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ASSEMBLY CONTROL PROCESS DEVELOPMENT FOR GAS TURBINES

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Abstract

This paper outlines an Assembly Control Plan process that has been developed at Rolls-Royce Defence Aerospace (Bristol) over the past four years on several gas turbine engine projects. The object has been to ensure Assembly Quality by a system of assembly risk reduction through close integration of Design, Assembly and Repair & Overhaul activity. It has been developed for engines in production, but importantly, it is being introduced at the beginning of the design cycle of new engines.

Short term Assembly Quality benefits include: an improvement in mitigation of assembly risk, bringing improved consistency of assembly; closer cooperation of Design Engineering with the Assembly area, Maintenance and Repair & Overhaul groups; and a greater focus on assembly from the beginning of the design phase. It is too early to assess accurately the long term Assembly Quality benefits, but cost reductions associated with better quality assembly – reduced test rejection, reduced despatch delay, improved overhaul methods, and improved customer satisfaction - are anticipated.

Key Words: *Aircraft Gas Turbines, Assembly risk reduction, Assembly Control.*

1. Introduction

Life spans of some aircraft and aircraft gas turbines are impressive: airliner lives are extending beyond thirty years; military aircraft life spans can be even longer. The Lockheed C-130 Hercules aircraft celebrated the fiftieth anniversary of its first flight last year, and production of the C-130J continues steadily. The Rolls-Royce Dart Turboprop first ran in 1953, was last produced in 1986, and is expected to be in service until 2025 – a life span of 72 years. A consequence of the extended engine lives and life spans is the revenue shift towards in-service support, a shift that is reflected in the designer’s changing role and in Total Care Packages.

Whilst life spans, individual engine lives, utilisation, expectation of reliability and so on are increasing, civil engine design and development cycles are reducing to below two years. Military engine programmes are following this trend. The number of different projects is decreasing and in consequence, a considerable load rests on the shoulders of today’s designer to learn and apply hard won past experience. As a consequence, along with excellent design CAD software, the design team has to be equipped with good knowledge tools, and better systems and processes to create long life engines.

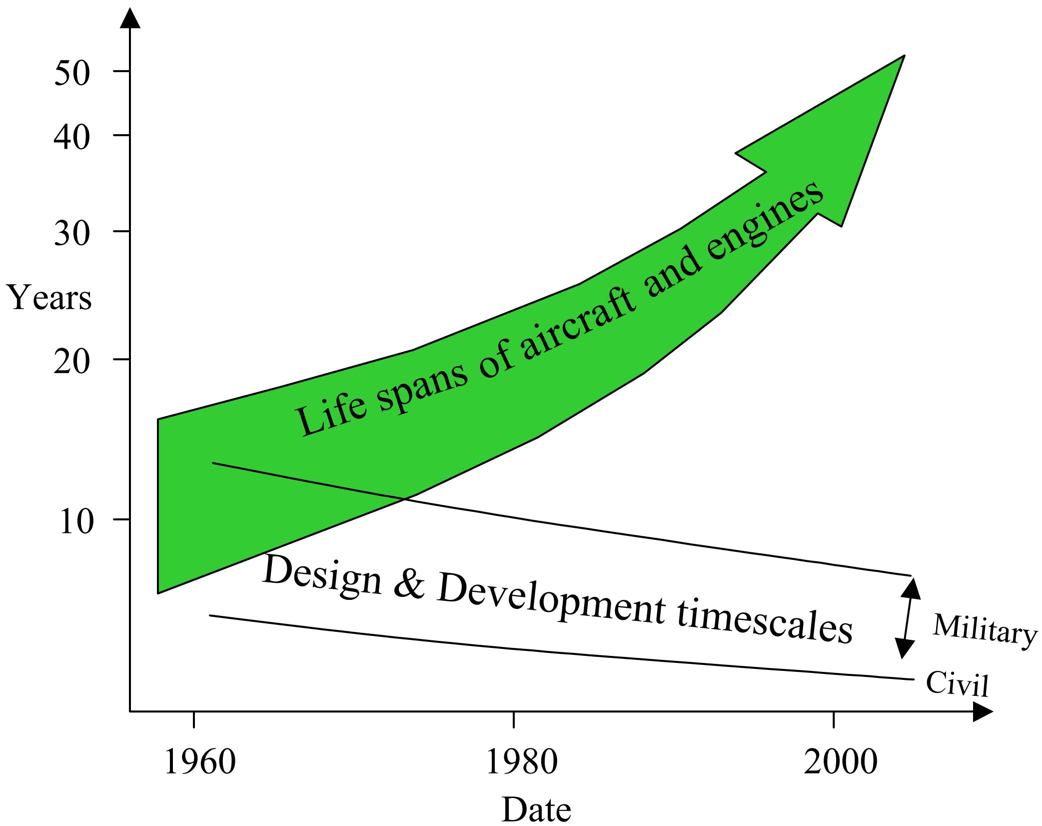

Figure 1. Short Design/Development cycles compared with Gas Turbine Life-spans dictate need for improving processes for designers.

