr. William Edward Deming, "If you can't describe what you are doing as a process, you don't know what you are doing." (Delbridge, 2013)

LITERATURE REVIEW

There is minimal research on repair development methods in the industry, as the details of a repair are typically kept within a given company as proprietary. Each component is systematically evaluated to address the specifics of the discrepancy, and once a repair has been validated, it is used repetitively until no longer needed. The following is the review of the current industry practices and proposed improvements.

Composite Repairs

Composite parts are used widely in the aerospace industry and originate from the process of combining a minimum of two materials to produce a new product that has properties desired by the design requirements. The most common are the carbon fiber composites in which laminate sheets are layered from plies of carbon fiber, forming a matrix which is beneficial to the structure of the part. The strength and rigidity of a composite can be controlled by varying the shape, amount, surface functionality and orientation of the major structural constituent in the matrix. This ability to tailor properties, combined with the inherent low density of composites and their relative ease of fabrication, makes these materials extremely attractive alternatives for many applications (Sheng, Xia, 2008). The high demand for composites has caused the common issue of disposal of discrepant parts fabricated from this material. These components are not biodegradable, and thus cannot be put in landfills nor incinerated due to pollution. Repairs of this core material are of critical importance so be may be used repeatedly (Mazumdar, 2002).

Composite repairs initiate by preparing the affected areas for the needed repair, including thorough cleaning. Figure 1 illustrates the repair to remove a step in which the part is applied with adhesive to the localized area. It is then re-layered with plies to re-establish the original surface, addressing the current shape of the discrepancy without modification of the original surrounding area (Sheng, Xia 2008).

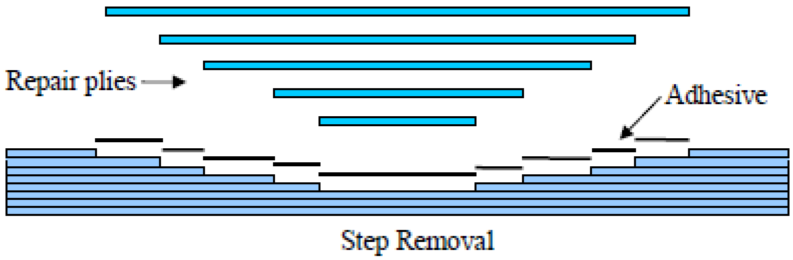


Figure 1: Composite step removal and repair

Figure 2 shows a scarf repair on the outer surface of the laminate that must be removed carefully with a high speed grinder at a shallow angle. Repair plies are then used to fill the removed area. The scarf repair reportedly provides an aerodynamically smooth surface and has a nominally uniform shear stress distribution within the joint (Sheng, Xia 2008). However, outer plies can be destroyed during the grinding process which affects the strength of the repair due to the modification of the original laminate.

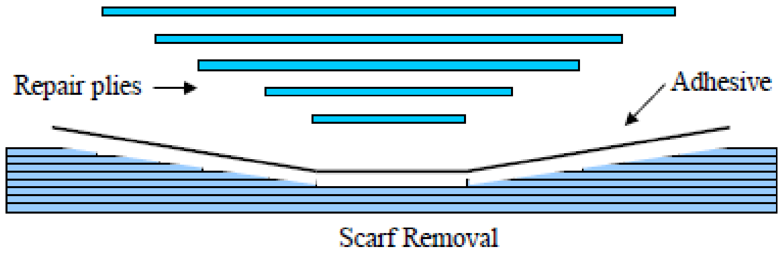


Figure 2: Composite scarf removal and repair

Composite hardware used as aerospace components can be susceptible to several other discrepancies which can be addressed in similar manners. Depending on the criteria, defects such as cracks, cuts, scratches and blemishes would need to be addressed so as to not propagate into a greater issue. Delamination, also known as inter-laminar fracture, often occurs in composite laminates as a result of low energy impact or manufacturing defects (Sheng, Xia 2008). A repair to address this discrepancy needs to evaluate the reason for damage while restoring the feature back the original form. Normally, localized delaminations are repaired by scarf removal of material and subsequent rebuilding, or by resin injection as seen in Figure 3. Resin-injection repairs eliminate the need to remove the outer undamaged plies and can result in higher recovery strength than scarf repairs. A resin-injection requires a special resin with a low viscosity at room temperature.

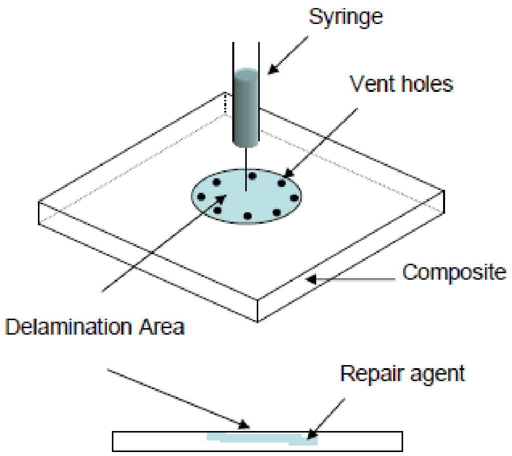


Figure 3: Resin-injection repair technique for composites

In 1999, the aerospace industry had consumed 23 million pounds of composites. A number that will continue to grow as this material is chosen for further applications. These materials offer dimensional stability and weight savings. Repairs for composites continue to be driven by these factors (Mazumdar, 2002).

Braze Repairs

Brazing is a bonding process currently used for the repair of the hot section components of gas turbine engines and has been used for thousands of years in other applications prior to aerospace. Brazing has become a widely accepted practice for the manufacturing and repair of products to meet a variety of field demands, from simple tools to complicated structures for aerospace engines. Brazing gives a beneficial alternative to welding processes due to the ability to batch process, being virtually free of the unfavorable effects of distortion and having no heat affected zone (HAZ). The two types of brazing process are: 1) conventional brazing used for commercial products and 2) diffusion brazing used for joining and rework of gas turbine components (Henhoeffer, R. Thomas, 2008).

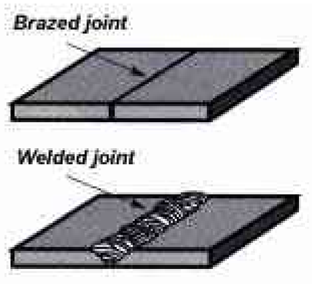


Figure 4: Brazed joint and welded joint (http://www.societyofrobots.com)

The visual differences in a brazed joint and welded joint are illustrated in Figure 4. A comparison of the application of features with weld and vacuum braze repair for special alloy components is shown in Table 1. Though there is a significant initial investment required for vacuum braze repair, the advantages noted often justify the capital needs. Brazing can even be used to bond ceramics as well as metal components unlike welding which depends on the process melting the base material.

Table 1: Comparison of Features in Welding and Brazing Repair

Property	**Welding**	**Vacuum brazing**
Heating	High Temperature local heating: Distortion, Residual stresses, Cracking in HAZ	Uniform heating: No distortion, No stresses, No cracking
Filler metal	Commercial fillers	Commercial fillers or self mixed and tailored pastes
Efficiency	On crack at a time / one part at a time	Multiple cracks and multiple samples
Operator Requirements	Skilled specialist	Less skilled operator

Welding is the preferred repair method when a significant portion of a component has cracking or erosion as the root cause of the discrepancies. This process can have significant technical and economical limitations from the large amount of material necessary to build up. Some repair methods use both braze and weld repairs together, while others will use a sequence of braze-to-weld- to- braze to successfully repair cracks.

The creation of cobalt-base superalloys presented a unique challenge to welders. These alloys were introduced with the design of the aircraft turbo supercharger nearly 100 years ago.

Currently, cobalt-based superalloys are used in gas turbine hot section components such as combustor casings, transition ducts and turbine vanes for aerospace applications. These hot section components suffer service damage as a result of thermal fatigue, creep, hot corrosion, erosion, or a combination. When damaged components are removed from the engine at the overhaul site, there is a significant opportunity for cost savings if they can be repaired, as the cost of new hot section components can be substantial. Successful repair techniques can effectively double the life of hot section components at only 10 to 20 percent of new part cost. This type of savings is critical in the airline industry when having the option of repairing a component versus paying new part cost. The customer can save money in a repair and the aftermarket repair station can save from not having to procure a new component (Henhoeffer, R. Thomas, 2008).

Unlike nickel-based superalloys such as Inconel, cobalt base superalloys have reasonably good ability to weld and are traditionally repaired by fusion welding processes such as gas tungsten arc welding. However, fusion welding has its limits for repair of gas turbine section parts. The available filler materials for fusion welding repair have inferior properties to that of the substrate, resulting in a joint that is weaker than the substrate. The high heat input used for fusion welding causes distortion of the substrate and formation of a heat affected zone of altered microstructure and inferior mechanical properties (Henhoeffer, R. Thomas, 2008).

An alternate repair process to fusion welding and its current limitation is the brazing process as seen in Figure 5. Brazing makes use of a braze alloy that is similar in composition to the substrate, allowing it to flow into the capillary gaps, such as cracks on the part, by using melting point depressants such as boron or silicon that lower the melting point of the braze alloy to below that of the substrate. Diffusion brazing is the process of the melting point depressants diffusing into the substrate, causing the braze alloy to solidify isothermally. Several advantages exist with braze repair over fusion welding repair such as the ability to batch process for multiple components with multiple defects to be repaired during one brazing cycle. Thermal deformation, a common problem in welding, is not an issue since the component is heated isothermally. In addition, braze joints of comparable tensile properties to that of the substrate can be reached with controlled parameters for desired mechanical properties (Henhoeffer, R. Thomas, 2008).

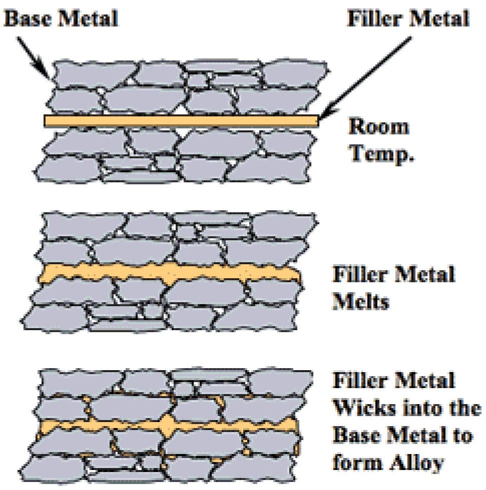


Figure 5: The brazing process in summary (http://www.solidmetals.net)

There are two categories of brazing process based on the area of application: narrow gap brazing for braze gaps less than 200 μm or wide gap brazing for braze gaps greater than 200 μm. In narrow gap brazing, the braze alloy is applied to the substrate by means of three different methods: powder, paste or foil. The braze gap is commonly restricted to 200 μm in narrow gap brazing because of the concern of brittle eutectic boride and silicide chains that generate at the centerline of the braze region due to excessive gap width, drastically reducing the mechanical integrity of the newly formed joint from its intended properties. In wide gap brazing, an additive alloy with the equal or equivalent composition to that of the substrate is combined with the braze alloy. The enhancement alloy supports the capillary action of the braze alloy and can act as a diffusion sink for the melting point depressants, enhancing the braze alloy by reducing the presence of brittle boride or silicide (Henhoeffer, R. Thomas, 2008).

Non-Destructive Inspection Techniques

Validation of a repair is crucial to the discussion of aerospace repairs such as welding. The capability to perform a repair does not mean it is an acceptable or even airworthy repair. Non-Destructive Inspection (NDI), also known as Non-Destructive Testing (NDT), is the controlled testing of the repair process, to fully evaluate the repair, whether it is the weld or some other process. NDI is an examination that is performed on a object to determine the absence or presence of flaws that may have an effect on the usefulness or serviceability of that object or to measure other objective characteristics (e.g. size, dimension, alloy content) (Khalifa, Mohamed, 2009). In relationship to a weld repair, the intent of this inspection process is to evaluate the possible failure modes of the welding process. Defects found after welding through the NDI process can include cracks and porosity which can lead to failures in service depending on the conditions (Khalifa, Mohamed, 2009).

The best synthesis of man, machine and material can be present in the process of manufacturing. Yet the variables in the process make defects seem inevitable. These defects can be pre-service defects or in-service defects depending on the time of origination during new production, in-service, or repair. There is no inspection process that is one hundred percent reliable but NDI is a critical component of a repair process to assist will lowering the chances of failures in service.

Visual inspection is one of the most basic types of NDI processes; the part is reviewed under white light for any visible discrepancy. This inspection is the most economical method of all the NDI processes. However, the discrimination required to find flaws is limited even with commonly used ten-power magnification. The need for assisting the human eye in finding these flaws preempted the creation of methods such as Fluorescent Penetrant Inspection (FPI). This process, also known as Liquid Penetrant Inspection (LPI), is used to reveal any surface breaking flaws that will bleed out a colored or fluorescent dye used in the inspection process (Khalifa, Mohamed, 2009).

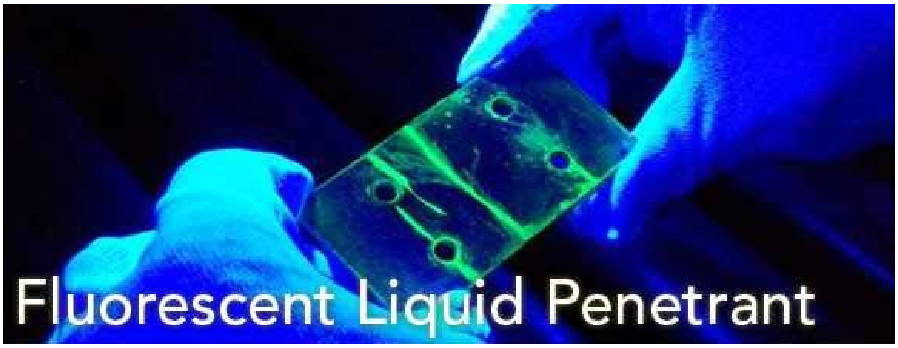


Figure 6: Fluorescent Liquid Penetrant applied to a part (http://www.solaratm.com)

The FPI process magnifies the visual surface flaw with the use of the dye that fluoresces when used in conjunction with an ultraviolet light as shown in Figure 6. The result is a glow which draws the attention of the operator to the indication. This indication is interpreted as a defect or another factor that would cause it to accumulate dye in the area, such as a bore. This solution can be applied to the component via a sprayer connected to a penetrant tank or locally utilized to the area of concern with a cotton swab (Khalifa, Mohamed, 2009).

The American Society for Testing and Materials (ASTM) is an internationally renowned leader of international voluntary consensus standards used around the world. Part of this organization’s intent is to ensure that globally manufactured products meet standardized requirements, reliability of process, and commonality across the global market. An ASTM standard practice is applied in the aerospace industry today for controlling the application of the liquid penetrant method.

The penetrant materials used for the inspection process have various classifications by their physical traits and service performance. The Aerospace Materials Specification (AMS) 2644 provides a list of classifications for the penetrant systems covered by the specification. It is also applies to the maintenance operations of FPI because it provides an approved products list (SAE Aerospace, 2006). For further research in commercial and military practices, consult ASTM E1417 Standard Practice for Liquid Penetrant Testing. This specification supersedes military specification MIL-STD-6866 Liquid Penetrant Inspection (ASTM International, 2013).

Magnetic Particle Inspection

The Magnetic Particle Inspection (MPI) is non-destructive inspection technique used to find defects similar to Fluorescent Penetrant Inspection (FPI). The differentiation comes from the process and material requirements. This inspection requires a ferromagnetic material, a ferrous based material such as iron and the ability to be magnetized. This process uses magnetic fields applied to the part along with a solution mixed with iron oxide powder to assist with the detection of a discrepancy. The magnetic field must be strong enough to work in conjunction with the solution to provide a stable inspection. This technique can be utilized in a diverse number of products of the aerospace industry such as casting and forgings. As depicted in the Figure 7, one of principles of MPI process starts with the magnetic field of a bar magnet noting a north and south end of polarity (Khalifa, Mohamed, 2009).

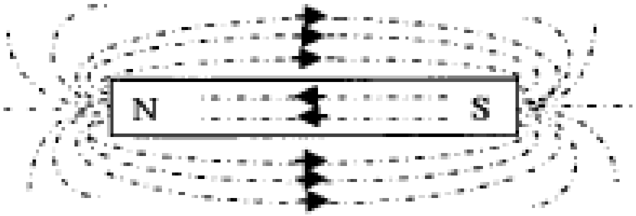


Figure 7: Magnetic Particle Inspection principle in use of magnetic field.

