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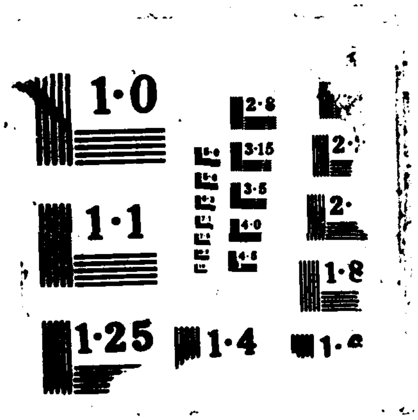
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STUDENT REPORT

FACTORS AFFECTING TWO-RUN SAMPLING REQUIREMENTS IN GAS TURBINE ENGINE PRODUCTION

MAJOR FRANK EARL DRESSEL 88-790

"insights into tomorrow"

DISCLAIMER

REPORT NUMBER 88-790

TITLE FACTORS AFFECTING TWO-RUN SAMPLING REQUIREMENTS IN GAS TURBINE ENGINE PRODUCTION

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Submitted to the faculty in partial fulfillment of requirements for graduation.

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In the future, numerous new or modified two-run (test, disassembly, inspection, reassembly, retest) sampling plans will be needed. This study reviews the key qualitative factors of engineering design, manufacturing tooling, procedures, and the work force, which affect two-run sampling requirements. Then the program's potential costs and benefits are discussed followed by the applicability and usefulness of Air Force and Systems Command quality assurance regulations 74-1 and MIL-STD-105D, MIL-STD-414, and MIL-E-8970. The study concludes that the four qualitative factors listed above, should be used to tailor future two-run sampling programs for maximum effectiveness at an affordable cost.

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PREFACE

The purpose of this research is to aid individuals involved with gas turbine engine production and the associated two-run quality sampling programs. With numerous new engines approaching production, critical decisions regarding their sampling programs will be needed in the near future. This research addresses the key qualitative factors of engineering design, manufacturing tooling, procedures, and labor which affect quality and the corresponding need for two-run engine sampling. Further, it discusses two-run sampling costs and benefits to assist future sampling program developments, modifications, and/or administration.

I would like to thank Mr. Brimelow from General Electric and the many professionals in Systems Command whom I had the pleasure of working with during the last four years. Their experience and insights were the key to my success. Special thanks to Don Williams, my sponsor from the Propulsion SPO, and Lt. Col Huffman, my ACSC advisor, for their support and guidance. Finally, thanks to my wife Jan and children Brian and Jeni, for their patience and understanding.

ABOUT THE AUTHOR

Major Frank E. Dressel holds a Bachelor of Science degree in Aeronautical Engineering from the United States Air Force Academy in 1975 and a Master of Science degree in Systems Management from the Air Force Institute of Technology in 1984. Since graduating from pilot training in 1976, he's flown over 2000 hours in C-141 and T-38 aircraft. His last assignment was in the Strategic Engines System Program Office at Wright-Patterson AFB as the F110 Alternate Fighter Engine production manager. While in this position, he supervised the General Electric Company's production build-up from seven engines in 1985, to 166 engines in 1986, and 298 engines on contract for 1987. This period included initial two-run sampling of all production engines to finally achieving required sampling of only one engine each month. He was directly involved with initial production in Ohio and personally lead the government production readiness reviews at follow-on assembly facilities in Strother, Kansas and Eskisehir, Turkey to include guiding two-run sampling progression and adjustments. He is married to the former Jan Likness of Colorado Springs and has two children.

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EXECUTIVE SUMMARY

REPORT NUMBER 88-790

AUTHOR(S) MAJOR FRANK E. DRESSEL, USAF

TITLE FACTORS AFFECTING TWO-RUN SAMPLING REQUIREMENTS IN GAS TURBINE ENGINE PRODUCTION

I. Purpose: To aid understanding of the qualitative factors affecting two-run sampling requirements in gas turbine engine production.

II. Problem: In the next five to ten years, numerous new or modified two-run sampling plans will be needed for future engines like the F119 and F120 or derivatives like the F100-PW-229 and F110-GE-129. In addition, adjusted sampling plans are needed when production facilities are added or changed significantly. Air Force and Systems Command quality assurance regulations call for hardware audits which the two-run sampling programs satisfy. These sampling programs serve as an important, but expensive, check of whole engine assembly quality and engine condition after running. A good understanding of the factors which affect quality and the corresponding sampling requirements is needed for cost effective programs which still can produce quality engines.

III. Analysis: The overall design and manufacturing quality system is briefly reviewed for understanding how a two-run sampling program fits in. The existing quality assurance regulations which call for hardware audits are then explained followed by the military standards guiding statistical sampling. Finally, the typical methodology for two-run sampling is reviewed followed by four recent examples of actual sampling programs.

IV. Conclusions: The key factors which should affect two-run sampling requirements are: engineering design with elements of design maturity and producibility, manufacturing tooling with elements of effectiveness and reliability, manufacturing procedures with elements of effectiveness and clarity, and finally the work force with elements of skills, experience, attitude, job stability, and likelihood of having their individual work sampled. Air Force and Systems Command quality assurance regulations 74-1 call for hardware audits but not necessarily ones repetitious enough to satisfy statistical sampling requirements. In two-run sampling of whole engines, the number of samples required by the statistical plans in MIL-STD-105D, MIL-STD-414, and MIL-E-8970 are cost prohibitive. MIL-E-8970, a statistical sampling plan for aircraft engines, was last revised in 1967 and no program in the last ten years could afford or justify the massive, simplistic sampling it calls for. Even if this standard is revised, a good understanding of the qualitative factors which affect two-run sampling is still needed.