A designer's natural inclination is to resolve the technical issues. However, today's designer has a wide field of 'Design for …' requirements to satisfy. The designer's portfolio includes Design for Assembly (DfA) processes which contribute to assembly quality, maintenance safety, to performance and low Life Cycle Costs. DfA techniques are used to facilitate ease of assembly, standardising and minimising parts count, structuring assembly sequence, mistake-proofing, and so on.

This paper describes an aspect of DfA: how an Assembly Control Plan process has been developed - how designers and engine assemblers apply risk reduction to assembly processes to ensure assembly quality. This process has been applied to engines in production, and that experience is outlined here. It is also being applied to new engines. Its introduction from the outset in new engine design improves the overall DfA processes.

2. The need

Aerospace history is littered with examples of incorrect assembly, more noticeable perhaps than other fields of industry because the outcomes are often more visible.
It was not uncommon in early aircraft and not unknown in some more modern aircraft for control surfaces to be connectable in reverse leading to rapid destruction.
A recent example of assembly failure was the Genesis spaceprobe that collected particles blown off the sun for two years. On return to earth the space probe buried itself in the Utah desert and subsequent investigation showed that a parachute-operating switch was inserted backwards.
Assembly errors in gas turbines may be for example the result of parts omitted or damaged during assembly or maintenance, blind assembly, or tight clearances - for instance between tubes or looms and the engine carcase or accessories. Assembly errors may be associated with (incorrect) torque tightening, or for instance in an assembly using heating or cooling techniques.

Incorrect assembly may lead to one or more of the following:

- Safety hazards
- Need for rework
- Need for re-design
- Premature failure
- Delivery delay
- Customer dissatisfaction, loss of confidence
- Increased cost of ownership

These are potentially serious. Strip and rebuild costs can be in thousands of pounds, pass-off test failure - tens of thousands, installed engine failure – a hundred thousand pounds or more depending on the depth of strip required.

Several years ago, a comprehensive programme was instigated to reduce component defects and in parallel improve the assembly process or in other words – minimise the defects per unit.

3. The programme and methodology

The initial approach to Assembly Control focussed on Safety, identifying features or tasks in assembly, which if performed in error or neglected, constituted a Safety hazard. Whilst satisfying a basic delivery need, it was appreciated that a comprehensive risk assessment process should be applied to reduce all assembly driven error.

3.1 Background:

Rolls-Royce applies a Failure Modes Effects and Criticality Analysis (FMECA) method to its systems, sub-systems and processes. The method is modelled on that used routinely by automotive and other industry and identifies potential failure modes and possible causes and effects in addition to evaluating each mode for its criticality.

A Process FMECA (PFMECA) is an iterative systematic group of activities intended to recognise and evaluate potential and actual manufacturing or assembly process risks and failure modes in terms of severity, occurrence and detectability using a scoring system and a Risk Priority Number (RPN) calculation.

An Assembly Control Plan (ACP) is developed by evaluating every feature or related tasks that occur in assembly as to their level of risk in the assembly process – using PFMECA, and then applying an appropriate level of control. This means that every component and sub-assembly and related tasks come under scrutiny.

The overall process for an ACP is in three stages:

- Assembly risk assessment
- Risk mitigation
- Validation of the resulting Assembly Method.