With an understanding of the magnetic field component of the MPI process, the solution is used as the indicator for the discrepancy. Similar to the magnetic bar, an open area of a component such as a surface crack for example, will have the north and south polarity but in reverse direction. The solution will accumulate in this area because of the reverse polarity, effectively showing the gap created by the crack. The fluorescent dye, which is part of the solution, will assist in revealing where the solution particles have gathered under the inspection of a black light as seen in Figure 8 (Khalifa, Mohamed, 2009).

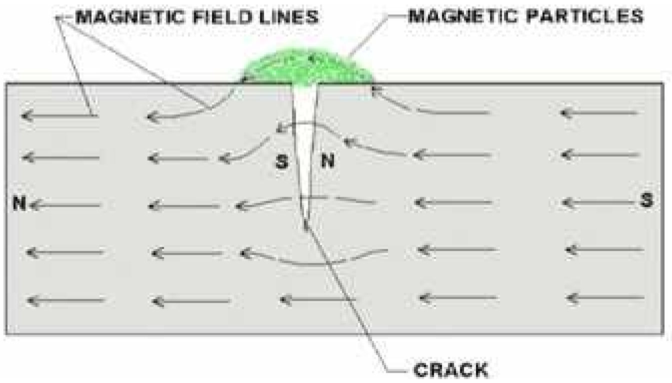


Figure 8: Magnetic field applied to area with magnetic particle solution (http://www.gotilley.com)

It is imperative to the inspection for cracks and defects to grasp the direction between the magnetic lines of force and the defects. The two forms of magnetic field that can be created in a component are longitudinal and circular. Longitudinal magnetic fields travel parallel to the extended axis while circular magnetic fields travel circumferentially about the boundary of the component.

The use of both magnetic fields is essential in finding any disruption in the material as the orientation of the crack will be noticeable at right angles. The NDT technician performing the inspection must be trained in the entire process. MPI is an extensive and sequential process, from preparation of component to the final state when visual inspection is executed to determine whether it passes or fails as seen in Figures 9 and 10 (Khalifa, Mohamed, 2009).

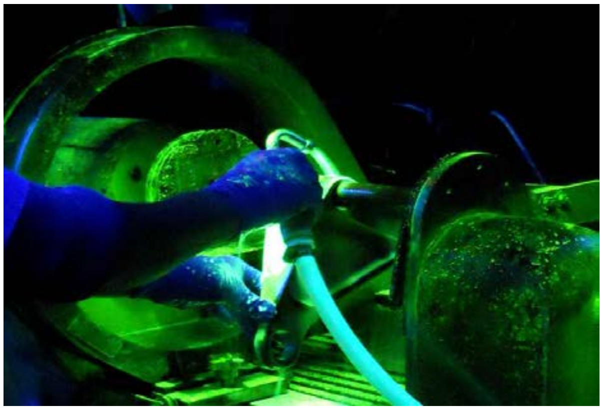


Figure 9: MPI technician applying the solution to component (http://www.advancedcoatingtech.com)

Figure 10: MPI technician reviewing at part for discrepancies (http://www.defense.gov)

As components vary, the requirements of the inspection dictate the sensitivity of this inspection procedure. The industry practice for this non-destructive inspection needs to be performed in a controlled manner. The ASTM specification can provide reliability of the inspection. For further research in commercial and military practices, consult ASTM E1444 Standard Practice for Magnetic Particle Testing. This specification supersedes military specification MIL-STD-1949 Inspection Magnetic Particle (ASTM International, 2013).

Whichever non-destructive testing practice is used, the definitions of the terms used can be referenced under an ASTM specification. ASTM E1316 is the standard created to provide a clear explanation of the terminology of non-destructive testing standards. This specification provides a uniformly understood language for the industry. Some of the non-destructive testing methods mentioned in the specification are liquid penetrant testing, magnetic particle testing, ultrasonic testing, and X-radiology. Figure 11 demonstrates the intent of flow in the non-destructive testing process when an indication of a defect is found (ASTM International, 2013).

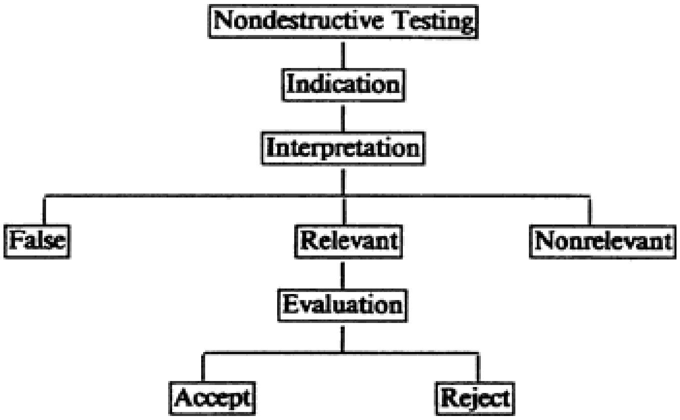


Figure 11: Non-Destructive Testing Flow Chart

Federal Aviation Administration Regulations and Consequences

The Federal Aviation Administration (FAA) is an organization under the Department of Transportation (DOT) which among other duties provides regulations and policies for the civil aviation industry. The origin of the FAA started with the passing of the Air Commerce Act in 1926. This act created a new aeronautics branch under the Department of Commerce for providing federally mandated safety standards and providing the opportunity for commercial aviation to drastically improve its potential. This new branch would task the Secretary of Commerce with supervising commercial travel, creating air traffic rules along with disciplinary action, pilot licensing, aircraft certification, airway establishment and the maintenance of air navigation. The creation of the FAA came when President Dwight D. Eisenhower signed the Federal Aviation Act on August 23, 1958, instructing that all civil aviation safety responsibility be under a new organization known as the Federal Aviation Agency (FAA). The first FAA administrator was the retired Air Force General Elwood Quesdada, appointed on November 1, 1958 (Federal Aviation Administration, 2010).

There have been several tragic events in air travel across the globe that has driven investigation and review root causes to ensure they are never repeated. The lessons learned from these historically disastrous accidents in air travel resulted in stricter policies to lower flight safety risk. The American Airlines DC10 crash of May 25, 1979, seen in Figures 12 and 13 prompted the evaluation and redefinition of what is to be considered a “major” aircraft repair. At the time, it was the worst crash in aviation history, resulting in the death of all 271 passengers and flight crew, along with two people on the ground (Barringer, F., 1981).

Figure 12: Photo of American Airlines Flight 191, DC10

Figure 13: Photo of Chicago DC10 crash site

Upon takeoff from Chicago’s O’Hare Airport, the plane suffered a left wing engine/strut failure resulting in complete separation of the left engine, strut assembly and three feet of wind leading edge from the aircraft. As the engine unit fell to the runway, the pilots continued with the takeoff. They were unaware of this disastrous collapse, having assumed that they had experienced only an engine failure. One of the root causes of this catastrophic incident was found to be an engine mount crack that manifested during maintenance. Continental Airlines had observed these cracks during other maintenance activities with repairs performed to address the discrepancies but since they had deemed the cracks to be minor, this was not disclosed to the FAA (Federal Aviation Administration, 2012).

Following the accident, new regulation and corrective actions were put in place. One of the lessons learned was a clear understanding of what can happen when a major repair is improperly classified on these aerospace components. An engineer in the aftermarket industry must be aware of the safety factors involved with attempting to restore a component with a discrepancy. The repair must have a validation of the action performed on it to address the discrepancy, while testing the product to ensure quality of the fit, form, and function of the product design intent. Before repair development can begin on a component, an aerospace engineer will classify the repair appropriately to ensure the proper FAA mandated process is followed. For further research in the classification requirements of major repairs, consult FAA regulation Title 14 CFR Part 145 Repair Station Certification (Federal Aviation Administration, 2012).

This is the last section of the literature review before moving on with the document to the methodology of the repair development. This literary discussion is meant to be a sobering reminder to those involved or will be involved in this field to remember the end users of the product. When stating end users, this is not talking about the airline or the airline mechanic but the passengers on board the aircraft that place faith in air travel as a safe practice.

METHODOLOGY

In the aftermarket industry, the process of repairing a part to serviceable condition is part of a bigger procedure. An Auxiliary Power Unit (APU) or propulsion engine will be taken to a repair facility for general inspection. Depending on the condition, it can go through several options of disposition as shown in Figure 14. The engine has to accumulate certain cycles of use in order to dictate the need for evaluation much like the car manufacturer's recommended maintenance schedule. At this point, the mechanic of the airline would follow the procedures of sending the engine to a repair and overhaul facility that is certified to perform the maintenance. Upon arrival at the facility, it is "inducted" or received at the first engine gate entry for initial evaluation. The overhaul engineer is notified of the arrival of the engine. A preliminary visual inspection is performed by the mechanic for any immediate defects such as broken pieces or fluid leakage. Several pictures will be taken for storage and documentation of early condition. Digital forms of the engine are processed in the background such as the purchase order to perform the necessary work.

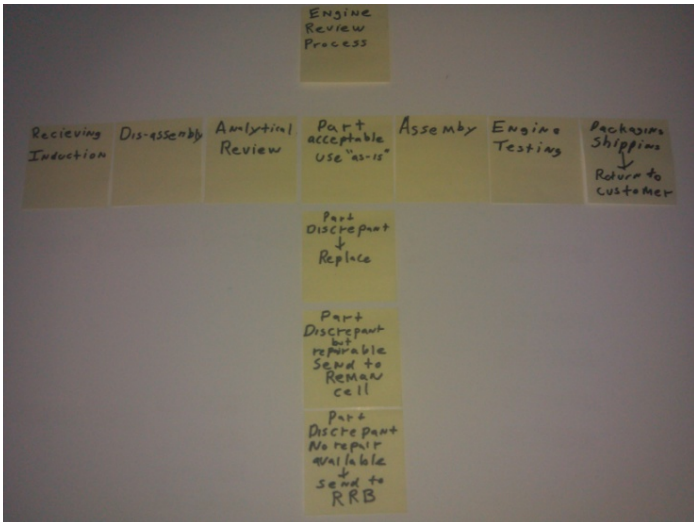


Figure 14: Initial process map of engine review process

Engine Review Process

The overhaul engineer typically has sections of the engine that he will instruct the disassembly mechanic to inspect based on prior dispositions of the same model. If these areas show an issue that the Overhaul Engineer (OHE) deems worthy of further inspection then sectional disassembly will be necessary. An inspection manual based off the engine will dictate the criteria to produce a prognosis of the engine as it is reviewed from main assembly to the sub-assemblies. The manual will have inspection criteria to review these new sections which at this point are still visual only. If it is decided that a full disassembly is necessary, then the mechanic will follow the manual procedure for proper disassembly of the engine. Once the initial steps of the engine review process are complete, the components are segregated into a large cart and bins based on the function. For example, electronic components would be routed to the electrical cell for pass/fail testing. The main parts of the engine will be sent to a neutral cleaning process to prepare for the next step: the analytical review of each component. A summary of this process is shown in Figure 15 and in the appendix for further review.

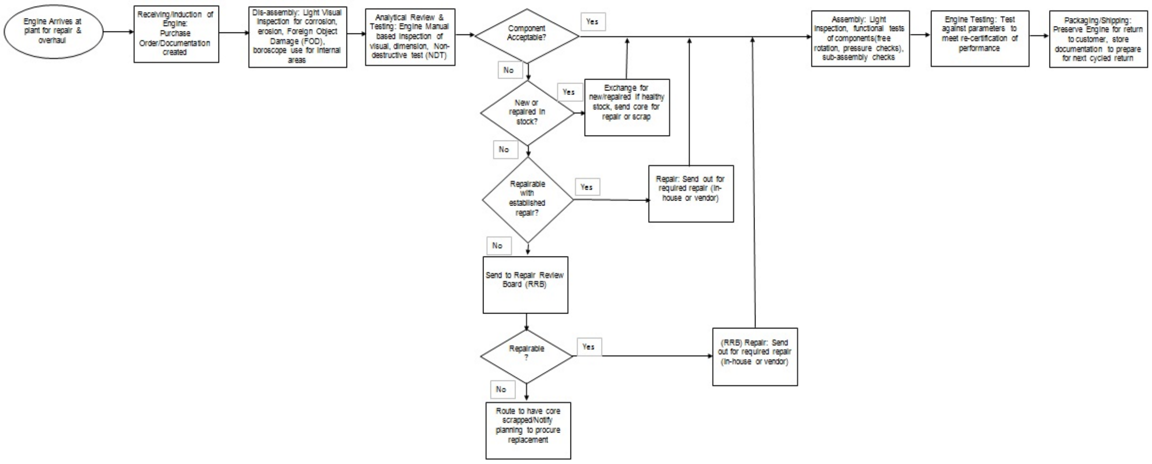


Figure 15: Refined process map of engine review process

During the analytical review process, each component will go through a minimum of a visual inspection. Depending on the manual requirements of the component, further inspection may be required. A visual, dimensional, and non-destructive testing can be common since it is now a single component that is being reviewed. At this point there are several decisions that can be made which depend on the condition of the component. If the part meets all the inspection criteria then it will be used in “as-is” condition to proceed with the main assembly. If the component has a discrepancy which can be fixed by an authorizing document stating the steps of repair then it would be routed to a specialized remanufacturing cell at the facility or to an outside vendor to perform these steps.

Even though a repair can be thought of as the first course of action when a defect is found, there are scenarios where a discrepancy exists that makes it uneconomical or impractical to repair. In this case, the initial component is deemed “scrapped” to be destroyed or sent to part storage for future review. The part demand is satisfied with a new or repaired component depending on the availability. If there are no available units to replace the current part and no current documentation to repair the discrepancy, then it can be routed to the Repair Review Board (RRB) to create a temporary repair method.

The next step in the engine review process is the assembly of all components. This is the step wherein mechanics are under the most pressure. This the time at which over 100 components have been evaluated and it is time to assemble them. Much like the disassembly process, the engine is assembled per its manual. This establishes a standard process for each mechanic. As the mechanic is assembling the engine, he is performing light visual inspection on each component they put on to ensure there in nothing immediately wrong with the assembly. The quality is built upon components becoming sub-assemblies until the full engine assembly is complete and ready for performance testing.

The final step of the engine review process is engine testing for performance of certain outputs of the engine. If it is a propulsion engine then it is mainly thrust, gas consumption, and temperature. If it is an APU then it can be electrical output, pneumatic power, or air pressure since this is partly the function of this appliance for the airplane. This is a pass/fail evaluation which means it meets the necessary requirements or fails. Upon failure, extensive steps are taken to ensure success on the next attempt. First Pass Yield (FPY) is a metric by which an OHE’s product line is measured. It is in the best interest to ensure each test attempt has a great probability for success. It is ultimately dependant on how well the current components support the combustion process because it is critical that the all components function as they were designed.

Whether the components are new or repaired, the end result is fit, form, and function. If there is a discrepancy, it will definitely be visible during engine test. If the engine fails, a root cause analysis is performed by the overhaul engineer and the supporting team to review. The investigation's results will implement an aggressive solution on the root cause to ensure it will not happen on any future tests of this specific model engine. Upon successful completion of engine testing, all the documentation is prepared to be presented to the customer. The overhauled engine is returned to service until the next cycle.

Remanufacturing Cells

The remanufacturing cells are specialized areas of the aftermarket facility which are structured to support the product part families of similar components. The logic behind this type of layout is for products to follow similar processes of machining. The ability to create standard tooling that can work on several parts can drastically reduce set-up times. The machinists and processors of these cells are component experts working with the same product line. This can provide consistency in the repair process. The authorizing document allows for the component to be repaired. The document will be translated into a repair routing that will give the instructions needed at each step in order for the full repair to be successful. These cells not only support the engine line but the product planning of the site because of the immediate need for a component. If production stoppage occurs at the Original Equipment Manufacturer (OEM) of the part, other means of attaining a part must be evaluated. A rough draft and refined summary of remanufacturing process are shown in Figures 16, 17 and in the appendix for further review.