V. Recommendations: Use these qualitative factors of design, tooling, procedures, and the work force to maximize quality at an affordable cost. Future engine programs should not blindly reuse existing sampling plans without first considering the potential impact of differences in these key factors. Finally, MIL-E-8970 should not be used as it's currently written but rather deleted as unnecessary or extensively revised. In the future, two-run sampling programs should continue to be an integral part of gas turbine engine production.

Chapter One

INTRODUCTION

Today's sophisticated aircraft rely on high quality gas turbine engines for their safe and effective operation. A key indicator of engine quality is the teardown audits conducted by the contractor before government acceptance. These audits are internal hardware inspections conducted after initial break-in testing and subsequent teardown. This quality program of internal inspections after initial engine operation and before final acceptance testing is commonly known as the "two-run sampling" program. These audits however are time consuming, expensive, and can possibly introduce new problems by the teardown and rebuilding process itself. Therefore, rather than inspecting every engine, a sampling plan is developed to maximize quality while controlling production costs. These sampling plans are tailored to best serve each engine and insure their high quality and reliability.

Numerous sampling plans will be needed in the next five to ten years for the production of new engines like the F119 and F120 Advanced Tactical Fighter engines and improved performance engines like the F100-PW-229 and F110-GE-129. New or modified sampling plans are also needed when production facilities are added or change significantly. For example, General Electric F110 production started in Evendale, Ohio, but has now also occurred in Strother, Kansas and Eskisehir, Turkey. Both places have obvious differences, such as work force, language, and/or tooling, which can affect quality and sampling requirements. These evolutions in engine production are likely to continue. What sampling plan is best for these programs to avoid excessive engine costs or quality problems? For example with the F110-GE-100 engine, General Electric estimates their shop costs for an engine test, teardown, inspection, and rebuild to be between $220,000 and $250,000 (13:--). On the other hand if not enough engines are sampled, excessive numbers of latent problems affecting safety and operations can be in engines accepted by the government. In addition, the production of other complex systems like avionics or airframes are also likely to use internal hardware audits to check quality. Air Force Systems Command (AFSC) Regulation 74-1 (24 July 1987) calls for "teardown and inspection of selected components, major subsystems, or contract end-items, where appropriate." (7:3) Therefore, the development and review of two-run sampling plans for teardown audits will continue to be important tasks for program managers and quality organizations to address.

The purpose of this paper is to discuss the factors which program managers and quality organizations should consider when developing two-run sampling plans for their engine's production program. It focuses on gas turbine engines; however, many of the factors are universal and apply to production of any complex system like avionics or airframes where teardown audits are planned. The intent is not to judge the merits of existing engine two-run sampling programs but to provide the factors needing consideration when developing, tailoring, and/or administering programs. Examples of recent sampling programs are provided for historical references with a brief discussion of some lessons learned.

Chapter Two is background information reviewing why engine quality is important, applicability of existing quality regulations, the mechanics of a two-run sampling program, and the sampling programs of several contemporary engines. It may be appropriate for readers already familiar with two-run sampling to skim much of this chapter. Chapter Three reviews each factor which should be considered for sampling programs: 1) engineering design, 2) tooling, 3) manufacturing procedures, 4) work force, 5) costs, and 6) benefits. Finally, Chapter Four offers conclusions and recommendations developed from the background and factors discussion. Again, the intent of this paper is not to justify two-run sampling or to rate existing programs in the gas turbine engine industry. Rather, it is to provide better understanding of the factors which should be considered when developing, modifying, or managing two-run sampling programs.

Chapter Two

BACKGROUND

Engine quality is an important factor of overall aircraft reliability and effectiveness. In flight, any malfunction likely to lead to engine failure is usually considered an emergency requiring immediate attention. Engine reliability is critical for all aircraft but naturally most important with single engine aircraft. F-16 flight safety data through 1987 compiled by the Air Force Flight Safety Center recorded 89 inflight engine shutdowns: of those, 51 were restarted, 9 made successful dead stick landings, and the remaining 29 resulted in loss of aircraft (17:--). Engine reliability depends on many things, but quality is one of the most basic. This quality is not a commodity that can be added at any one particular assembly work station. Rather it must be a management and design philosophy as well as an integral part of every step in production. This chapter reviews quality's role in production, the applicability of current regulations and standards, how two-run sampling is conducted, and the sampling programs of several contemporary engines.

QUALITY FROM START TO FINISH

In modern gas turbine engine manufacturing, the foundations of good engine quality lie in the early design and testing phases. Producibility, reliability, maintainability, and corresponding quality must be designed in early and evaluated before normal production begins. The full-scale development phase is a critical step for evaluating these traits in early or preproduction engines. In actual production, quality is checked in thousands of areas starting at the smelters and continuing throughout component production and assembly. For example, in final assembly, each engine has its own "build book" where operations, when accomplished, are also recorded by the assembler. In addition, hundreds of critical assembly points are independently checked by certified inspectors and also recorded in these build books (18:--). Finally, the overall engine operation is wrung out in a test cell following an extensive acceptance procedure. This acceptance testing lasts approximately three to six hours including thrust and vibration measurements, acceleration-deceleration checks, fuel and oil consumption checks, and backup system checks. If test parameters are within limits, the engine is removed from the test stand and undergoes final inspection by contractor and government personnel. This is primarily a visual, external inspection with limited internal borescope inspections where possible. If the inspectors are satisfied with the engine and the contractual requirements are satisfied, the government inspector accepts the engine.