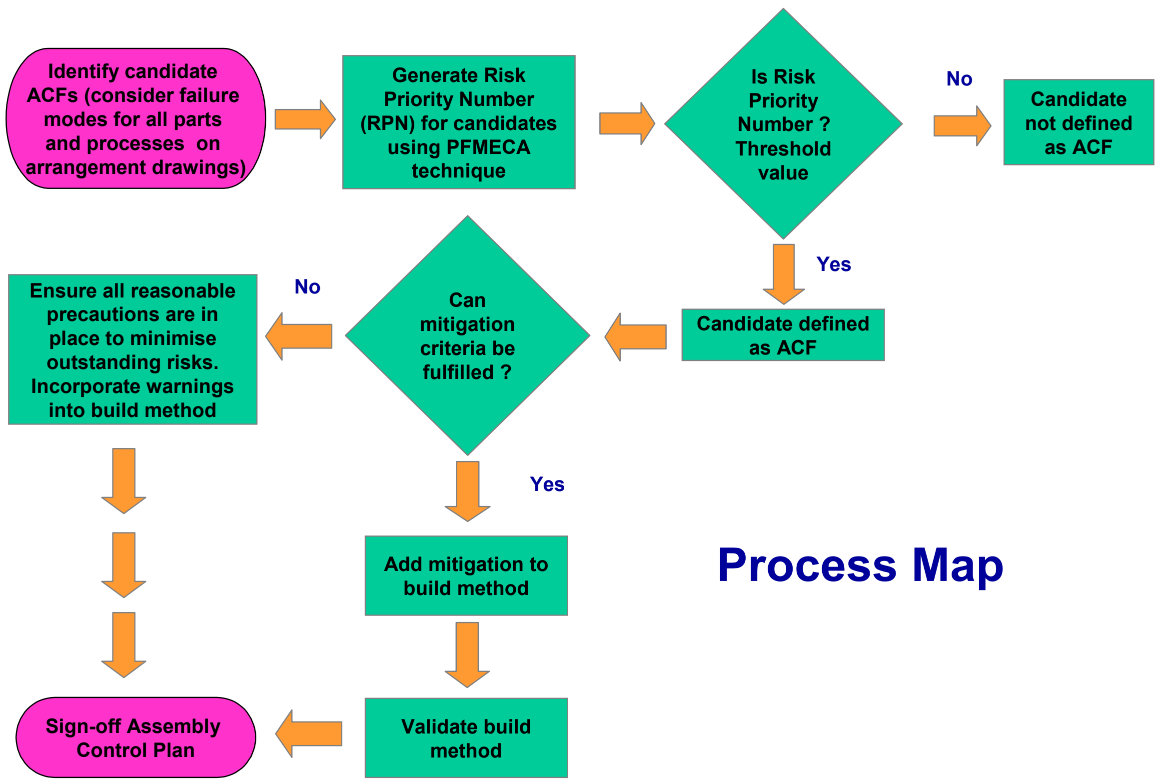

Figure 2: Simplified flowchart of the Assembly Control Plan process as applied to production engines

The creation of an ACP starts with the generation of a candidate Assembly Control Feature (ACF) list.

3.2 Generation of a candidate, then final ACF list :

An Assembly Control Feature (ACF) is defined as an assembly feature or task, which may have adverse effects on safety, reliability, maintainability, and cost of ownership or customer satisfaction.

For an existing engine, a candidate list of all assembly risks is created. The risks are assessed numerically using the common PFMECA risk assessment technique to create a Risk Priority Number (RPN). The RPN is the product of 'severity' – of the failure mode, assessed by Engineering; 'occurrence' and 'detectability' rankings – of the defect assessed by Assembly. The candidate ACFs list is filtered: those with a RPN above a predetermined threshold level are the formal ACF list which are then subject to mitigation action (or redesign if possible). Figure 3 gives examples of assembly defects that might be considered.

ACFs - Potential mitigation for process defects			
Potential Process Defect	**Potential Failure Effect**	**Potential Mitigation**	**Remarks**
Omission e.g. 'o' seals	Oil leak / fuel leak / performance loss	Leak tests during build.	
Incorrect torque	Bolt failure / FOD	Smart tooling / Bar coding of tightening operations.	Closer clamp control than conventional torque wrenches.
Blind assembly damage	Crack initiation / fretting		Confirm all aids, protective packaging and tooling are in place.
Inadequate temperature control leading to change of material properties	Premature component failure	Bar coded oven temp limiter.	
Titanium pipe damage	Cracking / fire hazard		Build line monitor of pipe damage. Build personnel to be made aware of the potential failure. Check out handling precautions.
Tube and loom clearance	Fretting / strain on tubes and looms	Dispatch check tick list identifying tube and loom positions where clearance may be an issue.	List can be revised as identification of failures occur.