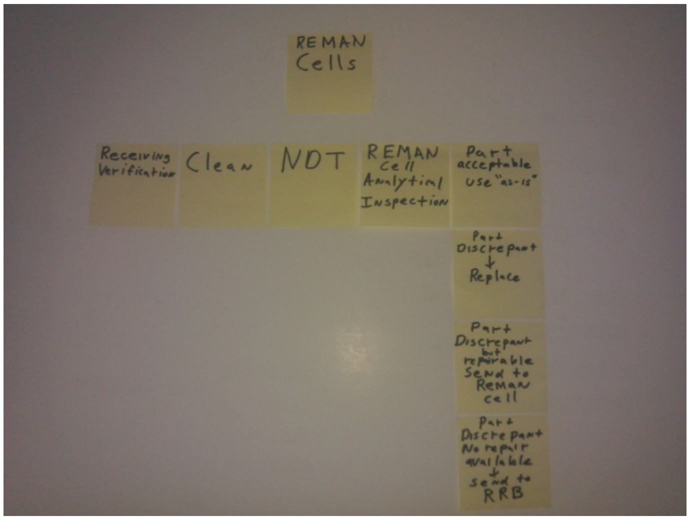


Figure 16: Initial process map of Remanufacturing cells

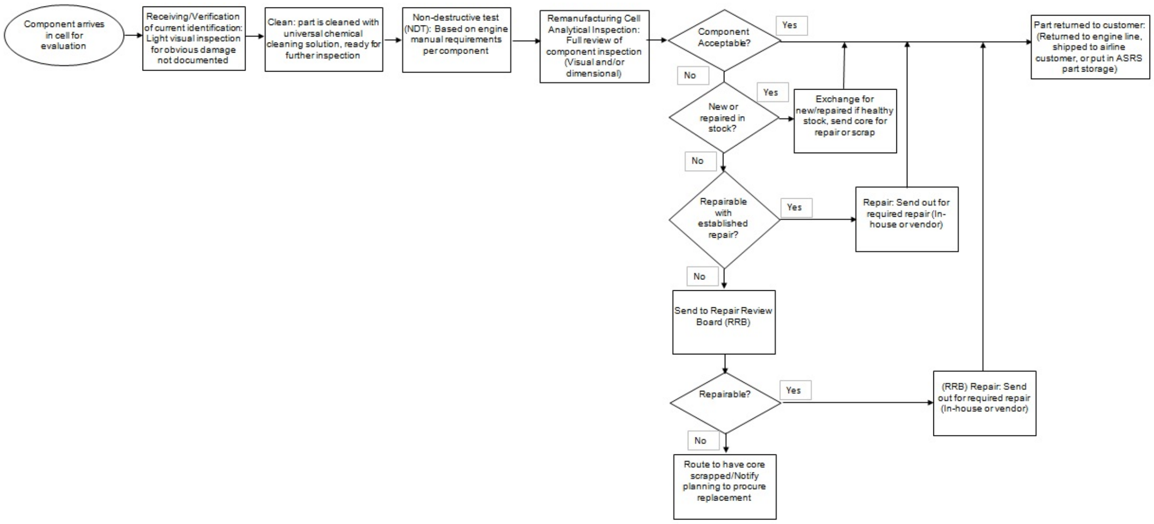


Figure 17: Refined process map of remanufacturing cells

If a new part is unavailable within the timeline of the demand needed, then components in storage are pulled and sent to a cell to be repaired. The demand for specific components is often unpredictable. Because of this, the cells are pressured to expedite products in these emergency situations to assist with the supply chain. There exist scenarios wherein a customer can send a component to a repair facility with specific instructions to perform only the stated work. An initial quote can be given once the repair scope is evaluated. The customer can decide whether to proceed with repairing the core or pursuing other options. This process is known as “fast shop” which offers customers the flexibility to dictate what is repaired based on their own initial inspection. Whether it is a customer direct part or a component with defect from the engine line, there is a typical process that is followed in the remanufacturing cell.

The part will have the initial packaging and documentation related to the customer order. This order will create a work order used to keep track of all the processing performed on the part. The first step of the remanufacturing process is the receiving load center where identification of the part is verified or re-applied as required per a standard marking method such as SAE International standard AS478. This step is critical to ensure the part can be identified thoroughly throughout the process and the correct repairs can be applied. Repairs can be part number and dash number specific. For further information on the standard part marking practice, consult SAE AS478 Identification Marking Methods (SAE International, 2007)

The second step in the process is the cleaning of the component through a process that involves the use of a neutral chemical wash that can be used on several materials to assist with the next inspections. These parts have been in service for some time and can have the presence of anything from dirt, oil, or even feathers. Some parts can have this step included in the first operation due to the component not needing moderate cleaning. The cleaning requirement selected is dependent on the part base material. Composite components, for example, would only need a wet cloth applied to perform this cleaning step.

The next step in the process is the NDT evaluation of the component which can be several methods depending on the base material. This step will be controlled by the manual as to what needs to be inspected and how. These types of inspections can include FPI, MPI, and White Light Inspection (WLI). The intent of this inspection process is to review the part for any cracks, separation of material, or sub-surface imperfections which can compromise the integrity of the part’s strength. The method stated by the manual will be based on the material and the operating environment conditions the component is subjected to.

As discussed previously, MPI requires that the part be made out of a material which can be magnetized. The part will be exposed to a solution that includes iron oxide and an illuminating solution which when a magnetic field is applied. Any discrepancies can be noted under a black light because a crack will form a north and south pole much like a magnet. The solution mix will accumulate in the discrepant area for discovery during visual inspection. FPI works in a similar fashion but without the magnetic field thus it is used on non-ferrous materials such as Aluminum, Magnesium, Titanium, and Inconel. The WLI will be used as a visual inspection for damage which can be seen without any special treatment to the part. Typically, WLI is meant to evaluate the component for obvious visible discrepancies.

Parts that are made of materials such as composites or plastics would have a visual inspection applied since it is impractical to perform FPI or MPI for reasons explained earlier. Regardless of whatever inspection method is used, the process will result in either a pass or fail. Any discrepancies are marked via an approved method to note the area(s) in need of repair. The follow-up procedure will address this and other requirements to fulfill the full inspection of the individual component.

After all the previous inspections and preparations have been completed, the part is now ready to be reviewed by an analytical inspector. This individual’s duties are to review all prior operations performed. Inspectors review the remaining requirements including applying a repair routing to fix each specific defect. The inspector reviews the inspection manual criteria which can include further visual and dimensional inspection. Upon full inspection, the inspector concludes his or her diagnosis of the current state of the part. If the part is customer owned, a quote can be requested to be based on inspection results. A decision to proceed with repair is then based on what the customer is willing to pay for, similar to a consumer taking a car to the mechanic.

At this point there can be several outcomes, similar to those described earlier that the engine analyst will have. If the part complies with all the criteria of the inspection manual and there are no obvious issues then it is certified as an inspected part. This part is returned to the customer or routed to part storage for future use. However, if there is a discrepancy, then the part can be processed on a repair routing to fix the particular defect and re-evaluated for a successful repair. If the discrepancy has authorization to repair but no routing in place then it will be given to the remanufacturing engineer (RME) to create a temporary routing based on the repair document.

The component can have a certain flaw that would make the component non-repairable. An example is physical damage so great that it would be either uneconomical to repair or little chance of full restoration. In this case, the core part would need to be scrapped, notifying the customer while evaluating the replacement options in part storage. If there are no parts to replace the current discrepant one, then it will be necessary under this scenario to perform a forced repair. In this case, the part would be evaluated by an engineering group known as the Repair Review Board (RRB) for an extensive investigation into the possibility of salvaging the product. If the part is in such an extremely deteriorated and damaged condition, that even this group of engineers does not feel it can be airworthy, then the part is scrapped. The supply chain as a team will have to resolve the issue of a replacement part. As stated previously, these process steps are shown in Figures 16, 17, and in the appendix for further review.

Repair Review Board

The Repair Review Board (RRB) is an area of engineering which examines parts for possible repairs based on the current condition of the each part. This specialized group collaborates to find a practical method of restoration to attempt to salvage the core due to the current demand for the part. Similar questions are asked as in the analytical process such as replacement options, need for repair, cost of part, etc. The first step in this process is to identify the discrepancy documented by an inspector prior to being submitted to the group. The discrepancy must be documented clearly, identifying what is wrong, to what degree and what states that it is discrepant. This is documented in a statement of condition violation per said manual. A rough draft and refined summary of RRB process are shown in Figures 18, 19, and in the appendix for further review.

An example of this problem statement can be: “Inlet plenum has crack approximately 3 inches long and through material which violates manual 99-01-99 per inspection criteria, request RRB action to review possible repair, please expedite for engine line”. Once the problem is clearly identified, then the part can progress to the next step which is the engineering review process.

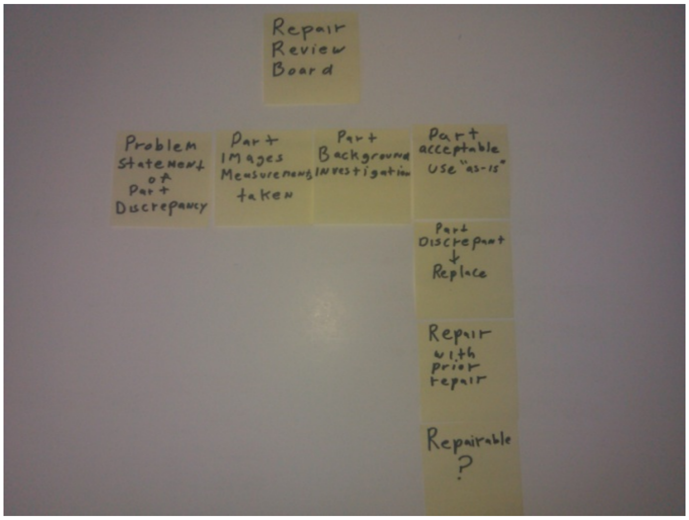


Figure 18: Initial process map of Repair Review Board

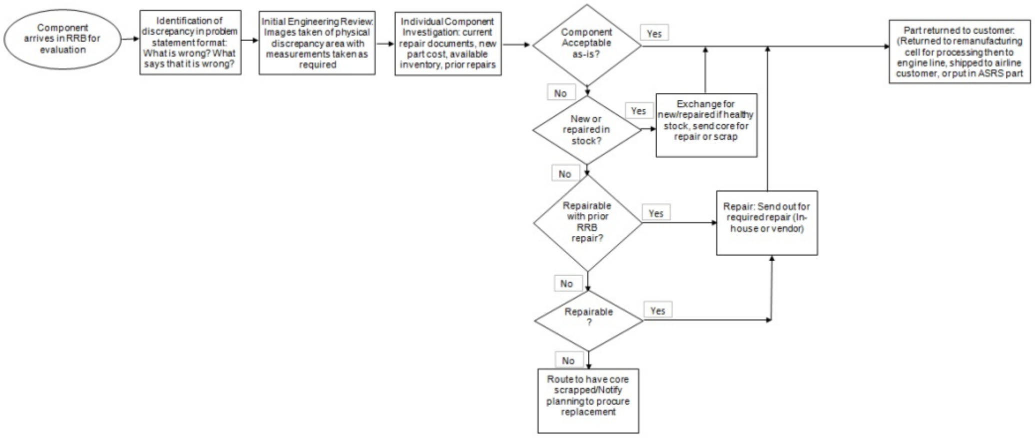


Figure 19: Refined process map of Repair Review Board

At this stage, images of the part are taken to note the original discrepancy. A discrepancy comparison is done to other historical repairs attempted for the same discrepancy. Any prior dimensions documented are re-inspected to verify the current state while other inspections are performed to assist with the brainstorming of possible repairs and calculations needed. After the documentation of the current state of the part is executed, the repair methods are reviewed based on several factors. If the repair has been previously attempted, then a good database will bring this to light relatively quickly, saving engineering time as long as similar conditions existed. The current repair authorization will be reviewed to ensure that no repair document exists or being released shortly by the RDEs.

Though several individuals have reviewed the part, chains in communication can break down. A part could have current authorization for repair but the initial investigation failed to find it. Due to this failure, time can be wasted from the days accumulated on the part in unnecessary processing. This document is designed to address this issue and convey knowledge of the process. If the discrepancy has never been observed before then it will need to be evaluated by several engineers. This group will ensure the part can be restored based on a single method of repair. If a weld repair is to be attempted to fix a crack in a gearbox then it becomes a question of the current capability of the repair station to perform the work requested per RRB instructions. A concern can be raised on the gearbox casting strength from attempting a weld repair. The materials engineer may require that a heat treat process be applied for material stress relief to ensure the state of the component remains within the blueprint standards for the design intent. Because of the welding processes' secondary effects, the structural engineer may advise a pressure test to ensure the gearbox will perform its function under operating pressure without failure in service.

Lastly, the same inspection method or of higher precision will be used to verify that the original discrepancy is fixed. If FPI was the initial inspection method used to find the crack then it is used again unless the RRB engineer specifies otherwise. If the repair is completed per the RRB instructions, then the part is given an approval of airworthiness to continue the remainder of the repair process. The RRB process is a last resort to prevent the core from being scrapped, causing an issue with the supply chain, and shipment of an engine. Even though this area of engineering greatly assists with crisis situations, it is not meant to be a rapid response system. The proactive resolution to this dilemma is through repair development engineering for this and other issues mentioned up to this point.

Repair Development Engineering

The issues mentioned earlier contribute to the need for proactive solutions repair development engineering. A repair development engineer's job entails many areas of the aftermarket facility. One of the areas that have been underdeveloped for this title has been creating repairs for engine components that are coming back from the field. At any given point in time, an engine will come into the repair facility as mentioned in the engine review process (pg 23). If there are no repairs for the components then it will be processed with a lot of non-value added actions that could have been avoided. RRB is meant to avoid crisis situations but isn’t meant to cushion the negligence of not having line of sight on future repairs.

As an example, in January of 2013, an APU model was coming in for only engine testing but was found to have a discrepant seal in the composite inlet plenum that would affect performance. The same day, the OEM project engineer at a different site had submitted a request to create a repair for the same issue as it had been reported to him by field observations months ago. There were large quantities of engines of this model in the field which were scheduled for maintenance checks during the upcoming months at the repair facility. The author was called upon to create repairs for the inlet plenum within a 24 hour period. This situation could have been avoided if several areas of the company such as project engineering, product planning, and RDE communicated to each other early in the process. However, it is ultimately the RDE’s duty to be proactive at every turn. The aftermarket follows the same metric requirements as other manufacturing divisions in the need for continuous improvement. Assisting to avoid these issues as an integrated supply chain may require early work. However, long-term benefits include avoiding the financial consequences of an unhappy customer, which exceeds the hassle of extra engineering work.

All aerospace engines, including several models of the latest design, will come to a repair facility once they have been in service for some time. In all cases, there are common of discrepancies observed on these engines. The OHE will notice that a pattern of discrepancies occurs on parts even when not foreseen during the design implementation and engine testing. Due to part cost, this needs to be addressed to provide an economical solution versus constant new part replacement. This issue can range from inserts that always needs replacement, cracks in a high stress point of a part, or visually worn surfaces. The OHE must have a sense of urgency to contact the RDE for review and substantiation for the creation of a repair to address the problem part. This will allow for full review of the cost of a new part over repair data. This can include estimated repair cost, part volume, part function, current facility capabilities, and other factors to ensure that this repair will not only save the customer and the repair facility money but also become a reliable repair to fix the root cause. The possible repair sources for typical repair development engineering work scope are shown in Figure 20.

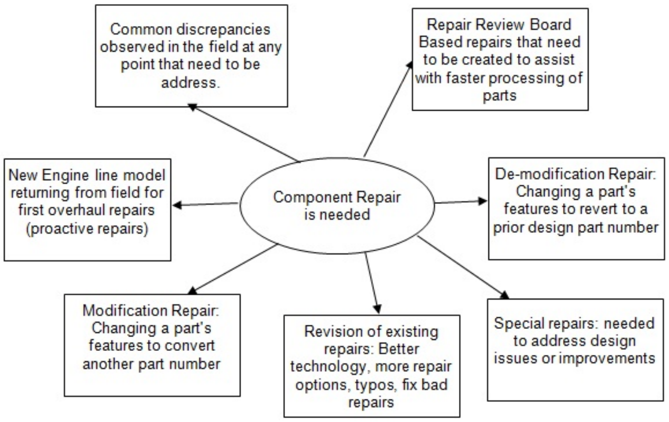


Figure 20: Possible repair sources for Repair Development

As stated before, the RRB is not a rapid response group and is meant to evaluate desperately needed crisis parts. If a discrepancy has been addressed in an RRB disposition in the past, then there needs to be a repair created based on prior successful documented repairs. This will help both the RRB and the RDE in learning from each group's role and working in conjunction to keep product moving. The RRB disposition is a highly calculated legal document, which includes the justification of why the part, if repaired in a certain form, is airworthy upon completion. The RDE will in turn evolve the documented repair created by RRB to create a repair authorization document in a standard form with each necessary step in a structured manner. Upon completion, the RDE's new repair document can now be applied at all repair facilities around the world if noted as such to help with the original discrepancy.