Ideally, these extensive in-process quality checks insure reliable engines but numerous conditions are often present which can seriously degrade quality. In early production, the system is immature with probable latent flaws in design, tooling, manufacturing procedures, and worker experience. Throughout its production life, changes occur which, coupled with human error, degrade quality and associated engine reliability. Finally, not all problems are uncovered during final test but rather need an internal inspection to find them. Because of these conditions, the two-run sampling program is used as a hardware audit for problems evident only after running in final test, and/or disassembly, and as an independent check of overall engine quality. Independent hardware audits are a basic tool of modern quality control (1:21-14 - 21-16) commonly used in commercial and defense related production. Their use in Air Force engine production is guided by regulations and standards which vary in usefulness/relevance for two-run programs.

APPLICABILITY OF CURRENT REGULATIONS AND STANDARDS

There is clear guidance in Air Force (AF) and AFSC regulations calling for independent hardware audits such as the two-run sampling program for engines. The 17 May 1985 Change 3 to Air Force Regulation 74-1, Quality Assurance Program, specifically added: "Use hardware teardown, as appropriate, as a means of verifying product integrity and that the contractual technical requirements have been met." (11:1) Systems Command regulation 74-1, AFSC Quality Assurance Program, implements this AF guidance by directing: "Full-scale engineering development and production programs will provide for a procedure for the teardown and inspection of selected components, major subsystems, or contract end-items, where appropriate." (7:Para 8) Further, it directs that they should be "tailored to the specific program . . . , occur at appropriate points in the manufacturing process before government acceptance . . . [and] be performed by contractor personnel and witnessed by appropriate Air Force personnel." (7:Para 8) These regulations are derivatives of Congressional directives in Federal Acquisition Regulations calling for improved quality and cost effectiveness in weapon system acquisitions (19:--). Both AF and AFSC regulations 74-1 are broad contracting guidance which do not specifically call for statistical sampling. The military standards which address statistical sampling are MIL-STD-105D, MIL-STD-414, and MIL-E-8970.

Military Standard (MIL-STD) 105D, Sampling Procedures and Tables for Inspection By Attributes, is the specific guidance for sampling products which can be classified as "defective or nondefective, or the number of defects in the unit of product is counted, with respect to a given requirement or set of requirements." (9:1) This military standard is also a commercial industry standard for statistical sampling by attributes.

MIL-STD-414, Sampling Procedures and Tables for Inspection by Variables for Percent Defective (10:--), is used for statistically conducting and analyzing measurements of the parameters or variables themselves (1:25-1). It, like MIL-STD-105D, uses statistics to monitor and control outgoing quality but with the advantage that the sample size can be smaller. However before valid statistical conclusions can be drawn, "the shape of the distribution of individual measurements must be known and stable." (1:25-2) This requirement limits its use with gas turbine engine two-run sampling programs which are characterized by small sample size and unique, indeterminate flaws.

Both MIL-STD-105D and MIL-STD-414 are best suited for high rate production in which large sample sizes are feasible. Edward Schilling, Quality Manager at General Electric's Lighting Business Group in Cleveland notes that "For a quarter of a century, the world's foremost AQL [Average Quality Level] sampling systems have been MIL-STD-105D and MIL-STD-414." (4:14) They originated during World War II for production of Army ordnance (2:155) and today, the concepts of statistical process control which these standards complement, are often used in engine component manufacturing such as with turbine or compressor blades. However, for two-run sampling of whole engines, the sample sizes needed for statistical validity are impractical and cost prohibitive. These problems are evident in MIL-E-8970.

MIL-E-8970, Engines and Related Propulsion and Power Equipment, Aircraft, Acceptance Tests of, Sampling Plan for, Statistical, is an old application of MIL-STD-106 (now MIL-STD-105D and MIL-STD-414) for aircraft engines (14:--). It was last revised in October 1967 and is not often used today because of its prerequisite for high rates of production, 16 units or more per month (8:para 3.3), and apparently very simple, inexpensive inspections for defects. For example, it calls for inspecting 125 engines before beginning 50 percent sampling of the next 125 (8:1-3). (In the recent rapid build-up of F110-GE-100 production, only 171 engines were built in the first year of full production (6:P0006).) Rather than disassembling nearly a whole year's worth of production for statistical significance, more limited, cost effective sampling is done (19:--). The current procedures for performing two-run sampling of engines are described in the following section. In lieu of appropriate standards or regulations, each engine's production contract specifies procedures which apply for it.

TWO-RUN SAMPLING METHODOLOGY

The goal of two-run sampling is to insure production of high quality engines. A sampling program achieves this by uncovering otherwise undetected defects or nonconformances which can then be addressed and resolved before delivery to the customers. The number of engines sampled by the two-run program is normally less than the total production at the time (unless 100 percent sampling) and hopefully represents the total population accurately. The selection of the two-run engine is random unless a specific engine is suspect and thereby warrants a closer look. A government representative normally chooses the engine just prior to test and after assembly is nearly complete. This precludes anyone trying to use a select team to build a "golden" but unrepresentative engine for inspection (12:--). Once the selected engine completes final assembly, it goes to a test cell for initial break-in and acceptance testing like any other engine.

This testing, for the sampled engine, is called the "green run" and is basically the same as the normal final acceptance test described earlier. One difference is that in a green run, faults such as minor oil leaks and vibration are noted but often overlooked for the time being, if they are viewed as harmless for the time being. These faults or problems, in the case of a final acceptance test, would have to be rectified before continuing, but in a green run, the investigation and correction usually waits until after test. In both green run and final acceptance testing, the full range of normal engine operation is simulated to the degree possible in a production test cell. High altitude or speed conditions are not simulated which can sometimes allow certain engine malfunctions or faults to go undetected until actual flight. Test cells which can simulate conditions found at high altitude and speed are several times more expensive to operate and are normally used only in development or experimental testing. However, with careful inspection, these faults can often be detected during teardown inspection. After testing is complete, the green run engine is then removed from the cell for disassembly and inspection (12:--).