Figure 3: Examples of common process defects, resulting failure effects and mitigation

During the Engineering and subsequent analysis a number of assumptions would be made, for instance, that all parts are new, available and fit for purpose; build would be performed in a specific build shop in Rolls-Royce by competent fitters. Also, at the initial assessment no special over-checks would be assumed.

3.3 Mitigation of ACFs, and creation of the ACP:

The Build Facility – the Manufacturing Engineers, Assembly planners and Assembly fitters now take the ACFs that are above the threshold and analyse how the risk might be mitigated. In essence, the assembly sequence for each candidate ACF is examined; if any checks (together with an assumed fitter check) are currently in place in the existing Build Method, these are noted. These may take the form:

- Fitter check
- Pre or post inspection check
- Flow checks, or other rig check
- Process controls

The assembly sequence must provide a minimum of two checks from the above to give proof of an 'enhanced protection over-check' which is further risk assessed by the Build Facility together with Engineering, redefining the ranking for the occurrence and detectability sections in the original candidate sheet. The RPN is revised. Risks that, despite design, checks or control mitigation activity retain a RPN above an agreed threshold, are termed ACFs. These are recorded and additional warnings are added to enhance the assembly instructions.

The next stage is validation. At this stage the Assembly Methods are updated and validated on the assembly line.

Following validation, the full suite of ACP documents are submitted for approval. The ACP is the full record of the risk analysis, mitigation and validation, together with the residue of remaining ACFs and the activity to manage these. From now on the ACFs are recorded and managed during assembly.

Although the process described is labour intensive, means to automatically transfer recorded data from risk assessment sheets to mitigation analysis sheets, and experience in identifying potential risk in a standardised manner has accelerated the process. The record of the process for each Solution or scheme is automated, and electronically archived as a permanent record as part of the Solution.

The assumption of a specific Build Facility location was made in order to create a standard for Assembly Risk Assessment. However, engines and modules are repaired and re-assembled at a number of repair stations outside Rolls-Royce, operated by Customers, Partner Companies and other repair organisations. Clearly conditions at other repair bases will differ. Process steps which mirror the three above will be used by Rolls-Royce Technical Publications to provide the ACP data for Quality Assurance at Build, Repair and Overhaul Operations elsewhere.

4. Results of ACP application – an example

The example described below illustrates application of the ACP process.

In the project used as an example, from a full suite of 99 assembly schemes, 1240 assembly features, tasks or related assembly notes were identified as candidate ACFs. As a result of risk assessment, 464 of these were confirmed as ACFs, ie. with RPNs exceeding a specified threshold number.

During subsequent mitigation analysis, 442 of the 464 ACFs were mitigated by implementation of an additional check or activity. In many cases this was by an inspector's overcheck.

This left 22 risks that remained above the threshold level. These were mitigated by additional warnings added to enhance the assembly instructions. Such risks were, for example, assemblies that could only be inspected by dismantling, for instance to check for 'o' ring seating, or possible damage to a hidden item such as a bearing. The warnings specified that all reasonable precautions regarding handling, cleanliness, recording and identification of balance data and care on blind assembly must be adhered to. Figure 4 illustrates the progress of the process.