Another common RDE duty is modification repairs. The different designs of the same basic part are identified with dash numbers, for example, part number 38449130-2, where the "two" is the dash number. The physical difference could be as small as a dimension, extra holes, or even another type of paint applied to a part. It is up to the RDE to review the requirements for feasibility to transform part "A" to part "B". The demand for this type of repair comes from several sources, such as new engine models which typically use newer dash numbers when only earlier dash numbers are available in the current inventory. Another example is if there is an issue with the previous dash number, such as wear observations from the field, and the new dash number has been designed to be the solution. Again, both the company and customer must review the cost factor since new part replacement is not always desirable. The modification process is not limited to dash numbers. A part can be modified to a completely different part, given that the repair is feasible and there is demand for the modified part. If the modification repair is deemed possible by the RDE and can satisfy part requirements, then it will be pursued as an option.

De-modification repairs are necessitated by scenarios involving complications with the latest dash numbers observed in the field. Airline mechanics and Field Service Engineers may observe abnormalities in the performance of the part. The RDE needs to review the feasibility of reverting back to the prior designs to satisfy the part demand. If the company only has the latest dash number in inventory, the difference will be evaluated. If successful, the de-modification repair can make use of the current inventory to address the crisis. Whether it is a modification or de-modification, ultimately, the customer chooses to perform the repair, regardless of the repair type. Typically, these repairs are performed because they result in better performance or longer service life. However, the customer must be willing to pay for this change of configuration or must otherwise buy a new part of the earlier design.

In the infinite effort of continuous improvement, change is inevitable yet resistance is a very natural phenomenon. Even in the aftermarket, there is evidence of this in revision control. This resistance exists partly because of the engineering substantiation required. There are various levels of approval involved in changing a document approved by the FAA to repair a discrepancy. Two engineers will deliberate on possible changes with one exceeding the reasoning of the other to come to terms with the changes proposed. The practice of revising existing repair documents is a proprietary controlled process to meet the requirements of FAA regulation Part 145 mentioned earlier (pg 21). Revision control is critical to knowing what has changed in the past and the approval step for a change to be implemented. The justification of the change can be the incorporation of new technology such as performing powder feed welding versus standard gas arc welding. It can also be driven by the need to have options when performing a repair. If a repair method's limitation cannot resolve the observed discrepancy then the RDE needs to document another option in the repair authorization to prevent possible engine line stoppage.

A real-world example of repair alternatives was an instance where a coating is typically removed through the use of chemical application. After some time, it was found to be ineffective after a certain amount of coating thickness. The option was created to route the product to have the coating removed via the mechanical process of Water Jet Machining (WJM). This process applies water at high pressure through a nozzle to perform various functions such as material removal (El-Hofy, 2005). In this case, the coating is a thin layer that under the force of the WJM stream will fall apart under the controlled parameters. Even the best RDE can make mistakes in the form of an unsuccessful repair upon application to a physical part. An unsuccessful repair can be the result of unforeseen inputs to produce the undesired output. When these repairs are unsuccessful, the RDE must review alternatives.

The revision review process will find an alternate solution that has the ability to produce the desired results. If a weld repair of a crack continues to fail after FPI, the final qualification of a weld, then the process needs to be reviewed. If the inputs of the process including personnel, equipment, and environment, are not the issue, then the method of repair needs to be questioned. In certain instances, it may be more practical to perform a patch repair on the part. A patch repair means a piece of sheet metal stock is placed over the discrepant area and secured together with rivets or other options. This will address the immediate crack or discrepancy. As there is now an increased material thickness on the part, a patch repair can even eliminate the need for future repairs.

Special repairs created by the RDE, address crisis situations when a component of an engine needs to be tackled. A Service Bulletin (SB) is an aerospace industry-standard document created for this communication. An SB is an FAA approved notice which publishes special information concerning equipment or provides modification instructions. This document is meant to notify customers of certain modifications and part substitutions to engines and accessories that require a record of accomplishment. An SB is issued when particular types of changes occur to parts and components which affect field engines. The type of SB issued will depend on the urgency of information and type of change being incorporated. This communication can be presented as a request to perform an activity that is optional to the customer. At the recommendation of the manufacturer, an SB is issued in a fashion similar to a car company's recommended maintenance schedule.

In a different scenario, engines listed in the SB are to be sent to the nearest repair facility for replacement or repair of a component due to concerns over the reliability. It can state to replace part X with part Y and continue process or to repair part X per the stated instructions to accomplish restored reliability. These special repairs will drive the customer to perform actions needed for mutual benefit of keeping the engines running, since an airplane that is grounded will not be producing money for the airlines. The majority of SBs will not be involved with this extreme case but as a repair development engineer, it is part of the process that must be known just in case it is ever mandated.

Aerospace Engine Sections and Common Repairs

A gas turbine engine works on the principle of energy extraction from the flow path of the hot gases which are produced by combustion directed to the turbines. The air coming into the engine will start off at a low pressure and a high velocity. This air flow progresses to a high pressure and a low velocity. At the combustion stage, the highly pressurized and oxygenized air is properly mixed with the fuel with a timed ignition. This in turn will have the ingredients necessary for a very hot flame that produces hot gases at high pressure and in a high temperature that will flow through the turbines. As these gases pass through the turbines, they will accelerate while losing pressure to the energy conversion. The process of converting energy to shaft power will drive the compressors and other accessories as the engine increases in complexity. The high velocity is what produces the thrust as a major output of the gas turbine engine (Treager, E., Irwin 1970).

The baseline for this process can be described similar to the Brayton cycle in which the pressure-volume (P-v) and temperature-entropy (T-s) are shown in Figure 21. The majority of engines today are designed to increase the capability to repair and replace these components without dissembling the engine completely or in some case, removing the engine (Henhoeffer, R. Thomas, 2008).

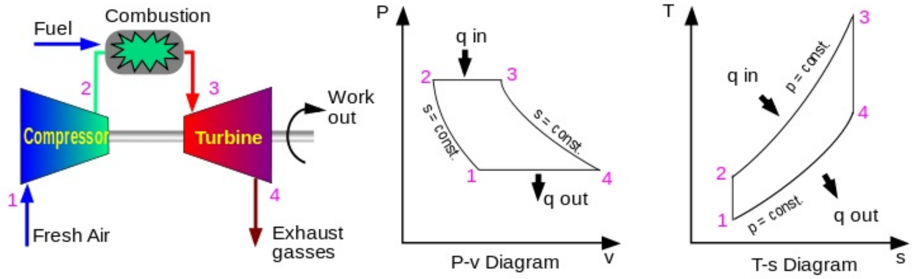


Figure 21: Simplified Gas Turbine cycle with P-v and T-s diagrams (http://www.wikipedia.com)

An aerospace engine can be reviewed in four sections for evaluation of the repairs needed based on the type of environment of component operations. The Intake-Compression-Combustion-Exhaust (ICCE) methodology is the description of the internal combustion process as it relates to the actual sections of the gas turbine engine. Each of these major areas can be broken down into modular components which describe the scenarios of possible operating condition that contribute to the wear and damage of the engine. The figure below is the initial step in the attempting to provide order to the ICCE repair review process to be described as shown with a basic process map. Each row signifies the specific area relating to ICCE along with the typical repairs based on part field observations and area component review. From this raw tool, further details will follow about the condition of each engine section along with an evolved version of what is shown in Figure 22.

Figure 22: Draft of repair process maps for the four engine sections

The intake component section is the start of the cold process in which air come into the engine, preparing for the next process step: Compression. As stated previously, the ambient air is in a state of low pressure with high velocity which must be changed as it enters the compression area. The opening of the air flow path will be relatively large to allow for a large amount of air to pass through while progressively tapering off to assist in increasing the pressure. Electrical sensors can be attached to these components to measure parameters such as air flow, moisture, and provide feedback to the plane's main recording computer and the pilot.

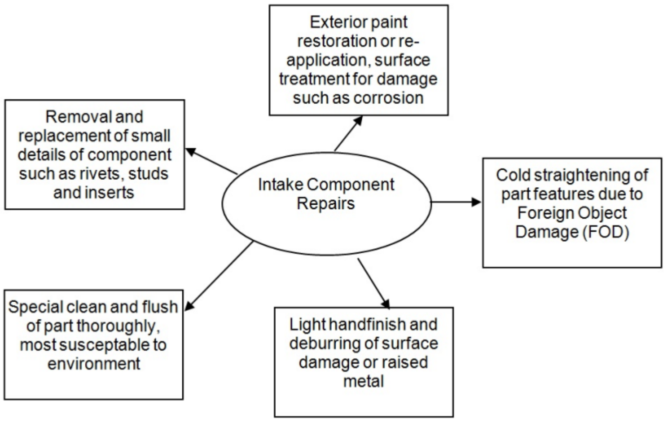


Figure 23: Intake component repair common practices

Figure 23 shows typical repairs for the intake zone and are generally small in nature because the design function is for the entrance to the air. However, because it is the immediate area of opening, it is susceptible to various kinds of debris damage. Repairs for what is expected could include general hand finish repairs to clean up nicks, scratches, dings and discoloration. Any rivets, nuts, bolts or fasteners would be replaced. Thus, the above repair process is faster in comparison to others.

The compression component section is a series of mechanical steps in which the ambient air is converted to pneumatic energy. The resultant increase in pressure prepares the air for the combustion stage. The sealing and routing of air is critical for proper pressure build-up and prevention of lost energy. Depending on the outside environment and the revolutions per minute (RPM) of the components, optimal compression can be achieved by turning a high velocity, lower pressure environment into a low pressure, high velocity environment.

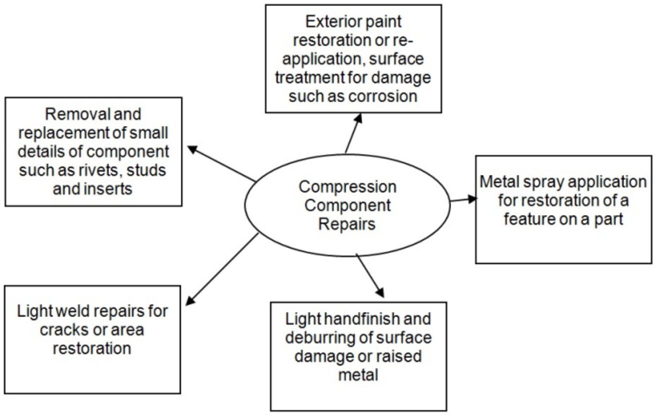


Figure 24: Compression component repair common practices

For this area to function optimally for compression through the different cross-sections and proper airflow, this area’s components require tighter tolerance for repair back to serviceable conditions. Repairs shown in Figure 24 include weld repair which may be associated with heat treatment for weld strength. They also include the NDT that is a fundamental FAA requirement. Some sub-components can be removed as an assembly wherein some parts are replaced or fabricated, so long as the entire unit can be restored to work together. This area must have proper sealing for the function of this modular section of the engine to function according to its design intent.

Balancing and centering becomes critical because most of the parts of the compression section are rotating components. The repairs can vary depending on the evaluation of each component and the wear factor on the engine, but typically these are the second longest repair time of the four areas described. This section can be a suitable opportunity for repair development as the tendency is to pursue new components for replacement versus repair of the current parts, since the damage is often found in the same location. The balancing will serve as a mechanical test of the components ability to rotate at operating speed while not becoming a contributing factor to the excessive vibration between engaging components and assemblies.

Unbalance in single rotating component may cause the entire assembly to vibrate. This vibration can cause extreme wear on the components of the assembly and significantly decrease their service life. The assembly as a whole will transfer the stress created from the vibration of the rotating components to the supporting structure. If this stress becomes too great on the structural supports and static components, it may lead to a complete assembly failure (Trebel, 1990). Whether the rotating component is being repaired is in the compressor section or not, balance is an important step in repairing these types of components.

The combustion component section will deal with an environment in which the air has been highly pressurized; it will convert the pneumatic energy created earlier to thermal energy. The air is guided towards the fuel atomizers where fuel particles blend with the compressed air for the beginning of the hot section process of combustion through ignition of all elements. This is the direct power generation for the entire process as this new energy begins its entrance into the next stage for another energy conversion.

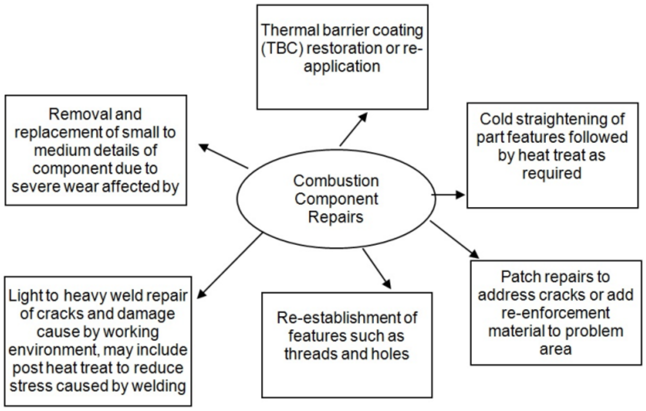


Figure 25: Combustion component repair common practices

The common repairs shown in Figure 25 are the most time consuming due to the damage from exposure of the combustion process. Thermal distortion and discoloration will be seen upon disassembly of this section which can later be observed through crack propagation. The components made out of these alloys have a limited life cycle which must be maintained in order to know how much repair can be performed to each component in this area. These will have weld repair loops similar to that of the compression zone but also include other tests such as pressure test, airflow adjustments and higher level NDT inspections such as X-ray. The pressure test will serve as a functional evaluation of the component to ensure no leakage is present that would hinder performance.

The failures experienced in the repair process can send a repair to be attempted from the beginning if it was not completed satisfactorily per functional tests and FAA mandated inspections. Due to this common problem, lean manufacturing concepts can be applied to the repair for potential improvements in first pass yield and other remanufacturing cell metrics. The typical practice of repairing a crack is performing a weld repair per the American Welding Society (AWS) D17.1 standard, Specification for Fusion Welding for Aerospace Applications. Since this process brings the material to the melting point and strains the product from performing a weld, the possible consequences need to be evaluated along with viable options to address the original discrepancy. This area of components will need the assistance of new technology to meet the aftermarket repair needs of faster completions for repaired products for the engine lines.

The exhaust component section is where the combustion energy is created. This energy follows the guided path through the turbines, which convert the thermal energy back to mechanical energy to rotate components in the compressor section and other accessories. The hot gases produced run through the last step as it rotates turbines connected to a main shaft or curvic coupling to synchronize the parts together. The thermal energy converted part of itself to pneumatic energy as it passes through the last rotating components. It exits the system through the static exhaust components to produce thrust for the engine and the airplane. The energy of the thrust produced at this level is guided into various part configurations to assist with heat dispersion, noise reduction, and general mechanical diagnostics.

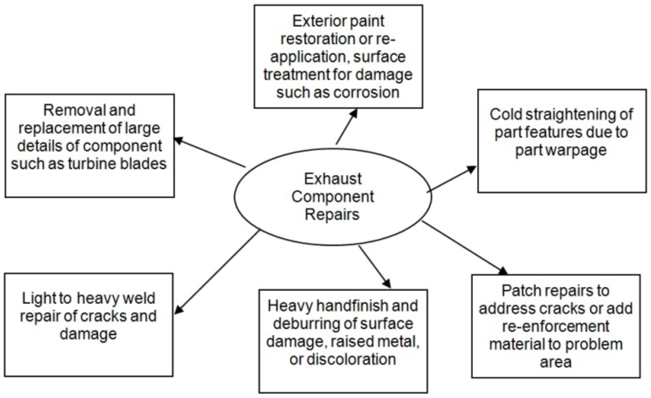


Figure 26: Exhaust component repair common practices

This last section of the engine deals with some of the damage observed from the heat exposure but not as intense as the prior area. Weld repairs are applied for small indication or damage but it mainly consists more of smaller restoration requirements including thermal coating patch mending as seen in Figure 26. There may be extensive straightening needed due to expected distortion. This requires the least time investment for repair completion than any of the other zones.

PART ANALYSIS

The previous sections have laid the mental framework for the review of a real world example of aerospace discrepancy and how repair development engineering can restore the part to airworthiness. As discussed in the introduction, the Design of Repair Development method, shown in Figure 27, is a tool for identifying the desired repair method. In the section, the DRD tool will be further broken down to each of the three sections as a discrepant aerospace component is evaluated using this procedure. The repair intent is to restore a feature to adhere to its blueprint design requirements, including any geometric dimension and tolerancing (GD&T) specified. As previously discussed, there are several methods that can be used such as welding, metal spray, surface plating, patch repairs, and installation of new details. After review of possible repair methods, one method meets the requirements within cost, technically feasibility, and aerospace standard practice.

