

Measurement Uncertainty Applied to Cost-Effective Testing

RATIONALE

The rationale of this new report is to show how the methodology of measurement uncertainty can usefully be applied to test programs in order to optimize resources and save money. In doing so, it stresses the importance of integrating the generation of the Defined Measurement Process into more conventional project management techniques to create a Test Plan that allows accurate estimation of resources and trouble-free execution of the actual test.

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1. SCOPE

The report shows how the methodology of measurement uncertainty can usefully be applied to test programs in order to optimize resources and save money. In doing so, it stresses the importance of integrating the generation of the Defined Measurement Process into more conventional project management techniques to create a Test Plan that allows accurate estimation of resources and trouble-free execution of the actual test. Finally, the report describes the need for post-test review and the importance of recycling lessons learned for the next project.

1.1 Introduction

Uncertainty analysis is a practical, scientific tool that is used to estimate the uncertainty of test measurements and of test results determined from the measurements. Prior to actually running a test, the methodology of uncertainty analysis allows the experimenter to learn much about the potential accuracy of a test result and to assess the relative effects of various error sources on the total test uncertainty. After data is obtained in the test, uncertainty analysis is used to quantify the goodness of the experimental results. There has been an increase in the awareness of uncertainty analysis over the past several years, and some of the key sources of information on it are given in References 2.1.1.1, 2.1.2.1, 2.2.1, and 2.2.2.

Unfortunately, the planning, design, and execution of testing programs is still too frequently carried out without reference at the planning stage to the detailed needs of the recipient/end-user of the test results and consequently without proper regard to the required uncertainty of the test measurements. A common scenario is that a test is planned within budgeted costs and timescales, utilizing facilities which are not optimal to the testing program but which are either already available or are readily accessible at reasonable cost. If the assessment of the uncertainty of the results takes place after the testing has been completed, then there is a risk that the accuracies actually obtained fail to meet the desired, sometimes contractual, requirements.

Obviously, cost-effectiveness in the use of testing resources is vitally important within both industrial and academic environments, and the scenario described above is based upon this necessity for economy. Finding that test results are too uncertain to be used effectively is not cost effective. However, the application of measurement uncertainty methodologies to the planning of the test program can benefit not only the final accuracy of the test but also the cost effectiveness of its execution. The action of defining the measurement processes, including the detailed breakdown of calibration hierarchies and elemental error sources, ensures that the test that is performed actually provides the required level of measurement uncertainty. It is not cost-effective to obtain a greater accuracy than is required. In this way, the use of expensive laboratory or industrial scale testing facilities may be optimized and real savings made.

It is the purpose of this report to present a clearly defined approach to the application of uncertainty methodology to the planning and cost effective conduct of test programs. The report is written in the aero engine-testing environment, in particular the determination of in-flight thrust. However, the approach described in the report can be applied to almost any experimental setting and is recommended to all who undertake testing programs for commercial gain.

The report begins by defining the basic requirements for a preliminary test plan from which estimates of resources, timescales, etc. may be drawn. It emphasizes the need to address the actual needs of the "customer" (whoever that may be) at the initial stages of planning. The required uncertainty of the test results must be established through expert dialogue between the supplier/test engineer and the customer/user. At this stage in the test program, an initial uncertainty analysis is performed using knowledge of the probable instrumentation uncertainties and experience of similar testing work. This initial uncertainty analysis helps to identify potential problems and to verify that the test has some reasonable probability of meeting the required uncertainty for the test results.

Potential problems with both human and material resources, schedules, and other major test issues are identified in this initial phase of the test program. The preliminary test plan section of the report stipulates the need to recognize the limitations, risks, and the importance of a clear definition of program accuracy requirements.

The report continues with the description of the development of the Defined Measurement Process (DMP) in detail. The DMP is comprised of three parts:

- Definition of the measurement chain, including details of the type and number of instruments to be used and their calibration requirements.
- An elemental uncertainty analysis, in which all possible sources of both systematic and random error are defined and estimates are made of the uncertainties associated with each error source.
- A results uncertainty analysis, where the effects of propagation of the elemental uncertainties into the results are assessed.