The engine disassembly is designed to allow visual access to critical internal components which experience has shown to be possible trouble spots. It is intended to be a nondestructive teardown with all hardware reused except for typical one time use consumables like gaskets. For the F110-GE-100 engine, the government and contractor agreed to tear down to the following major subassemblies:

1) Accessory Gearbox
2) Compressor Rotor
3) Front Compressor Stator
4) Rear Compressor Case
5) Compressor Discharge Nozzle Assembly
6) High Pressure Turbine Rotor
7) Augmentor/Exhaust Nozzle
8) Fan Stator (6:Attachment 1)

There is a current initiative in the Propulsion System Program Office of Aeronautical Systems Division (ASD/YZ) and the Air Force Plant Representative Offices (AFPROs) at Pratt & Whitney and General Electric to increase teardown standardization between companies and engines. Increased standardization is desirable to a point but ultimately the detailed teardown plan should be tailored to best serve each unique engine. In fact, the teardown should not necessarily be exactly the same for each sampled engine within a program. If for example, a component is suspect, the teardown should be tailored as necessary to gain proper access. Conversely, as a production system matures and no problems are noted over time for a particular component, the teardown may skip it if quality can be insured by other means such as test cell diagnostics.

Throughout disassembly, the workers and inspectors are looking for excessive wear, damaged components, misassemblies, foreign objects, poor fit, or anything else unusual or out of blueprint tolerance. The hardware is laid out for quality and engineering review with certain components like bearings often sent to specialists. Any faults found are recorded and classified in four categories of severity or origin. From the F110-GE-100 production contract are the following fault classifications/definitions:

> Class I Fault -- A serious defect that can cause engine failure or malfunction prior to the specified repair/overhaul period and can be found only by disassembly of the engine.
>
> Class II Fault -- A serious defect that can cause engine failure or malfunction prior to the specified repair/overhaul period and can be detected without disassembly of the engine.
>
> Class III Fault -- A minor defect that will not cause engine failure or malfunction prior to the specified repair/overhaul period.
>
> Class IV Fault -- A defect that is caused by the disassembly operation, or by malfunctioning, resulting from improper operating instructions or procedures. (6:Attachment 1)

Any class I or II faults and excessive numbers of class III or IV require investigation and development of corrective action plans (6:Attachment 1). The objective of these hardware audits is information. Information of what the problems are so they can be fixed and engine quality/reliability improved. One of the essential questions that must be answered is whether the fault found is an isolated occurrence or indicator of an out of control production system. If it is an isolated case, limited to that one engine, no corrective action may be needed. In the case where other engines are also suspect, corrective action may include an increase to even 100 percent sampling until confident that the problem's cause was found, understood, and corrected. In addition, engines already delivered to the customer which were not sampled may also require inspection and correction of deficiency. Because of the time and money invested in these two-run inspections, the full potential of improved quality should be realized for all associated engines, not just for the one engine found with the problem.

Once the needed information is gleaned from the hardware, the engine is rebuilt and undergoes final acceptance testing. If it passes the standards called for in the acceptance test procedure, it is removed from the cell, given a final inspection, and normally accepted by the customer.

A key aspect of a two-run sampling program which should be determined early is the sampling rate: whether 100 percent, 50 percent, one per month, etc. This rate ideally has a firm statistical, quantitative foundation as suggested by MIL-STD-105D and MIL-STD-414 and guarantees a minimum acceptable outgoing quality level. Unfortunately the relatively low rate of engine production coupled with many currently unquantified variables call into question answers derived from most classical sample rate calculations. For this reason, Chapter Three qualitatively discusses the factors which should be considered when determining a sampling rate and the overall plan. Understanding these factors allows each plan to be tailored for its situation and effectively maximize quality at a affordable price. Examples of contemporary engine sampling plans are provided for comparison and brief analysis.

CONTEMPORARY TWO-RUN SAMPLING PROGRAMS

F101-GE-102
for the B-1B
(Evendale, Ohio Facility)

Clearance Block	Planned	Actual
I	16 of 16	23 of 23
II	8 of the next 16	8 of 16 *
III	8 of the next 32	8 of 32
IV	6 of the next 60	6 of 64
V	one per month	one per month **

* Partial teardowns to inspect only the bearing were done on two additional engines.

** Government and contractor agreed not to conduct two-run hardware audits during the final two months of production.
(Reason: Quality had been high and consistent, and production would finish before any corrective actions could have taken effect.)

F110-GE-100
for the F-16C/D
(Evendale, Ohio Facility)

Clearance Block	Planned	Actual
I	16 of 16	20 of 22 *
II	8 of the next 16	15 of 32 **
III	8 of the next 32	8 of 32
IV	6 of the next 60	6 of 64
V	one per month	one per month

* Program was not ready to advance to 50 percent sampling after only 16 engines due to numbers of class I, II, and III faults and the slow pace of corrective actions. Two engines were not sampled to accelerate their delivery as maintenance trainer engines.

** Program was again not ready to advance to 25 percent sampling after only 16 additional engines. There were serious problems with oil scavenge pumps, damaged power takeoff couplings, and gearbox retainer rings.

F110-GE-100
for the F-16C/D
(Strother, Kansas Facility)

Clearance Block	Planned	Actual
I	2 of 2	2 of 2
II	1 of the next 2	1 of 2
III	1 of the next 4	1 of 4
IV	1 of the next 10	1 of 10*

* Ten percent for remainder of steady production.
Assembly of new F110 engines stopped in Fall of 1987 due to excess capacity at the Evendale facility following completion of F101 production. (F110 warranty work continues.)