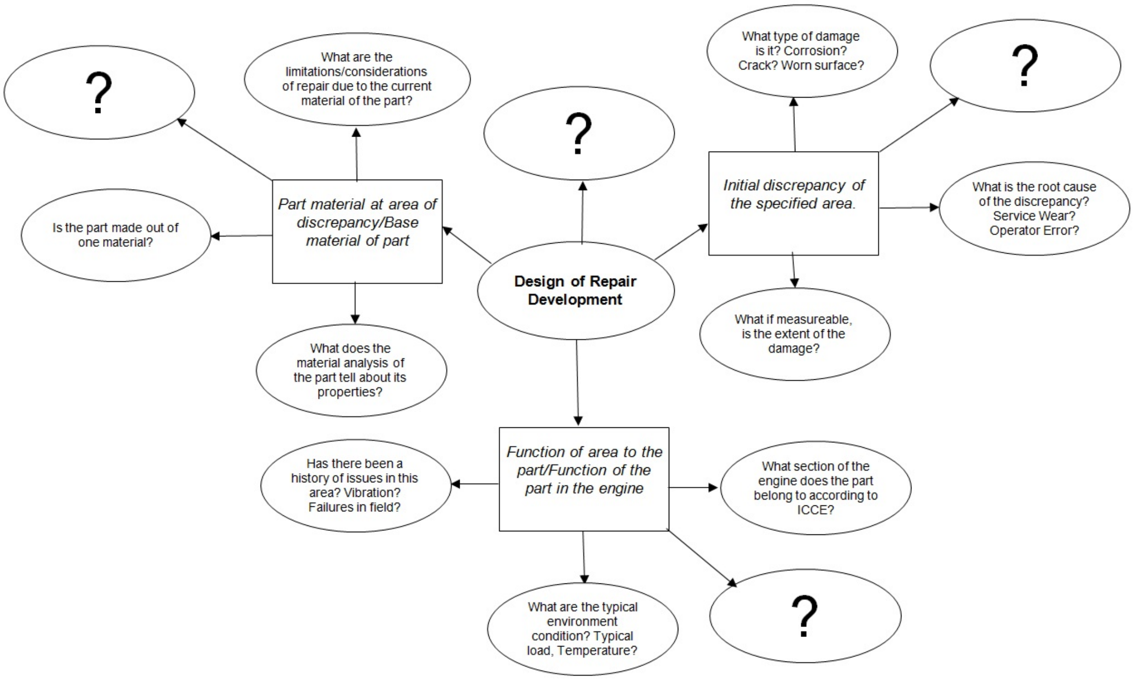


Figure 27: Design of Repair Development method

Figure 28: Aerospace part with discrepancy

Figure 28 shows a rotating component of an aerospace gas turbine engine known as a tie shaft which was found to have one of the outside diameters of the part to be discrepant per the limits of the blueprint. In the practice of the DRD, this part was reviewed to implement the high level steps of the tool and was further evaluated into sub-steps as required.

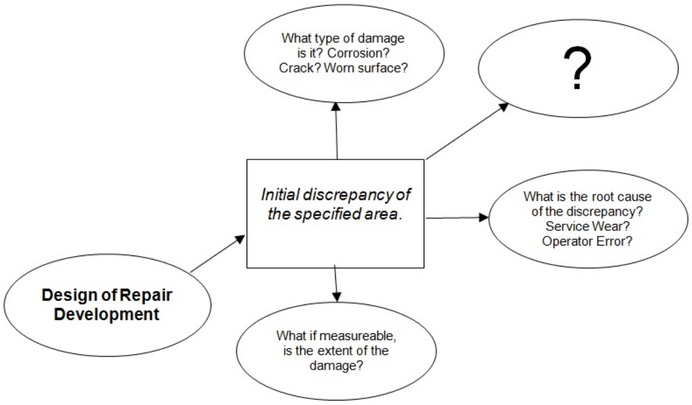


Figure 29: Discrepancy review of DRD tool

The first step in reaching a repair was reviewing the initial discrepancy as shown in Figure 29, the segregated portion of the DRD tool. The type of damage that caused the discrepancy was most likely from service wear while interacting with the mating component. The visual damage will dictate that the extent of the discrepancy be evaluated through measurement if possible. In this case the outside diameter shown is required to be 1.2345 to1.2348 inches. At the time of evaluation at the repair facility, the part measured to be 1.2335 inches. In comparison with the blueprint requirements, part condition has the discrepancy of this outside diameter undersize by

.0010 inches. This outside diameter where the discrepancy was located was at approximately halfway distance of the entire part as shown in Figure 28.

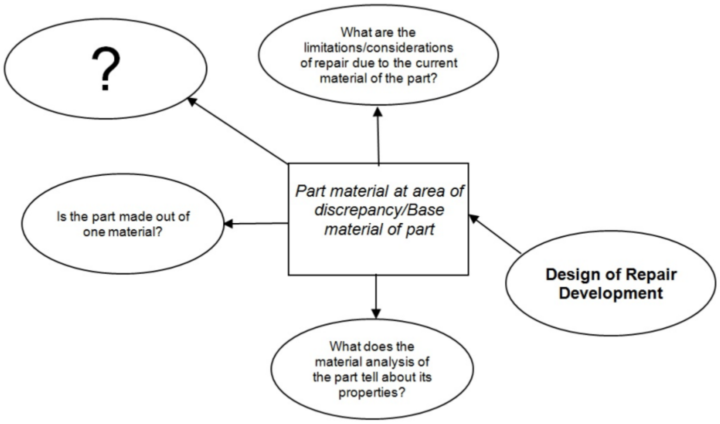


Figure 30: Material review of DRD tool

The second step of DRD, shown in Figure 30, was the material evaluation at the immediate area of the discrepancy and the base material of the part. In some cases components can be fabricated with sections that are made of different material and special consideration needs to be taken into account so that the proposed repair will not affect the design intent of these subcomponents within a part. In this case, the entire part was made out of the same material and was fabricated as a single piece without subcomponents from heat treated bar stock. During the initial investigation of the part discrepancy, the material of the component was found to be Inconel 718, a nickel based “super alloy” used as a base material on various aerospace components due to the mechanical properties typically associated with it. Each material can be given specifications in the blueprint to meet the requirements of the design intent of the components which can include certain manufacturing processes. The variety of manufacturing techniques is large and is dependent upon a number of factors such as the material from which the part is made, the duties the part must perform, and the cost of the process (Treager, E., Irwin 1970).

One of the material specifications behind this component is the Aerospace Materials Specification (AMS) 5662. This specification requires that the component meet material properties when new production parts are fabricated such as material yield and ultimate strength (ksi).

Further specification can be specified in the blueprint to detail other factors of the material condition such as “heat treat” requirements, in this case per AMS-H-6875, which are processing procedures that alter the mechanical properties of the material to suit the end use. Nickel alloys such as this one are often used because they have unique physical property characteristics after being heat treated. In the review of the material of the part, it was important to remember that many nickel alloys can be covered by a code body of specifications (ASTM, AMS, SAE, MIL). Further research can be investigated on nickel alloys under the American Society for Testing and Materials (ASTM) number and Unified Numbering System (UNS) number. (Budinski, K. G., & Budinski, M. K. 2005).

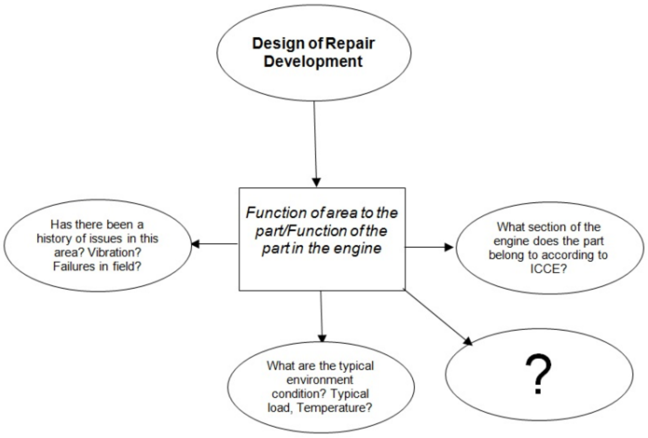


Figure 31: Function review of DRD tool

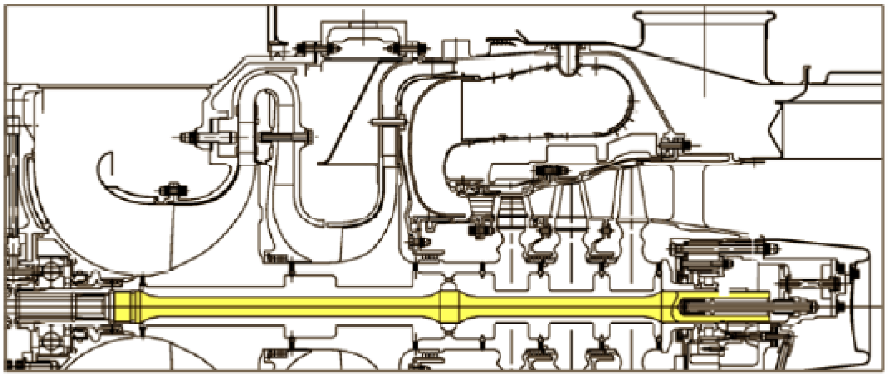


Figure 32: Partial engine cross-section highlighting the discrepant part

The third step of the DRD, shown in Figure 31, was the function of the area of the component and the function of the component itself in the engine. As shown in Figure 32, the tie shaft is a rotating component which connects various other parts of the engine to transfer power and address further functions of the engine. This tie shaft is often connected with other components by thread connections which do not function during engine operations and are used only during assembly and disassembly of the rotating group. This component is called a tie shaft partly because it ties together the rotating components that form the power section of the gas turbine engine.

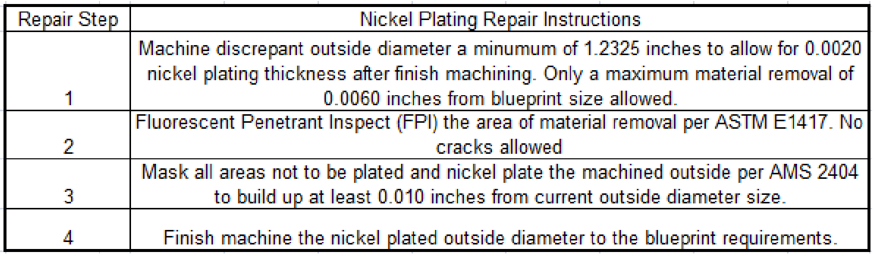
The main force on the part was tensile load that is generated when it is stretched during assembly. Each of the shaft section is subjected to the same axial load. For operation in an assembly, both the outside diameter of the shaft and the inside diameter of the mating components had engineering controlled size differences required by the individual blueprints to insure a certain fit between mating components to prevent these parts from becoming loose during operating temperatures.

Most rotating components are considered critical to the process of the gas turbine engine and thus need to ensure that following successful completion of the proposed repair, the part will be structurally and functionally acceptable for use. For each component in the engine, a material analysis was executed to perform an investigation of the component by carrying out various tests such as fracture examination, hardness, dimensional check, and mechanical properties. This test can sometimes be a destructive test to evaluate the strength of the material for assistance in product life evaluation and aftermarket evaluation. The repair development engineer will need to be able to extrapolate the needed information from these tests in order to assist in making a sound decision for a repair process. In this case, the investigation was about the 1.2345 to 1.2348 outside diameter and all tie shaft information related to this component.

Finite Element Analysis, standard stress calculation, and other engineering tools will need to be used to further calculate the effects of the current discrepancy of the part on the material. Some of the common question asked on rotating components: What was the current cross-sectional area now due to the current discrepancy? What was the cross-sectional area percentage difference due to the current discrepancy? What were the critical areas on the part? What was the stress ratio? What was the increase in stress concentration by the force from the operating load on the part? What was the current margin of safety for yield or ultimate? As stated previously, the main load on this part was tensile load that was generated when it is stretched during assembly and each of the shaft sections was subjected to the same axial load. When reviewing possible repairs, it was critical to review the condition in which the component operates.

After the three elements of the DRD were reviewed extensively, possible repair methods were evaluated for feasibility. For rotating components, it is not practical to try to attempt to weld repair an outside diameter for restoration as this will greatly affect the component’s function. The typical standard for outside diameter restoration is a plating or metal spray process in which a compatible alloy is built up on the material so that it can be machined down to original size. As long as both processes can meet the original blueprint requirements, either repair method can be applied so it is in the best interest of repair station to have repair process options. For the purposes of this component, a nickel plating process was proposed to restore the part to airworthiness integrity satisfying fit, form, and function.

Table 2: Repair Development method for outside diameter



Repair Step	Nickel Plating Repair Instructions
1	Machine discrepant outside diameter a minumum of 1.2325 inches to allow for 0.0020 nickel plating thickness after finish machining. Only a maximum material removal of 0.0060 inches from blueprint size allowed.
2	Fluorescent Penetrant Inspect (FPI) the area of material removal per ASTM E1417. No cracks allowed
3	Mask all areas not to be plated and nickel plate the machined outside per AMS 2404 to build up at least 0.010 inches from current outside diameter size.
4	Finish machine the nickel plated outside diameter to the blueprint requirements.

In Table 2, the proposed steps for restoration of the discrepant outside diameter were outlined in sequence of required execution. The nickel plating process requires that the outside diameter be machined down to allow for even plating build up and remove the initial discrepancy. The Fluorescent Penetrant Inspection (FPI) was needed to ensure no cracks are present on the surface that was machined. The process of nickel plating was contained within the AMS specification noted to perform the necessary steps that complied with this specification. Upon successful completion of the nickel plating, the part was to be machined back to the requirements of the blueprint such as size, surface finish, and Geometric Dimensioning and Tolerancing (GD&T).

Nickel and other plating methods can produce a surface which can be as functional or in some cases even better than the parent material. In traditional manufacturing, plating is used when new parts are machined to provide a surface which can assist in the part function. It was a matter of researching these special processes through on the job experience, consulting with special process control engineers and reviewing the engineering history on what has been applied to similar parts. There were extensive engineering calculations that were invested into each component that functions on a gas turbine engine. It is the RDE’s duty to review the current conditions and factors surrounding the part through a critical thought process and pursue the engineering resources as necessary.

As stated previously, several factors have to be taken into account in order to attempt a proposed repair and some of the further thought processes required to find the best possible options for repair development will come from applied experience. In some cases this may require involvement from specialized engineering support such as structural design engineers, material science engineers, project engineers, and overhaul engineers to ensure all the critical elements are reviewed. The Design for Repair Development method is an applied tool that will reveal the gaps in engineering support and aid in the request for resources if necessary. For this example, the tool was applied in all phases to save a quantifiable amount of engineering time in restoring the part to airworthiness.

CONCLUSIONS

Conclusions

This research document investigated the study into the creation and application of repair development methodology that can be utilized by current and new manufacturing engineers of the world. For those that are currently working in the aftermarket repair stations, this research provided a thought process that can be built upon to suit their needs. The engineering students who are less experienced will find a baseline of critical thinking in preparation for typical engineering issues to be resolved in the aftermarket industry. In the process of development of the tools and figures, it was an educational procedure to inform the reader about the various aspects that involve the remanufacturing and restoration of aerospace engine components. Each of the sections discussed can be further investigated to attain a deeper understanding from what was presented in this thesis.

As stated in the introductory pages, the principal objective of this research was to build a methodology around the practice of repair development of aerospace components. This study was meant to inform the reader in a structured manner about the process of evaluation of a component in a proactive and reactive approach. The DRD tool was used as a means to derive to a repair to address discrepancies of an aerospace engine component by reviewing the three factors such as part function in which they operate in the engine. Each of the research objectives was answered at several levels through the educational process of the document flow to culminate with an aerospace part analysis to apply the methodology of DRD. Each of the three sections of DRD were explored and applied in the part analysis section when an aerospace component example was presented. The document's anticipated results yielded several outlined processes that are part of the repair development engineering environment which are part of documenting the methodology of the repair development process.

To compare the time savings capability of the DRD tool, a repair document was chosen based on the timeline of the author's promotion date to RDE. In June 2012, repair document was requested to be created by the author to address the discrepancy of cracks ranging from one to six inches on an inlet plenum for an APU. Between research, documentation, and airworthiness substantiation, the repair development took ~120 hours to complete. Due to the ambiguity of the starting point for repair development, the author made several mistakes in the process of creating a repair.

The first error came from not having investigated thoroughly the part material of the plenum. The first draft of the repair document was repairing cracks with weld repair under the assumption that the material. It was revealed to the author during review by the materials engineer that the outer shell of the plenum was actually made out of two sheets of different metals, aluminum and stainless. A test part used to examine the possible weld repair also distinguished this material combination and unfortunately was scrapped due to the attempted weld. The process of welding to address the cracks was not a practical approach due to the part material.