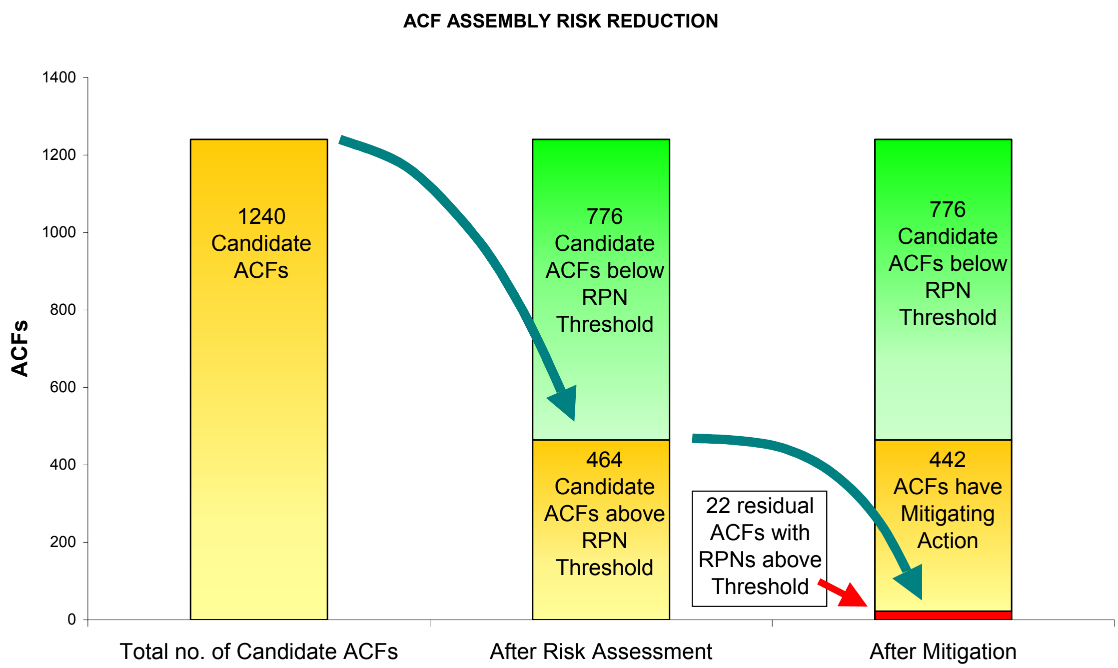

Figure 4: ACF Assembly Risk Reduction

Figure 5 records the groupings of the 464 ACFs. Just over half (51%) of the overchecks related to torque tightening of fasteners. The level of risk varies with the application of the fasteners. Further studies have been performed to rationalise torque tightening into three levels of risk with appropriate degrees of inspection. One of the outcomes of the high proportion of fastener ACFs is renewed attention to automatic tightening and recording systems. Such systems are in wide use in the automotive industry. Use of sophisticated or expensive tooling at the Production Build Facility creates a 'downstream' issue at External Build facilities, discussed below.

Of the remaining ACF groupings, 18% are due to potential omission and 9% due to possible inadequate clearances for tubes and harnesses. The rest are split between incorrect assembly or procedures, omissions and potential damage. As a results of these risks improved parts handling, kitting to avoid omissions, and process controls (for example improved oven or cooler control and monitoring for key assembly operations) have been incorporated.

A specific example of thermal control introduced was recording of temperatures of bearing assembly components, including a bearing inner track and seal components, to confirm that no overheating had occurred with consequent damage to sensitive parts. The RPN when unmitigated stood at 4 x the threshold level. Mitigation action reduced the risk to an acceptable level below the threshold.