F100-PW-220
for the F-15 and F-16
(East Hartford, Connecticut Facility)

Planned: One in 40 or at least one per month as a follow-on to existing F100-PW-100/200 production based on commonality and previous demonstrated quality on earlier engines. (16:--)

Actual: One in 40 or at least one per month until October 1986. After questions of hardware accountability arose, sampling increased to one in 20 or at least one per month. (16:--)

Chapter Two discussed how manufacturing quality must be a consideration from start of engineering design, to production finish. For two-run sampling, the applicable regulations were reviewed and noted that clear guidance exists in the regulations for justifying two-run sampling. But, the specifics of how and when to sample contemporary engines are missing or obsolete. Then, the typical two-run sampling methodology was reviewed as it currently exists and finally, four examples of contemporary sampling plans were listed for comparison. With this background information regarding engine quality and existing two-run sampling programs, Chapter Three analyzes the qualitative factors which will affect future two-run sampling requirements.

Chapter Three

FACTORS WHICH AFFECT SAMPLING RATE

The level of uncertainty regarding engine quality and the expected costs versus benefits of the two-run program are the factors which should affect sampling rate. For example, if you are confident that the other quality programs and inspections have already produced an engine you can stand behind, little or no sampling is necessary. However, if there are concerns with a new design, tooling, procedures, or the work force, then extensive two-run sampling may be called for until the uncertainty is resolved. But two-run sampling is not the only way to insure high quality engines. If the costs of two-run sampling exceed the expected benefits, a lower sample rate or other methods should be explored. Understanding these factors upon which sampling rate is based will then lead to more effective two-run programs and ultimately better engines.

This chapter first evaluates the four basic factors which affect assembly quality: engineering design, tooling, manufacturing procedures, and the work force. These four, in the author's experience, are the key factors which must be evaluated when developing a sampling plan and are not limited to only the prime contractor or blue collar workers for example. After the factors and their various elements are evaluated, then the potential costs and benefits of two-run sampling are reviewed.

ENGINEERING DESIGN

Engineering design is one of the most important factors affecting quality (1:8-7) and subsequent need for sampling. The maturity and producibility of a particular design directly affects the potential for error and problems in production. Design maturity grows naturally as more engines are made and bugs are uncovered and resolved. Producibility also improves over time as challenging processes become routine or are replaced by easier methods. The maturity of an engineering design includes the number of engines delivered since the last change, and if changed, how much commonality with a proven design remains. Producibility is the relative ease of making a product correctly (1:2-6). Both of these design elements contribute to the need for normally higher sampling rates at the beginning of production which taper off as maturity and producibility improve over time.

Maturity

The simplest measure of design maturity is how many engines were delivered since the last design change and with how many problems. Certainly, an established design, with no recent changes, and numerous trouble-free deliveries suggests maturity and consequently low two-run sampling requirements. The challenge is when the overall design is new or extensive changes to a proven design have occurred. In those cases, the degree of commonality with previous, mature designs can be useful for comparison. Because a two-run teardown/inspection focuses on conditions inside the engine, internal changes should affect sampling rate the most. Changes in accessories, tubes and cables, or other components which are external and do not need a general engine teardown to inspect, normally do not affect sampling. (However, there can be potential synergistic or unforeseen internal side effects of numerous external changes which still merit increases in sampling rate.) Changes within the core of the engine normally do require increases in general two-run sampling rate until the uncertainties are reduced by numerous successful inspections. With localized internal changes, cost savings are possible without increases in risk if the teardown can be tailored to expose only the new, unproven areas. For example a new #3 bearing lubrication design may only need a limited teardown to expose that bearing with its associated changes. However, major changes like General Electric's F110 fighter engine (derivative of their F101 bomber engine) or Pratt & Whitney's F100-PW-229 increased performance engine (derivative of their F100-PW-220 with major core changes) should have the benefits of an extensive two-run sampling program to uncover the inevitable problems (19:--). Besides looking at a design's maturity or commonality, two-run sampling requirements can be assessed from the design's inherent producibility.

Producibility

Producibility is a design's ease of manufacture including its tolerance of nonconformances without ser'ous consequences (1:2-6). A poor design often includes complicated, confusing assemblies, susceptible to human error. For example, a jigsaw puzzle with numerous apparent solutions but only one that is functionally correct can trap even meticulous assemblers if their error is not readily detectable. One solution to this problem is unsymmetrical assemblies, "Murphy proofed" so that the parts go together only one way--the correct way. Often designs which are not very producible require numerous special tools and the proverbial "three hands" to get it together. On the other hand, producible designs are generally simpler with ease of manufacture and assembly (and later maintenance) in mind. Producible designs also use manufacturing processes which are well understood and established such as casting processes which are consistent and can be easily verified as good or bad (18:--). Unfortunately, new or improved designs usually push the state of the art in manufacturing for required performance or cost reasons. Often when the manufacturing processes themselves are not well understood, needed inspections are unwittingly omitted or ineffective. Full scale development and preproduction engines should check for these problems but they are often crafted by the most skilled technicians with engineers looking over their shoulders. For this reason, it is important that two-run sampling double check the routine production of engines with new designs before they are delivered to the customer (12:--).

Engineering design with its elements of maturity and producibility is a significant factor affecting planned two-run sampling rate. But an engine's design also affects two-run sampling by its collateral influence over required tooling and procedures.

TOOLING

Tooling is the equipment used to make or repair a product like jet engines. It often can be used in more than one product line but usually requires adapting hardware/software for the particular model. For this paper, tooling includes the full spectrum of machines needed to build engines, from simple tools like a wrench, to complex machines with adapters, fixtures, and computer software. In the factory, production tooling is tailored for fixed, mass production while maintenance support tooling is often multipurpose, mobile, and built for austere, field operations. Good tooling, either for production or maintenance, is designed to effectively do the intended task and do so in a consistent, reliable fashion. Both characteristics of effectiveness and reliability affect two-run sampling.