Another mistake made was not remembering the function of the inlet as a static component which encloses the ambient air to start the compression process. This component will not be exposed to extreme loads or temperatures so less aggressive repairs can be performed to address the cracks. In an APU, this component is part of the intake section of the engine; therefore typical repairs can be reviewed for possible solutions. The field observations of cracks ranging up to six inches would require a repair to address this amount of variability. After reviewing the material, function and discrepancy, the final repair proposed was a patch repair using sheets of aluminum to cover the cracks. Each patch would be applied with standard rivets used in other areas of the part to match the similar design intent. In comparison to weld, the patch repair would not require an NDT inspection, no heat propagated distortion, and add reinforcement material to the part, all resulting in faster processing time. If this repair development had been implemented using the DRD, the document would have been completed in ~40 hours. When comparing to the initial timeline of ~120 hours, if the cost of engineering is ~$125 per hour then it becomes an engineering savings of ~$10,000 per repair project. Since the creation of DRD, the author has applied this tool to over 10 repairs with processing times ranging from 30 to 40 hours. It is the author’s intention to share this tool across the company to educate and assist in the aftermarket industry on the practice of repair development engineering.

Recommendations for Future Research

The scope of this thesis was limited to the current practices of the aerospace industry. Further research in repair development can be executed in emerging technology that is being developed and applied specifically for the aftermarket industry such as Cold Spray. Cold Spray is newly implemented process that has observed expanded applicability in the aftermarket industry. Cold spray a kinetic spray process that utilizes supersonic jets of compressed gas to accelerate the near-room temperature powder particles at high velocity. These powder particles move at speeds ranging from 500 to 1,500 m/sec. These un-melted particles plastically deform and consolidate on contact with their substrate to create a coating (Accuwright Industries, 2013). This technology has been used primarily to restore features that have been repaired previously with other repair methods. Similar to existing repair practices, this process has its advantages and disadvantages along with extensive substantiation that needs to be provided to justify the need for the new repair process. New and existing Non-traditional machining methods will have to be researched to review the possibility of application in repair development. It will be the RDE who dares to try these technologies that will have the advantage of research exploration to provide their company with the technological advantage, and potential patent possibilities. The future of repair development engineering in aerospace engines will be driven by those who can think innovatively and see the simple in the complex. “The aerospace aftermarket has and always will be an engineering-driven industry, what is great today will be considered only good tomorrow.” (Shepardson, T. 2013)

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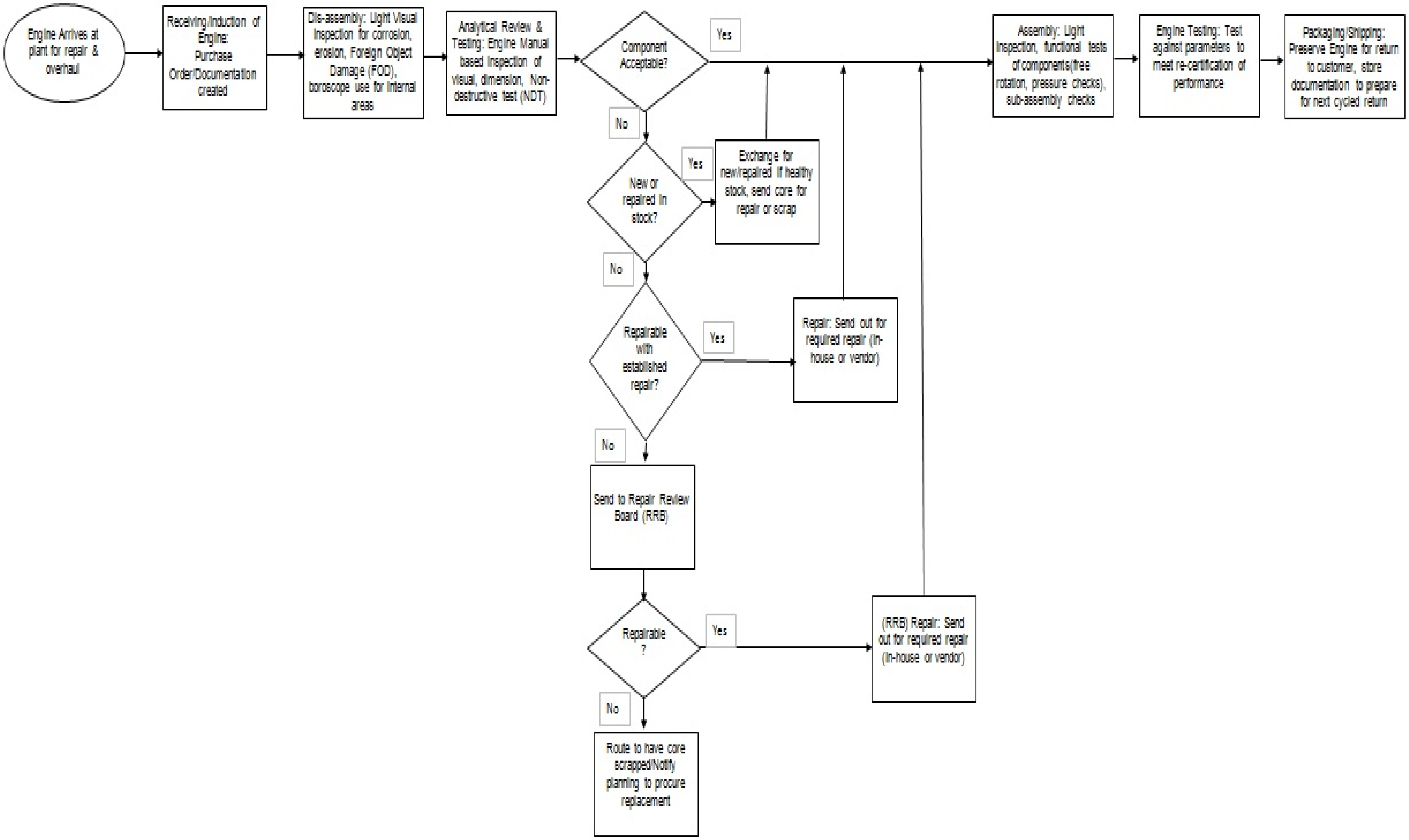
APPENDIX A

INITIAL PROCES MAP OF ENGINE REVIEW PROCESS


Engine Review Process
Recieving Induction
Dis-assembly
Anlytical Review
Part acceptable use "as-is"
Assemby
Engine Testing
Packaging Shipping ↓ Return to customer
Part Discrepant ↓ Replace
Part Discrepant but repairable Send to ReMan cell
Part Discrepant No repair available ↓ send to RRB

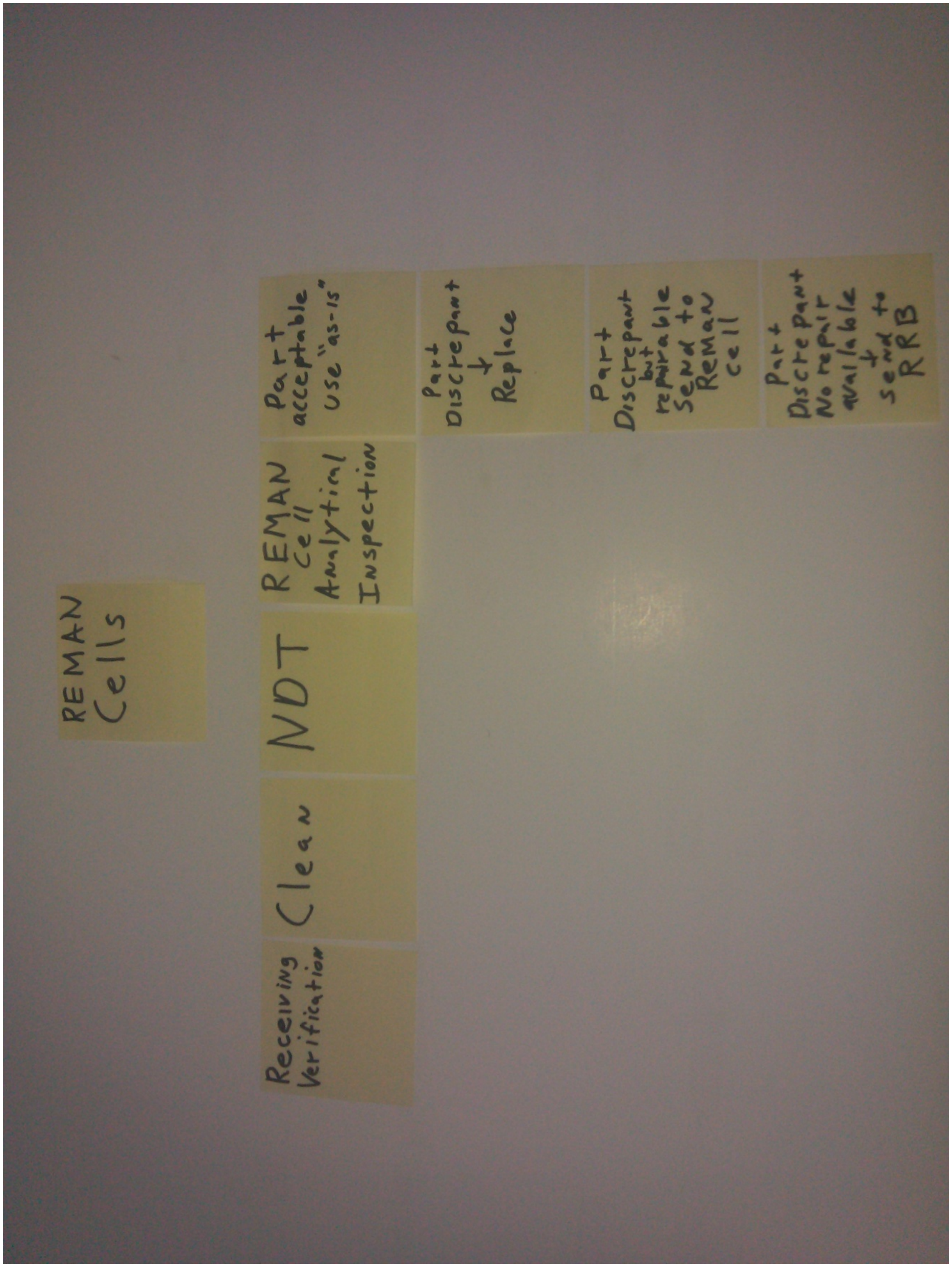
APPENDIX B

REFINED PROCESS MAP OF ENGINE REVIEW PROCESS


Engine Arrives at plant for repair & overhaul
Receiving/Induction of Engine: Purchase Order/Documentation created
Dis-assembly: Light Visual Inspection for corrosion, erosion, Foreign Object Damage (FOD), boroscope use for internal areas
Analytical Review & Testing: Engine Manual based Inspection of visual, dimension, Non-destructive test (NDT)
Component Acceptable?
Yes
No
New or repaired in stock?
Yes
Exchange for new/repaired if healthy stock, send core for repair or scrap
No
Repairable with established repair?
Yes
Repair: Send out for required repair (In-house or vendor)
No
Send to Repair Review Board (RRB)
Repairable ?
Yes
(RRB) Repair: Send out for required repair (In-house or vendor)
No
Route to have core scrapped/Notify planning to procure replacement
Assembly: Light Inspection, functional tests of components(free rotation, pressure checks), sub-assembly checks
Engine Testing: Test against parameters to meet re-certification of performance
Packaging/Shipping: Preserve Engine for return to customer, store documentation to prepare for next cycled return

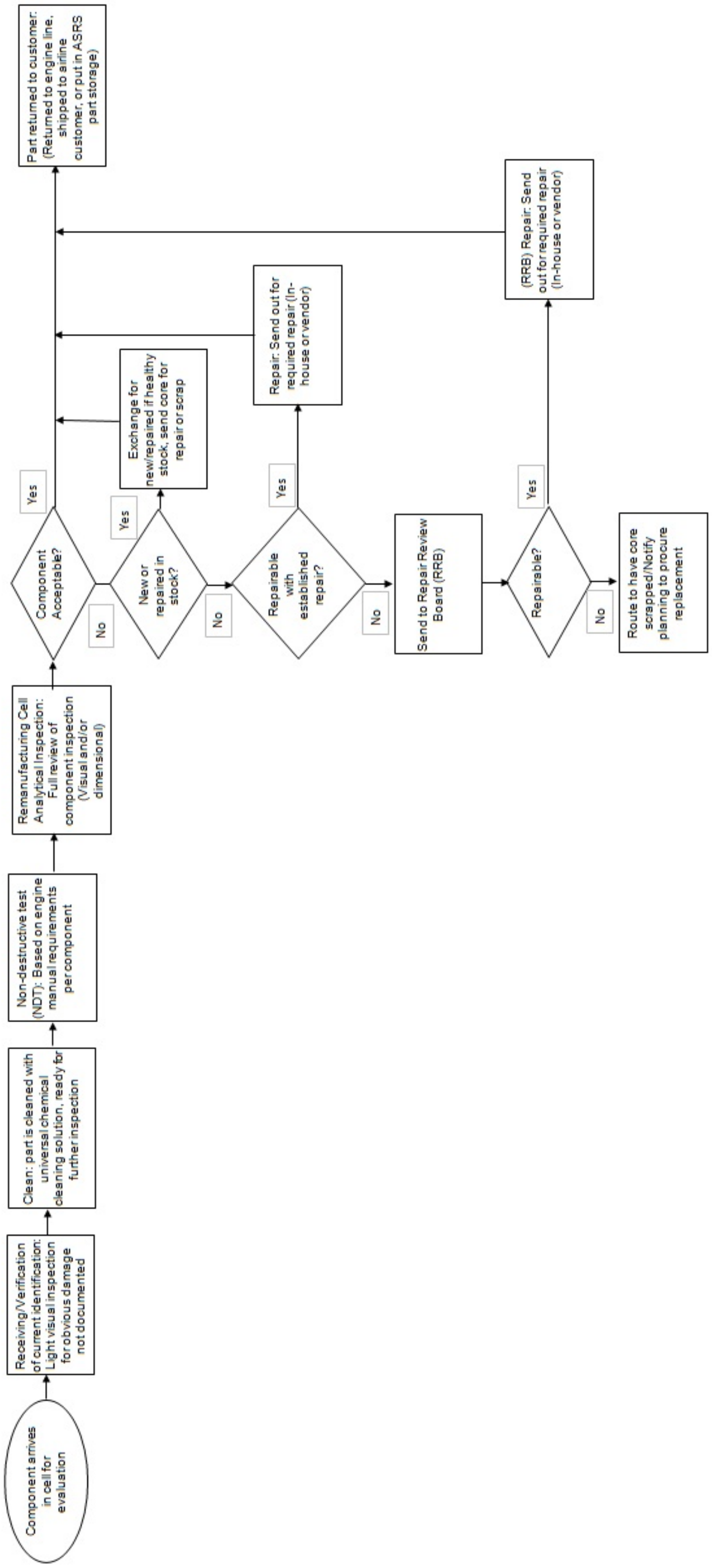
APPENDIX C

INITIAL PROCESS MAP OF REMANUFACTURING CELLS


REMAN Cells
Receiving Verification
Clean
NDT
REMAN Cell Analytical Inspection
Part acceptable use "as-is"
Part Discrepant ↓ Replace
Part Discrepant but repairable Send to Reman cell
Part Discrepant No repair available ↓ send to RRB