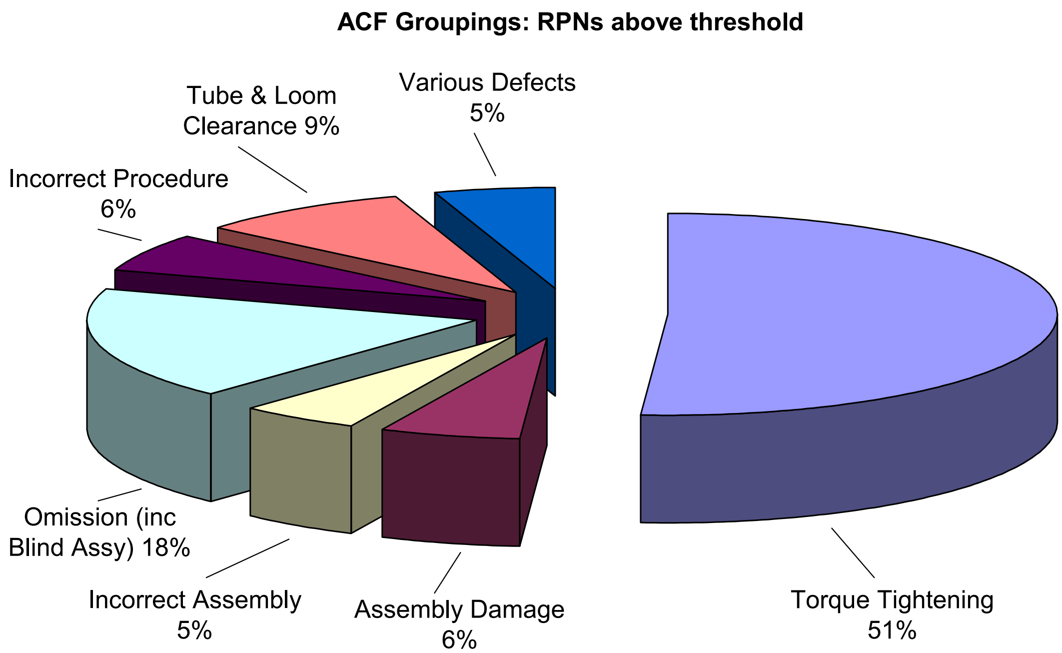

Figure 5: ACF groupings

4.1 Benefits and discussion:

Prior to the application of the ACP process, there were 69 overchecks in total employed during engine build. Following the risk assessment and mitigation activity, there were 488 overchecks in total incorporated into the enhanced assembly instructions. In simple terms, resulting from the comprehensive scrutiny and risk assessment there was a <u>sevenfold improvement in assembly process risk recognition and mitigation.</u> This is not a reflection of previous blindness to risk, but rather a culture of reliance on skilled assembly personnel and a consequent subjective approach without a basis for rigour.

An additional outcome of the process was that reviewing for all assembly concerns rather than only focussing on safety led to a modest increase of 70 ACFs above the unmitigated RPN, from 394 to 464. Covering all potential assembly concerns, as opposed to safety alone implies only 18% further effort in mitigating activity. This more than justifies the broader approach.

The traditional reliance on trained and skilled assembly personnel has wider implications. The older engines tend to be more complex and in some cases need 'watchmaker' attention. The ACP process applied to such engines means that greater attention can be given to assemblies that are sensitive to skill and close attention to method.

Assembly, dis-assembly, Maintenance and Repair & Overhaul operations are performed at external build facilities, including those of customers. The differences between external facilities and the Rolls-Royce production assembly are recognised as a significant issue – but one where ACPs can have a big impact.

Customers develop their own preferred assembly methods, the tooling may differ, the conditions under which assembly or maintenance is performed may be arduous – for example line maintenance on an installed engines, inclement weather, fitter competence and so on. There may be several customers for one product, of differing size and experience. Applying ACPs to their operations will be related to the ability of the customer, or whoever operates the off-site area to perform their own risk assessment and analysis. The ACP provides a baseline in the Assembly area at Rolls-Royce for its own assembly Quality and a yardstick for all assembly performed elsewhere. This enables the external facility to assess its own operation – and particular attention can now be paid to higher risk activity. It is recognised that Rolls-Royce might introduce sophisticated or expensive tooling that is economically justifiable on production build but is not appropriate at an external facility. The ACP would highlight this difficulty, rather than let it go unnoticed, and alternative measures would be considered.

As Rolls-Royce builds its Total Care Packages - fixed servicing and support packages – also termed Mission Ready Management Systems (MRMS), ACPs as part of an Assembly Orientated Design approach will contribute to Assembly Quality and the success of MRMS. The automotive and short-term consumer goods industry is less concerned about the cost to maintain. In contrast - for the Aero engine industry high quality, low cost, through-life maintenance is vital.

What of cost? Hardware problems are very costly: as mentioned in Section 2, test failures can cost tens of thousands of pounds, and more if late delivery costs are caused. The cost of a single aircraft installed engine strip and rebuild, for example to replace a fan unit, or alternatively, three pass-off rejections with investigation and rework, will be of similar order to the cost of the whole ACP generation exercise for one engine type. Demonstrating improvement due to preventative methods is of course difficult, but positive trends are strongly anticipated.

The assessment of the build shop is that the extra overcheck systems will add typically 8% to the assembly time, per engine; this is considered a good investment in view of the costs cited above.

Further benefits to be mentioned here are that the ACP provides a common basis for Design Engineering and Assembly, Maintenance, R & O to work together, and this is particularly true for introducing ACPs to new designs.

5. Application of ACPs to new Project design

As described, Rolls-Royce Defence Aerospace division has extended the ACP process beyond (initially) avoiding potential safety hazards. The process has been applied to production engines and is now being applied during the design process to new engines and products. ACP application to new engines provides the mechanism to optimise for assembly quality from the earliest design stages.

At an early stage in a new engine design, as the concept matures, the assembly process is refined and gives rise to the assembly tree – how the engine or module is put together. Each scheme or solution defines the design intent and outlines the assembly method at that stage or node in the assembly tree, which in physical terms is a component, sub assembly, assembly, or at the top level a module or the complete engine. The engine Assembly Planners develop an explicit assembly method for each engine sub-assembly, assembly or module, which covers every part and task within an engine or system. This process starts at the highest level – engine or module – and works its way down to sub-assembly or component level. In practice, the tree tends to be populated from bottom up, but this should be paralleled by development of the overall design, top down. Top-down design is consistent with Assembly Orientated Design, which is the desirable discipline for MRMS.