Effectiveness

A tool's effectiveness is how well the operator can use it to accomplish the assigned task without damage (12:--). For example, the task of tightening a nut can perhaps be done by either a socket wrench or pair of pliers. But the worker with a socket wrench can apply the needed torque faster, and without damaging the nut's surface finish. A build stand that holds the engine at a handy work height or can even manipulate it in one or two axes and dimensions is more effective than a poorly designed, inconvenient stand. Or finally, a test cell that allows quick, safe, and precise installation, operation, recording, and removal of the engine is less likely to induce flaws needing two-run sampling to detect. These flaws induced by tooling can be quite insidious. Early in the F101 production program, main engine bearings were being damaged by its installation tooling (18:--). This condition/problem was only detected after disassembly in the two-run program. With this problem uncovered, the causes could be identified, and new tooling (and installation procedures) developed to avoid bearing damage in subsequent engines. Two-run sampling hopefully detects these initial flaws and, as importantly, continues to check for them over the life of the production program. These continuing samples are necessary for many reasons including tooling which is not always consistent or reliable.

Reliability

Workers with good reliable tooling can build engines right the first time, and then, repeat it over and over again. This ability depends on a producible engine design as well as simple, sturdy tool design and manufacture. In addition, scheduled calibrations and overhauls are often called for to maintain the tool's initial consistency and reliability. Once production is proven and stable, a tool's consistency possibly influences required two-run sampling the most. When an unidentified tool damages hardware or no longer does its intended task and these conditions go undetected until the two-run sample, the inspections must increase until the cause is understood and controlled (19:--). Another potential reason for inconsistency is a change in tooling.

When the tooling used to build engines changes substantially, the two-run sampling should normally be increased until the effects of the new tooling are understood (18:--). This is especially important when other operational or quality checks are unlikely to catch the new flaws. For example, if a factory's production is increased by augmenting final assembly capacity with maintenance support tooling, the workers may inadvertently misuse it and induce new flaws. To compensate for this change, the two-run sampling program can be an important tool to insure no degradation in engine quality. Tooling's consistent effectiveness depends on its design, manufacture, and maintenance, but also the written procedures for their use and the workers' care and skill.

MANUFACTURING PROCEDURES

Manufacturing procedures are the written, step-by-step instructions for making, testing, and inspecting a product. D.M. Turnbull and C.W. Higby in their article "Writing Quality Procedures" note that "procedures are the cornerstone of a quality system . . . designed to serve people who must implement them." (5:19) Engineers and industrial methods specialists take the engineering design and planned tooling and write the detailed work instruction needed to build engines. In the author's opinion, the two most important elements of manufacturing procedures are effectiveness of the intended methods for building a product and clarity of the written communication.

Effectiveness

Manufacturing procedures ideally describe the best way to build a particular product (19:--). However, the best, most effective way to build a product like an engine evolves and improves following typical learning curves. For example, process engineers need to understand what the best temperatures and pressures for forging a compressor disk are or, whether it is best to install the fuel control on the gearbox before or after mounting the gearbox on the fan frame. Also, alternate methods are often developed which can be equally effective. This may be a result of two different vendors making the same part or differences caused by production versus maintenance support tooling. In either case, the written procedures depend on practical, definable methods from which the writers can work.

Clarity

A sampling plan should also consider how clear and concise is the written communication from the mind of the writers/industrial engineers to the readers/workers tasked to build engines. All the pitfalls of written communication such as confusing wording and acronyms are a threat to effective, understandable procedures. The review process for procedures should obviously be thorough and consider reader education and native language. For example, the Turkish coproduction program includes assembly of F110 engines in Eskisehir, Turkey, where the workers are not fluent in English and need procedures in their native language (15:--). When production started, two-run sampling needed to increase above the then current, U.S. facility's rate to check for flaws possibly induced by the English-Turkish translation. Once the Turkish procedures are used in building their first engines, residual translation problems can be identified and corrected with a corresponding increase in quality and confidence.

Build procedures evolve and mature much like engineering designs and so are more error prone early in production or after changes and revisions. To compensate for this tendency, a two-run sampling plan should consider the effectiveness and clarity of the procedures and inspect more frequently until they do mature. In the case of Turkish coproduction, besides a concerns with procedures were concerns with the relative experience of the Turkish workers.

WORK FORCE

The people making engines have a significant influence on required two-run sampling throughout production because they affect quality long after the engine's design, tooling, and procedures have matured. If sufficiently skilled and motivated, they can often overcome confusing procedures and awkward tools to successfully make good products early in production. But new workers are hired, experienced ones move on or retire, and all have bad days which lead to mistakes. In a survey by Harvard Business Review of manufacturing executives from "Fortune 500" companies, the largest source of quality problems was work force workmanship (3:164). Other experts like J. M. Juran point the finger at management for the source of most quality problems (1:18-46). Undoubtedly, both management and the workers turning wrenches are responsible for problems with quality and are important factors to consider when developing or modifying a two-run sampling program. The elements within a work force are skill level, job stability, attitude, and the likelihood of having individual work selected for inspection.