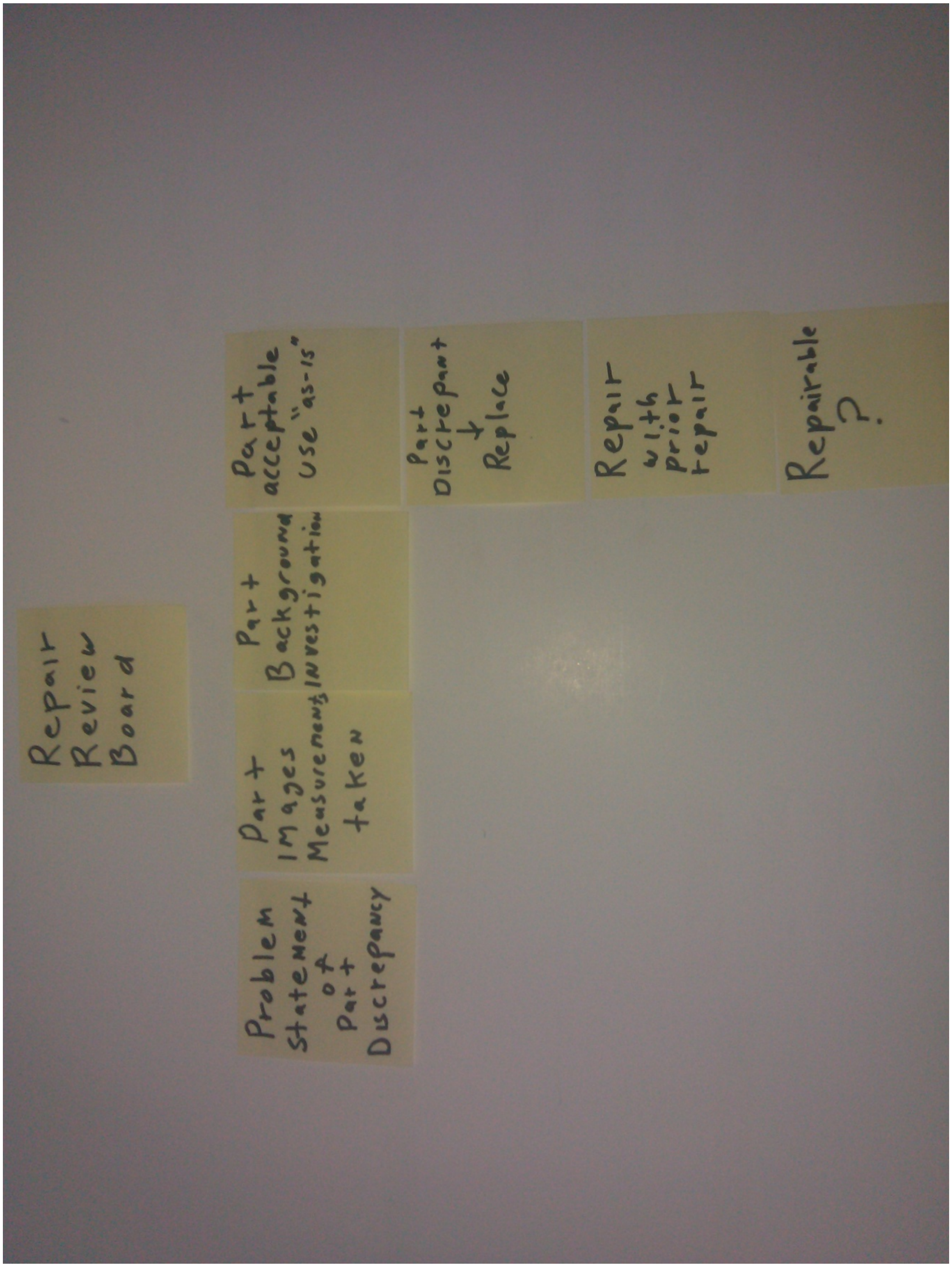
APPENDIX D

REFINED PROCESS MAP OF REMANUFACTURING CELLS


Component arrives in cell for evaluation
Receiving/Verification of current identification: Light visual inspection for obvious damage not documented
Clean: part is cleaned with universal chemical cleaning solution, ready for further inspection
Non-destructive test (NDT): Based on engine manual requirements per component
Remanufacturing Cell Analytical Inspection: Full review of component inspection (Visual and/or dimensional)
Component Acceptable?
Yes
No
New or repaired in stock?
Yes
No
Exchange for new/repaired if healthy stock, send core for repair or scrap
Repairable with established repair?
Yes
No
Repair: Send out for required repair (In-house or vendor)
Send to Repair Review Board (RRB)
Repairable?
Yes
No
(RRB) Repair: Send out for required repair (In-house or vendor)
Route to have core scrapped/Notify planning to procure replacement
Part returned to customer: (Returned to engine line, shipped to airline customer, or put in ASRS part storage)

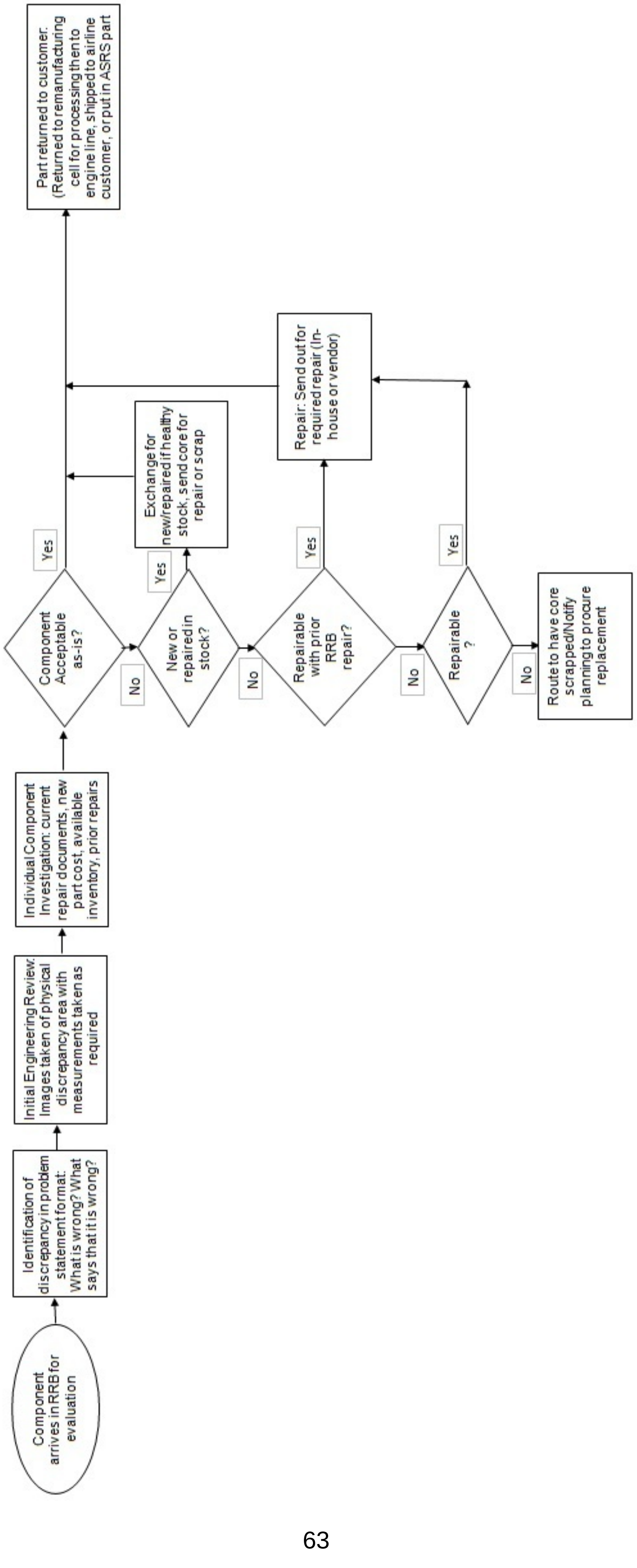
APPENDIX E

INITIAL PROCESS MAP OF REPAIR REVIEW BOARD


Repair Review Board
Problem Statement of Part Discrepancy
Part Images Measurements taken
Part Background Investigation
Part acceptable use "as-is"
Part Discrepant → Replace
Repair with prior repair
Repairable ?

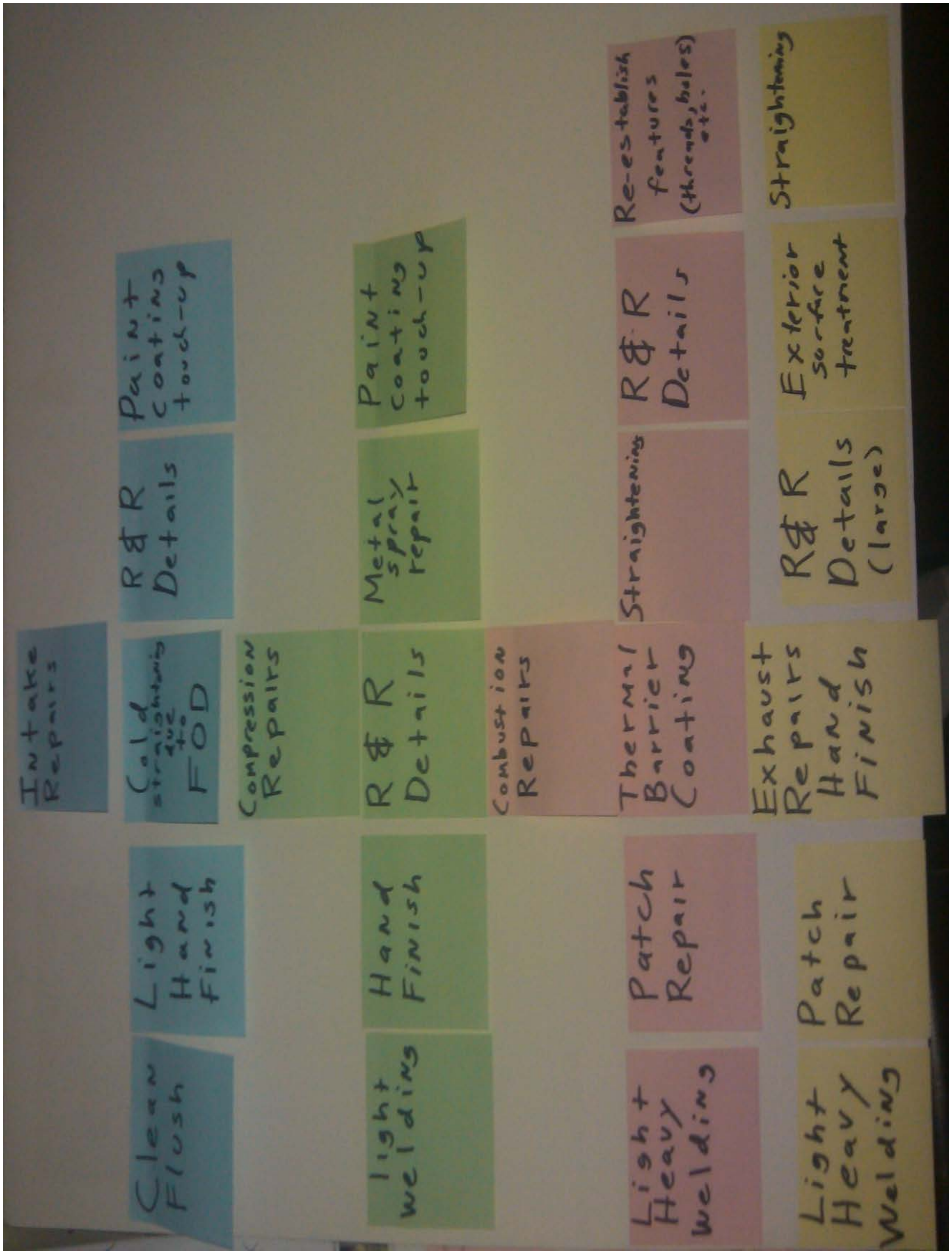
APPENDIX F

REFINED PROCESS MAP OF REPAIR REVIEW BOARD


Component arrives in RRB for evaluation
Identification of discrepancy in problem statement format: What is wrong? What says that it is wrong?
Initial Engineering Review: Images taken of physical discrepancy area with measurements taken as required
Individual Component Investigation: current repair documents, new part cost, available inventory, prior repairs
Component Acceptable as-is?
Yes
No
Part returned to customer. (Returned to remanufacturing cell for processing then to engine line, shipped to airline customer, or put in ASRS part
New or repaired in stock?
Yes
No
Exchange for new/repaired if healthy stock, send core for repair or scrap
Repairable with prior RRB repair?
Yes
No
Repair: Send out for required repair (In-house or vendor)
Repairable ?
Yes
No
Route to have core scrapped/Notify planning to procure replacement

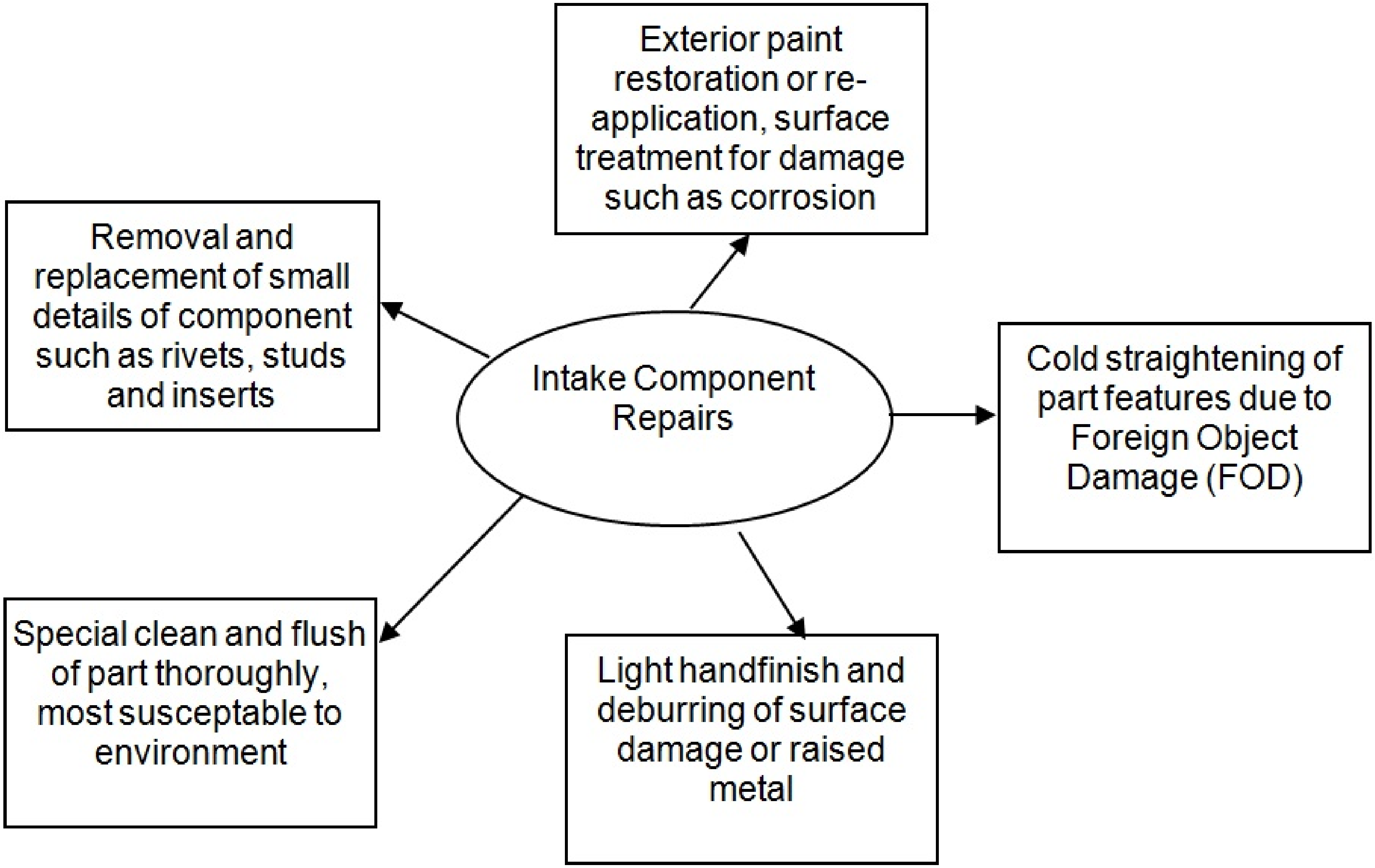
APPENDIX G

INITIAL PROCESS MAP OF ENGINE SECTION REPAIRS


Intake Repairs
Clean Flush
Light Hand Finish
Cold straightening due to FOD
R&R Details
Paint coating touch-up
Compression Repairs
light welding
Hand Finish
R&R Details
Metal spray repair
Paint coating touch-up
Combustion Repairs
Light Heavy welding
Patch Repair
Thermal Barrier Coating
Straightening
R&R Details
Re-establish features (threads, holes) etc.
Exhaust Repairs
Light Heavy Welding
Patch Repair
Hand Finish
R&R Details (large)
Exterior surface treatment
Straightening