For a new product the designer will develop a candidate ACF list for the schemes and parts comprising the complete assembly from an early stage. Taking the candidate ACF list through the rigour of the full RPN assessment with the assembly personnel, as in the production engines, will enable the designer to scrutinise the design for acceptably low risk assembly throughout the design process. In a new engine the designer has a greater opportunity to redesign and eliminate assembly hazard, compared with legacy engines. The ACP process as applied to production engines has focussed largely on parts and features. As the ACP process develops it will parallel the top down process. Operating the ACP process from the beginning keeps the assembly risks and issues to the forefront of the mind of the designer. It also guarantees close liaison with assembly from the outset.

In practice, the ACP process applied to new design is a predictive technique - as opposed to a reactive checking technique.

6. Human Factors – in assembly:

There are various Human Factors issues relating to the designers and assemblers work, and the adoption and effective working of the Assembly Control Plan – and these are recognised and seen as areas for further study.

As an engine design develops, the design intent is captured on a scheme by the designer. This will include essential assembly data. The Assembly Method will be written and developed by the build area in conjunction with Design. During engine development the Assembly Method will be developed by experienced assembly personnel and a degree of flexibility in approach is likely to overcome unforeseen assembly issues. As the engine design matures the Assembly Method becomes firm. The designer assumes that the fitter rigorously uses the Assembly Method for later Development and for all Production engines.

For the engine assembler or fitter, the Assembly Method will be adhered to on the Production build line, however there are issues and pressures to operate the method in ways not anticipated by the designer. Such factors are important and need to be taken into account when ensuring that the ACP control activity is performed.

The ACP places extra workload on the designer in comprehensive assembly risk assessment, the Assembly planner in mitigation of identified risk and on the fitter in ensuring that the control activity is performed. Prompt lists are being developed to avoid missing possible risks and activity, however, the temptation to fill in checklists superficially has to be resisted.

7. Summary of benefits

At this stage of application of the ACP process, the value benefits are difficult to quantify: these will arise as trends on test rejections and reliability emerge. Application of ACPs has full support from the Rolls-Royce Defence Aerospace Engineering and Production Management.

Key benefits that will accrue reflect the needs that are summarised in Section 2, namely: minimisation of safety hazards; avoiding premature failure; reducing delays and costs due to test rejection and consequent late delivery penalty; avoiding customer dissatisfaction; reduced cost of ownership.

Demonstrated benefits from the legacy engine ACP programme:

- Sevenfold increase in risk perception and mitigation
- Objective numerical basis for assembly risk assessment replaced subjective approach
- Extending the focus beyond safety increased effort by only 18%
- Improved processes now built-in to the Assembly Method
- Designer and Assembly drawn closer together

In addition to these there are benefits for new product design:

- Assembly issues tackled earlier in design process
- Reduced designer learn curve
- Designer is more effective in a multi disciplinary role
- Greater focus on better build techniques
- Reduction in variation of build process, within and without Rolls-Royce

Further potential benefits are:

- Avoiding cost of failure analysis and rectification
- Raising the Customer 'delightedness' with the product, and the likelihood of return orders
- Promotion of better build techniques to line maintenance and reduced maintenance cost
- Move towards Assembly Oriented Design to benefit MRMS/Total Care Packages

Finally, avoidance of a single major failure will more than offset the non-recurring cost of an Assembly Control Plan.

8. Conclusions

Incorrect assembly may lead to safety hazards, premature failure, test rejection, customer dissatisfaction and increased cost of ownership.

Using Process FMECA techniques, a process has been developed and introduced that reduces assembly risk and improves product quality. The process is being applied retrospectively on production engines, and is being introduced from the concept stage of new engines. Engineering, Assembly and Repair & Overhaul work closely together to create an agreed Assembly Control Plan.

Short term Assembly Quality benefits include: a marked reduction of assembly risk, bringing improved consistency of assembly; closer cooperation of Design Engineering with the Assembly area, Maintenance and Repair & Overhaul groups; and a greater focus on assembly from the beginning of the design phase. It is too early to assess accurately the long term Assembly Quality benefits, but cost reductions associated with better quality assembly – reduced test rejection, reduced despatch delay, improved overhaul methods, and improved customer satisfaction - are anticipated.

Acknowledgements: I would like to record the input to this work by Mary Bloomberg, who led a team developing the Assembly Control Plan.

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