Skills

The skills of the work force can first be assessed by considering their general and technical education. Can they read the work instructions/procedures and do they have the necessary training for their tasks? Are training programs in place to bring the new workers up to building high tech engines? What are the employment conditions in the local area? It's in the contractors' best interest to hire experienced job applicants but when production rate rapidly expands, the demand for experienced workers often outstrips supply. Also, union seniority rules may dictate hiring the forklift driver or janitor over a more experienced former jet engine mechanic (18:--). Whatever the actual or expected work force is/will be, their skills and education need to be assessed. For example, the formal education level of the native Eskisehir, Turkey work force was slightly less than their American counterparts. But they were handpicked for years of experience and positive attitude from the Turkish J79 engine depot in Eskisehir (15:--). Until the Turkish work force's skills and experience on the new F110 engine are proven, there will continue to be extensive two-run sampling.

Job Stability

The job stability on a particular engine program can both promote program esprit de corps and also familiarity with particular engine nuances. If the workers are supported by management and assembly reorganizations are minimized, pride and teamwork can grow. Forces which disrupt job stability are large production rate changes, facility modernizations, work force reorganizations, etc. However, once the work force stabilizes, people can learn the finer points of their particular job and co-workers' strengths and weaknesses. This job stability fosters pride, teamwork, a positive attitude, and quality engines (13:--).

Attitude

Workers' attitude and motivation, along with their experience and skill also affect quality and need to be considered in two-run sampling decisions. Their pride, work ethic, union, and relationship with management all have a bearing on quality. A can-do, quality-first attitude, fostered and supported by management, can go a long way in reducing quality problems. The workers involved in the Turkish program are often highlighted in their national television and newspapers because of the honor and prestige of the program. Their individual commitment to the program success is obvious in their professional attitude (15:--). In the case of F110 engines being assembled in Strother, Kansas, the depressed general aviation and farming economy in the greater Wichita area (including Strother) provided a large pool of experienced workers with "small town" Midwestern work ethic (18:--). The high unemployment in the area, especially among those with technical skills, reinforced the attitude that their job performance was critical. In addition, due to layoffs at Boeing, Cessna, and Beech, numerous General Electric-Strother workers already had certified Aircraft & Powerplant licenses and appreciated the criticality of quality before they were hired. This attitude in the Strother work force was in marked contrast to the attitude existing in Evendale, Ohio, at the beginning of F110 production there.

The General Electric plant in Evendale in 1987 had over 18,000 employees with 7100 union workers. The largest union, the United Auto Workers, in 1984-1986 could almost guarantee job security regardless of personal job performance (12:--). This coupled with (in 1984) relatively inexperienced middle management with expanding, modernizing, reorganized work areas, fostered a cavalier attitude which seldom promoted quality. This apathetic attitude toward quality was further reinforced by a demanding production schedule which left little time for quality in many employees' eyes. During this period, two-run sampling turned up serious problems such as contaminated bearings and misassemblies which reflected this poor attitude (18:--). With time and improved work force stability, experience, and attitude, these problems lessened, and two-run sampling then became more infrequent.

Likelihood of Having Individual Work Sampled

The last element of the work force which should be considered regarding quality and two-run sampling is the likelihood of workers having their individual work sampled. A belief that their work may be selected for a tough, important, inspection often is more influential than a remote, esoteric flying safety statistic. If all engines are being sampled or one assembly team builds all engines, those workers know their personal work is on the line. However, if the sampling rate is low with the work force large and transitory, the chance of personal identification with a defect can appear insignificant. This situation can be offset by timely fault identification and follow-up once a problem is discovered but is much more difficult in a large, impersonal work force.

The level of uncertainty regarding engine quality is dependent on the factors just discussed: engineering design, tooling, procedures, and the work force. A two-run sampling program is like a safety net design to catch faults which earlier quality checks missed either because the faults are not evident in subassembly checks, or in the test cell, or require a disassembly to inspect condition. This safety net provides obvious benefits but is not without cost. The following sections discuss the costs and benefits that can be expected from a two-run sampling program for modern gas turbine engines.

COST

The monetary costs of the two-run sampling programs are not readily apparent on current Air Force engine contracts. There are no contract line items for two-run sampling and none are expected in the near future (20:--). But there are very real program costs borne by both contractors and government. AFSC regulation 74-1, paragraph 8a(3) states, "Since the Air Force requires the teardown inspection, costs associated with the inspection procedure will be borne by the Air Force." (7:3) Most production engine buys are competitive firm fixed price contracts (20:--). Within the limits of the competitive contracting environment, the companies recoup their costs for two-run sampling with the sale of each engine. As noted in Chapter One, Mr. Brimelow, General Electric's program manager for the F110-GE-100 engine, estimated that their average shop cost for each two-run inspection (test, teardown, inspection and rebuild) is between $220,000 and $250,000 (13:--). These costs are for direct labor, use of test cell facility, floor space, and replacement hardware. There are also indirect costs in schedule/delivery delays and production capacity limitations.

The impact on engine delivery of a two-run teardown is between two and four extra weeks depending on program maturity and the type of faults uncovered. An engine's normal cycle time from start of piece part assembly to government acceptance is only eight to twelve weeks so delivery of sampled engines is significantly delayed. This schedule impact is usually the hardest early in production when sampling rate is very high and problems are numerous. When the program is behind schedule or new engines are needed in the field, this delay for teardown can appear excessive and unnecessary (until serious problems are uncovered). Also, while workers are disassembling and rebuilding sample engines, they and their tooling are not building new engines. This restriction in production capacity is proportional to sampling rate; therefore, programs generally need to lay in the most extra capacity early in production. For example, 100 percent sampling of four engines per month needs approximately four extra engines worth of assembly capacity. Only one engine worth of extra capacity is needed when sampling one of 30 engines per month. Hopefully, when full rate production is achieved, demonstrated engine quality normally allows less sampling and impact on overall capacity. Most of the extra capacity for early sampling can be absorbed and used to support subsequent full rate production. However, while any two-run sampling continues, some extra production capacity will always be needed and paid for.