Using this procedure, an estimate of the uncertainty of the final results is obtained and can therefore be compared to the original requirement. Where there is a discrepancy, in the sense that the uncertainty is either greater or smaller than what is demanded, the test plan can be modified, the DMP revised, and a new uncertainty estimate made. The uncertainty analysis gives significant guidance on where the problems are and what needs to be corrected. By iteration of these processes, the test plan can be optimized prior to or during the initiation of any actual testing work. This optimized plan may then be reviewed and agreed upon by the customer, if necessary, before a final Test Plan is published.

Once the test plan is finalized, the next stage is to perform a preliminary test and to review the results obtained. The quality of the data can be checked against the expectations from the DMP, and the discrepancies can be investigated. Comparisons are made between the current test results and expected results obtained from similar tests or model simulations. These comparisons provide checks of the uncertainty estimates and help to identify problems with the test program. The report emphasizes the importance of planning this preliminary test into the program since it offers the last, but most effective, opportunity for revisions to the test plan before serious testing proceeds.

Following the execution of the tests, the actual results must be analyzed and their uncertainties estimated. Since much of the groundwork for this exercise will have been carried out already in an earlier stage, the effort required here is reduced.

Finally, a post-test review is recommended, where the results obtained and the uncertainties associated with them are compared with predictions and discrepancies are investigated. Such investigations should be reported openly and may be used to assist in planning the next similar testing program.

1.2 Concluding Remarks

Measurement uncertainty is a tool that can be applied to test programs in order to optimize resources and save money. Sections 3 through 8 of this document describe how this tool is used, with an example. Figure 1 gives a roadmap of the report.

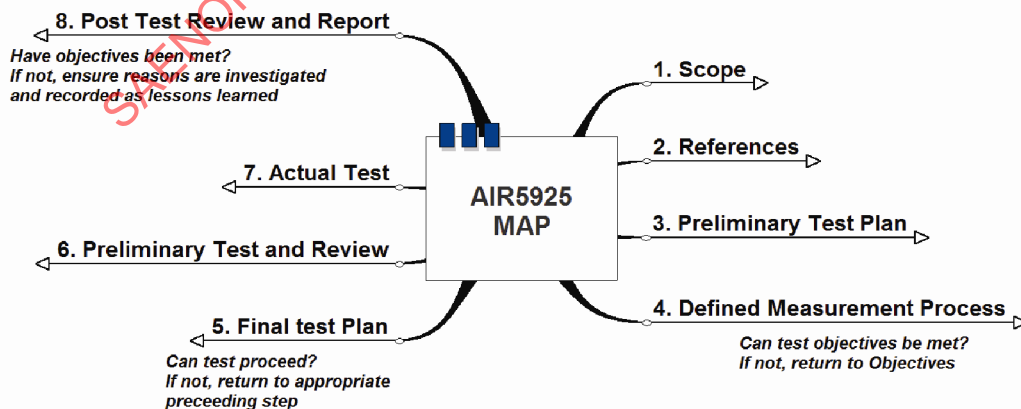


FIGURE 1 - AIR5925 MAP

2. REFERENCES

2.1 Applicable Documents

The following publications form a part of this document to the extent specified herein. The latest issue of SAE publications shall apply. The applicable issue of other publications shall be the issue in effect on the date of the purchase order. In event of conflict between the text of this document and references cited herein, the text of this document will take precedence. Nothing in this document, however, supersedes applicable laws and regulations unless a specific exemption has been obtained.

2.1.1 SAE Publications

Available from SAE International, 400 Commonwealth Drive, Warrendale, PA 15096-0001, Tel: 877-606-7323 (inside USA and Canada) or 724-776-4970 (outside USA), www.sae.org.

2.1.1.1 AIR1678A, Uncertainty of In-Flight Thrust Determination (Issued 1985, Reaffirmed 1992, and Revised 2002).

2.1.1.2 AIR1703, In-Flight Thrust Determination (Issued 1985 and Reaffirmed 2004).

2.1.2 ANSI Publications

Available from ANSI, 25 West 43rd Street, New York, NY 10036-8002, Tel: 212-642-4900, www.ansi.org.

2.1.2.1 American National Standards Institute/American Society of Mechanical Engineers, Test Uncertainty, PTC 19.1-1998, ASME, New York, 1998.