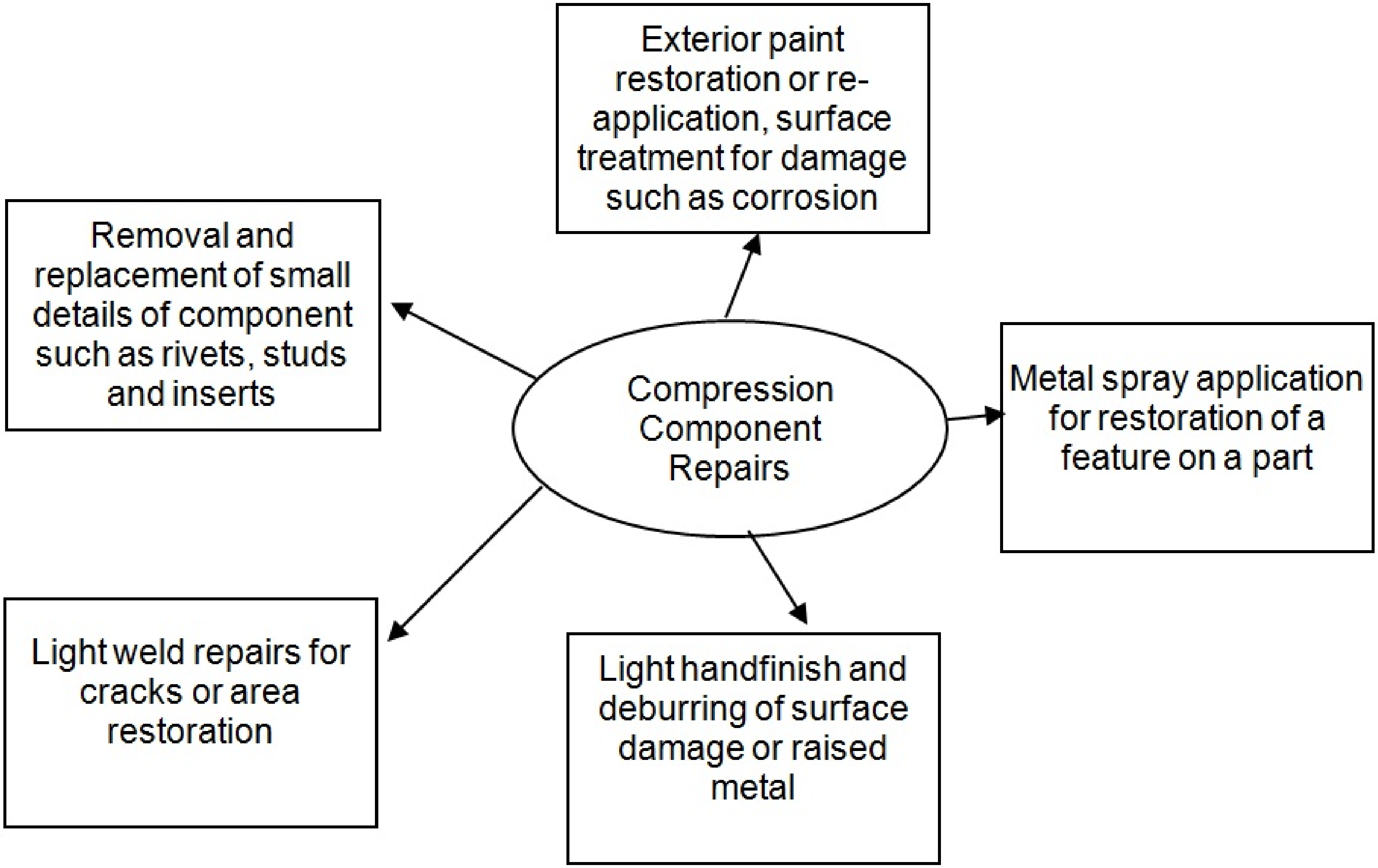
APPENDIX H

INTAKE COMPONENT REPAIR COMMON PRACTICES


Intake Component Repairs
Exterior paint restoration or re-application, surface treatment for damage such as corrosion
Removal and replacement of small details of component such as rivets, studs and inserts
Cold straightening of part features due to Foreign Object Damage (FOD)
Special clean and flush of part thoroughly, most susceptable to environment
Light handfinish and deburring of surface damage or raised metal

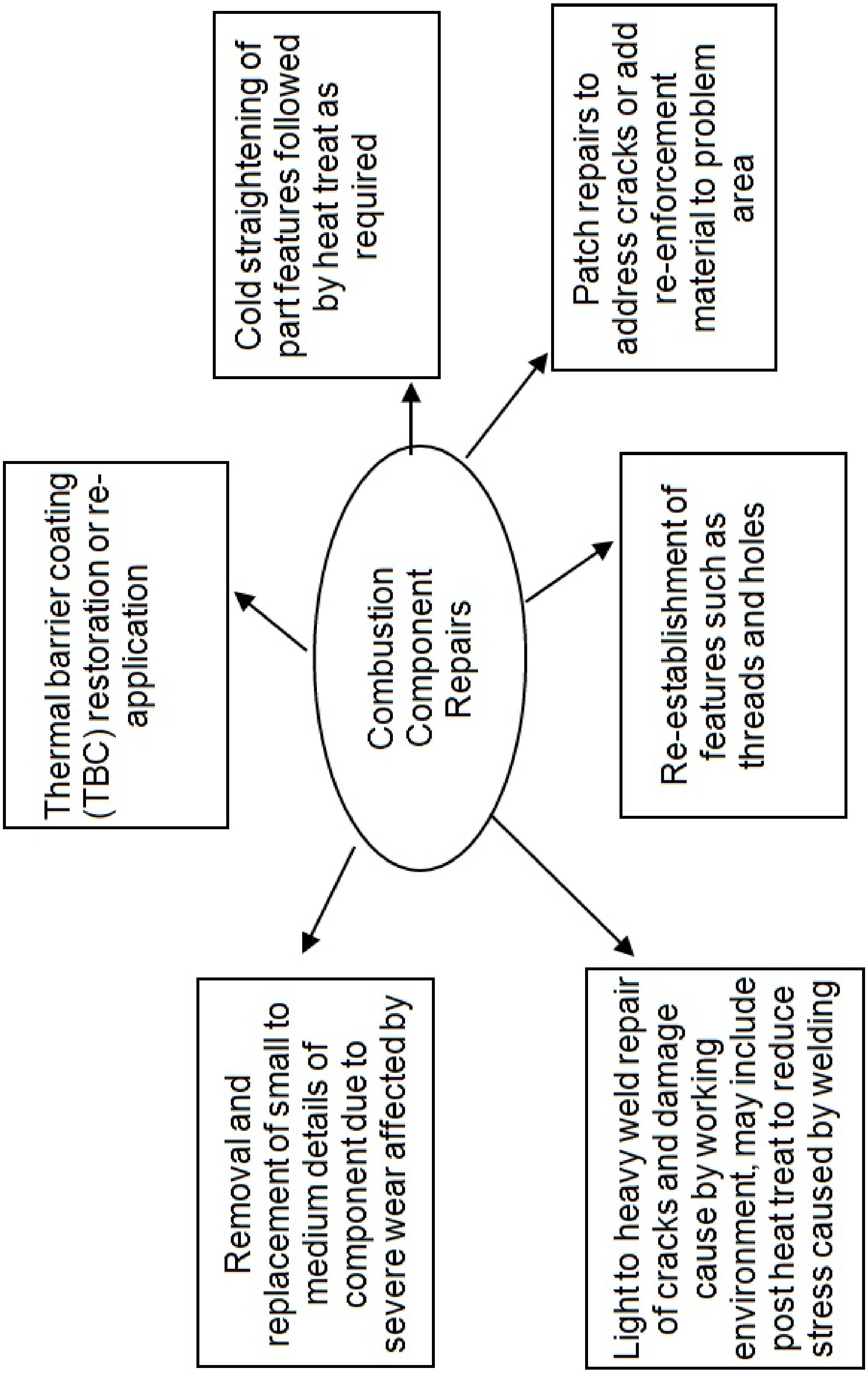
APPENDIX I

COMPRESSION COMPONENT REPAIR COMMON PRACTICES


Exterior paint restoration or re-application, surface treatment for damage such as corrosion
Removal and replacement of small details of component such as rivets, studs and inserts
Compression Component Repairs
Metal spray application for restoration of a feature on a part
Light weld repairs for cracks or area restoration
Light handfinish and deburring of surface damage or raised metal

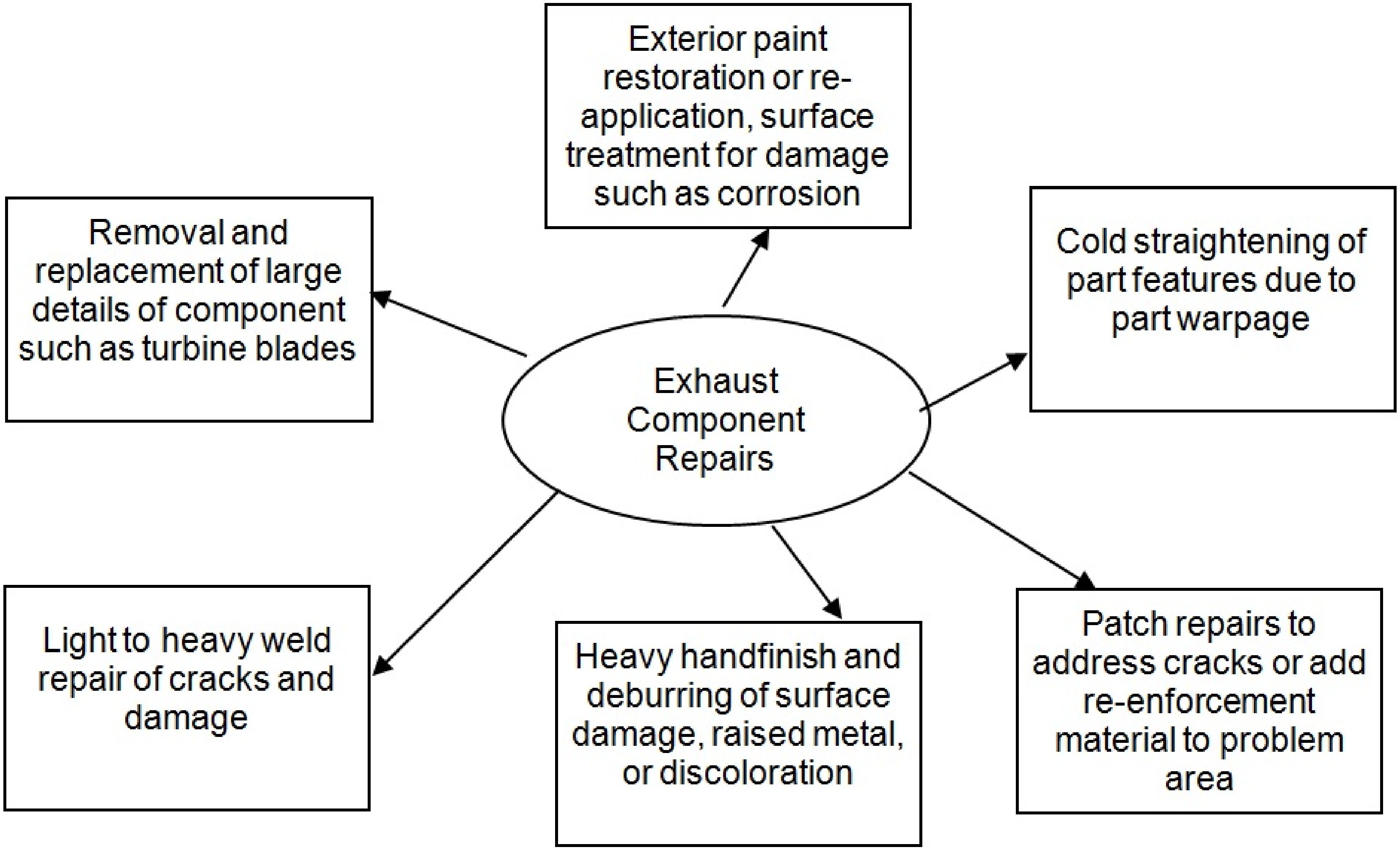
APPENDIX J

COMBUSTION COMPONENT REPAIR COMMON PRACTICES


Combustion Component Repairs
Thermal barrier coating (TBC) restoration or re-application
Cold straightening of part features followed by heat treat as required
Patch repairs to address cracks or add re-enforcement material to problem area
Re-establishment of features such as threads and holes
Light to heavy weld repair of cracks and damage cause by working environment, may include post heat treat to reduce stress caused by welding
Removal and replacement of small to medium details of component due to severe wear affected by

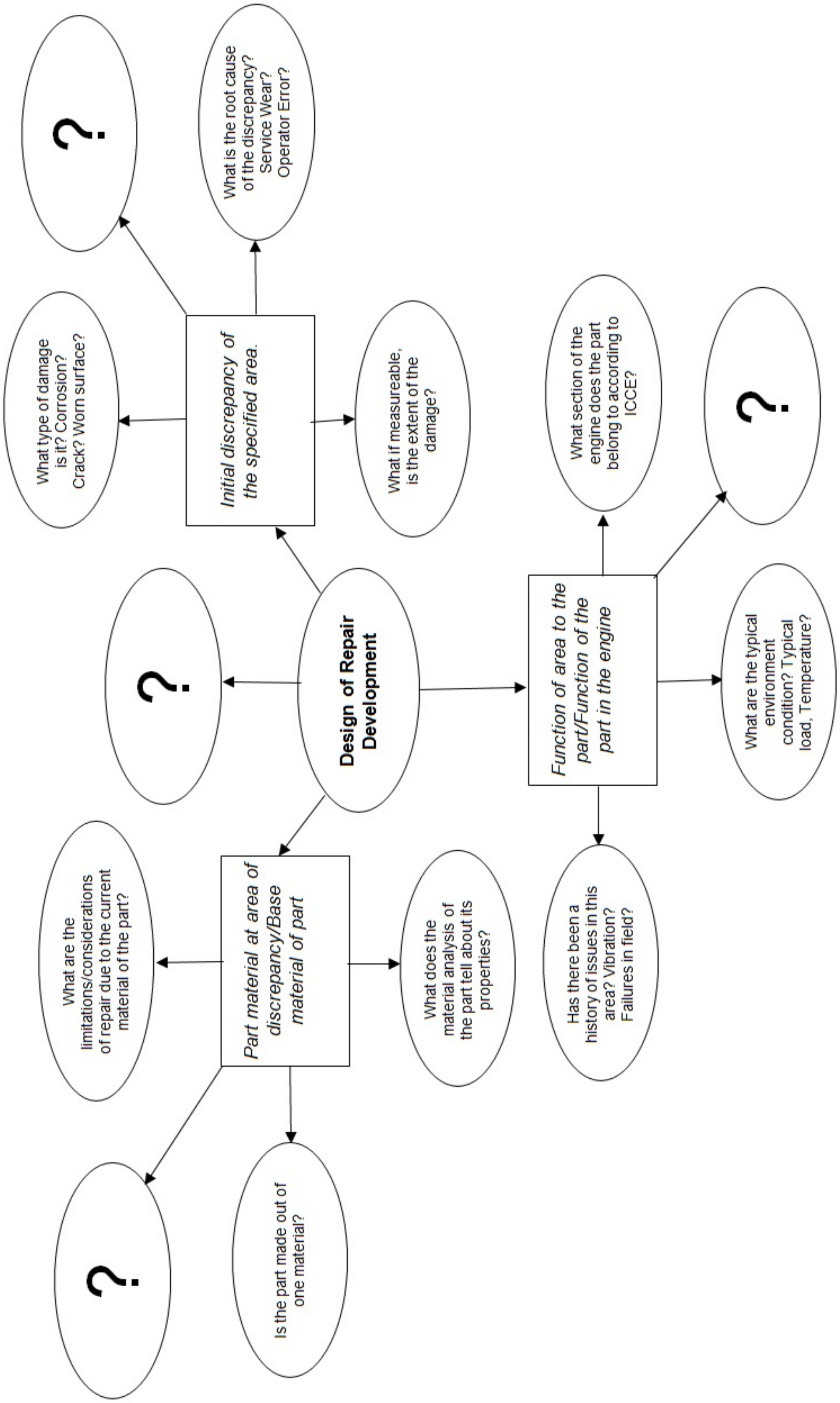
APPENDIX K

EXHAUST COMPONENT REPAIR COMMON PRACTICES


Exterior paint restoration or re-application, surface treatment for damage such as corrosion
Removal and replacement of large details of component such as turbine blades
Cold straightening of part features due to part warpage
Exhaust Component Repairs
Light to heavy weld repair of cracks and damage
Heavy handfinish and deburring of surface damage, raised metal, or discoloration
Patch repairs to address cracks or add re-enforcement material to problem area

APPENDIX L

DESIGN OF REPAIR DEVELOPMENT METHOD


Design of Repair Development
?
Initial discrepancy of the specified area.
What type of damage is it? Corrosion? Crack? Worn surface?
?
What is the root cause of the discrepancy? Service Wear? Operator Error?
What if measureable, is the extent of the damage?
Function of area to the part/Function of the part in the engine
What section of the engine does the part belong to according to ICCE?
?
What are the typical environment condition? Typical load, Temperature?
Has there been a history of issues in this area? Vibration? Failures in field?
Part material at area of discrepancy/Base material of part
What are the limitations/considerations of repair due to the current material of the part?
What does the material analysis of the part tell about its properties?
Is the part made out of one material?
?