The monetary, schedule, and capacity costs of a two-run sampling program should be fully compensated by the expected savings/benefits. If this is not the case, either lower quality should be acceptable or if not, other, more cost effective methods developed to insure an acceptable level of quality. These costs are substantial, so both the contractor and government should understand the full range of program benefits.

BENEFITS

The benefits of two-run sampling are the rewards of higher quality and the positive side-effects of inspecting/studying numerous actual production engines with running time. With current procurements including extended engine warranties, higher quality saves both the buyer and seller money and capability while also giving everyone a better understanding of normal engine conditions.

The reward of higher quality by this sampling is through the reduced risk of latent, undetected flaws which could jeopardize engine reliability or performance. This reward is normally highest with single engine aircraft but important for any application. The inevitable flaws caught by sampling are easier and cheaper to fix while they're in the factory than when scattered around the world in operational aircraft. Plus, the earlier a flaw is detected, the fewer engines there are with the problem which need repair. The two-run sampling identified a serious bearing contamination problem on both the F101 and F110 engines early in their production. The nature of this problem was such that perhaps hundreds of operational hours could have elapsed before discovery otherwise. By that time, hundreds of engines would have been delivered with damaged bearings out of tech order limits and needing a major teardown for repair (12:--). The two-run sampling program detected the damage early and the causes were corrected. Once these kinds of serious problems were identified and corrected, quality improved, and sampling rate could be reduced as confidence increased.

The beneficial side-effect of running new engines, then disassembling and inspecting them, is that besides improving their quality, sampling also provides valuable, early experience and understanding of "normal" engine condition. The initial objective of sampling is to find the problems, but fortunately, most of the engines are ok, built to specification, and working fine. However, everyone involved with the process learns a great deal of what is normal. Early in an engine design's life, this experience is invaluable for incident investigations, relaxations or tightenings of manufacturing tolerances, and understanding what the future real engine maintenance will be like (13:--). The numerous teardowns and reassemblies of F101 and F110 engines found bolts that could not be loosened or assemblies which would not go back together after engine operation. These were not due to manufacturing errors but rather, previously undetected design problems caused by thermal cycles (18:--). By understanding these "normal" characteristics, whether good or bad, two-run sampling can accelerate the valuable system maturing process.

These two-run sampling benefits of higher quality and system understanding need to offset the previously mentioned costs for the program to be effective. To maximize this cost effectiveness, a good understanding is needed of the four factors discussed earlier: design, tooling, procedures, and the work force. Understanding these factors, and the expected costs and benefits, allows the most effective development, tailoring, and/or administration of two-run sampling programs for gas turbine engine production.

Chapter Four

SUMMARY AND CONCLUSIONS

Modern gas turbine engines have come a long way in performance and reliability. During the Korean war, early jet engines needed a major overhaul after only 15 hours, just to maintain some semblance of reliability. Today, engines cost millions of dollars, but are expected to be fuel efficient, high performance, and capable of operating thousands of hours before major maintenance. A significant prerequisite for achieving this is quality design and manufacturing. A key indicator of this quality is the two-run sampling programs conducted before government acceptance of the engines. With numerous new or derivative engine designs approaching production, critical decisions regarding their two-run sampling programs will be needed in the near future. The intent of this report is to provide the understanding of the factors which should be considered when developing, tailoring, and/or administrating a two-run sampling program.

Quality is a part of engine production from concept design to customer acceptance. There are extensive procedures and checks to insure quality throughout production with two-run sampling serving as a final check. The goal of this sampling is to insure production of high quality engines by gathering information of any flaws overlooked and allowing corrective actions before delivery. Air Force and AFSC regulations 74-1 call for hardware audits which current engine two-run sampling programs clearly satisfy. However, these programs are not intended to meet the statistical sampling requirements found in MIL-STD-105D, MIL-STD-414, or MIL-E-8970. For two-run sampling of whole engines, the numbers required are cost prohibitive, and this is especially apparent in MIL-E-8970. This standard was specifically written for engines but last revised in 1967. No engine program in the last 10 years was able to afford or justify using the massive, simplistic sampling called for in MIL-E-8970. For this reason, this obsolete standard should be eliminated or completely revised to specify today's comprehensive inspections on more limited numbers of engines. Even if MIL-E-8970 is eliminated, hardware audits and the two-run sampling plans to implement them in engine program are here to stay. A good understanding of the qualitative factors which affect two-run sampling requirements will continue to be essential for their effective employment.

These qualitative factors which affect two-run sampling requirements are engineering design, tooling, manufacturing procedures, the workers, and the expected costs and benefits. The elements within each factor are for engineering design--design maturity and producibility; for tooling--effectiveness and reliability; for manufacturing procedures--effectiveness and clarity; and finally, for the work force--skills or experience, attitude, job stability, and likelihood of having their individual work sampled.

The costs of two-run sampling are substantial and are not borne solely by the contractor. He is responsible for producing a quality engine but is also in business to make a profit. Procurement regulations allow charges to the government for these hardware audits/samples but competitive, firm fixed priced contracts do not include a specific line item for them. Therefore, it is the best interest of both buyer and seller to strive for the highest quality with a cost effective two-run sampling program.

The benefits from the money invested in two-run sampling are both the rewards of quality, reliable engines and the side-effect of understanding the normal engine condition earlier in its life. It does not take many F-16 losses to offset any savings derived from quality shortcuts. However, two-run sampling is not a panacea for otherwise poor quality practices but it does catch flaws missed by other checks and serves as an effective monitor of overall system quality. In the future, two-run sampling programs, built by understanding the qualitative factors of design, tooling, procedures, and the work force, should continue to be an integral part of gas turbine engine production.

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