2.2 Applicable References

2.2.1 International Organization for Standardization, Guide to the Expression of Uncertainty in Measurement, ISO, Geneva, 1995.

2.2.2 Coleman, H. W. and Steele, W. G., Experimentation and Uncertainty Analysis for Engineers, 2nd ed., John Wiley and Sons, Inc., New York, 1999.

2.2.3 Robert V. Hogg and Elliot A. Tanis, "Probability and Statistical Inference", Macmillan.

2.2.4 "Experimental Determination of Time Constants and Nusselt Numbers for Bare-Wire Thermocouples in High-Velocity Air Streams and Analytical Approximations of Conduction and Radiation Errors," Marvin D. Scadron and Isidore Warshawsky, NACA TN 2599, January 1952.

2.2.5 Boris Iglewicz & David C. Hoaglin "How to Detect and Handle Outliers" Volume 16, The ASQC Basic References in Quality Control: Statistical Techniques Series. 1993.

3. THE PRELIMINARY TEST PLAN (FIGURE 2)

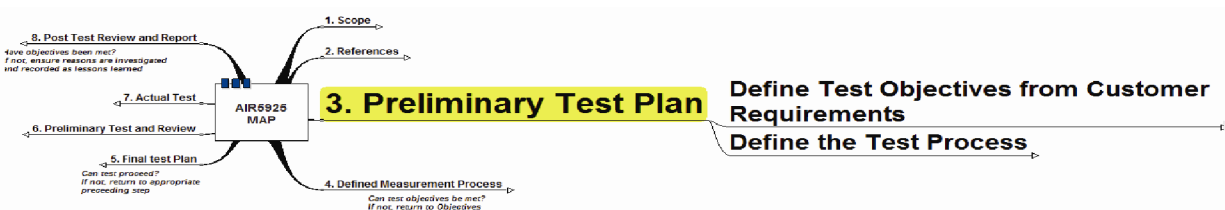


FIGURE 2 - PRELIMINARY TEST PLAN

3.1 Introduction

Uncertainty analysis applied in the earliest stages of a test program can help in the decision making process and can lead to an economical use of resources. The Preliminary Test Plan defines the test objectives from customer requirements and then defines the test process. An initial uncertainty analysis at this stage, based on historical information, lessons learned and best estimates provides guidance for the defined measurement process and test plan development which will follow.

3.1.1 General

The first stage in any test program is to prepare a Preliminary Test Plan. This plan will be used to develop a detailed Defined Measurement Process. Since this plan is intended to be preliminary, it must be prepared with scope for review and revision at a number of stages during the program.

Due to time constraints, some preparatory work may need to be initiated before publication of the Final Test Plan. When this is the case, priority must be given to understanding the consequences of any revisions to the time, cost and technical estimations during the development of the Preliminary Test Plan. Furthermore, it is essential that customers and external contractors, if employed, are included in the appropriate areas of the document control process.

The inclusion of measurement uncertainty principles into the planning process does not demand a large increase in the complexity of the task. The work associated with uncertainty will result in a plan that is significantly more reliable and cost-effective.

To illustrate this, an example of a typical in-flight thrust determination will be worked throughout this report. The full in-flight thrust determination process is complex but is based upon straightforward measurements which must be optimized if the result is to be sufficiently accurate. The sections that follow will describe the preliminary test planning process in general terms and then address the example in the same terms. In this way, it will be seen that the relatively complex measurement process can be planned methodically.

3.1.2 The Worked Example

The worked example is a case of in-flight thrust determination of an aircraft engine, using information taken from flight tests, ground level tests and other component rig measurements to derive a value of net thrust at two defined flight conditions. This example applies a Gas-Path/Nozzle Analysis method (based on the ideal thrust group of thrust divided by jet area and ambient pressure F/AP) utilizing a residual error procedure. This concept and other methods for determining in-flight thrust are summarized in Reference 2.1.1.2. Good test practice dictates more than one method should be used to provide greater test confidence; however, additional methods can impact the test program.

The example in this document will concentrate on the flight test part only; the other parts are assumed to have been completed, with all the results of those tests available for use in the derivation of the flight test results. Figure 3 shows the flowchart for the entire process with the flight test part to be worked in this document located at the right of the diagram enclosed by the dashed line.

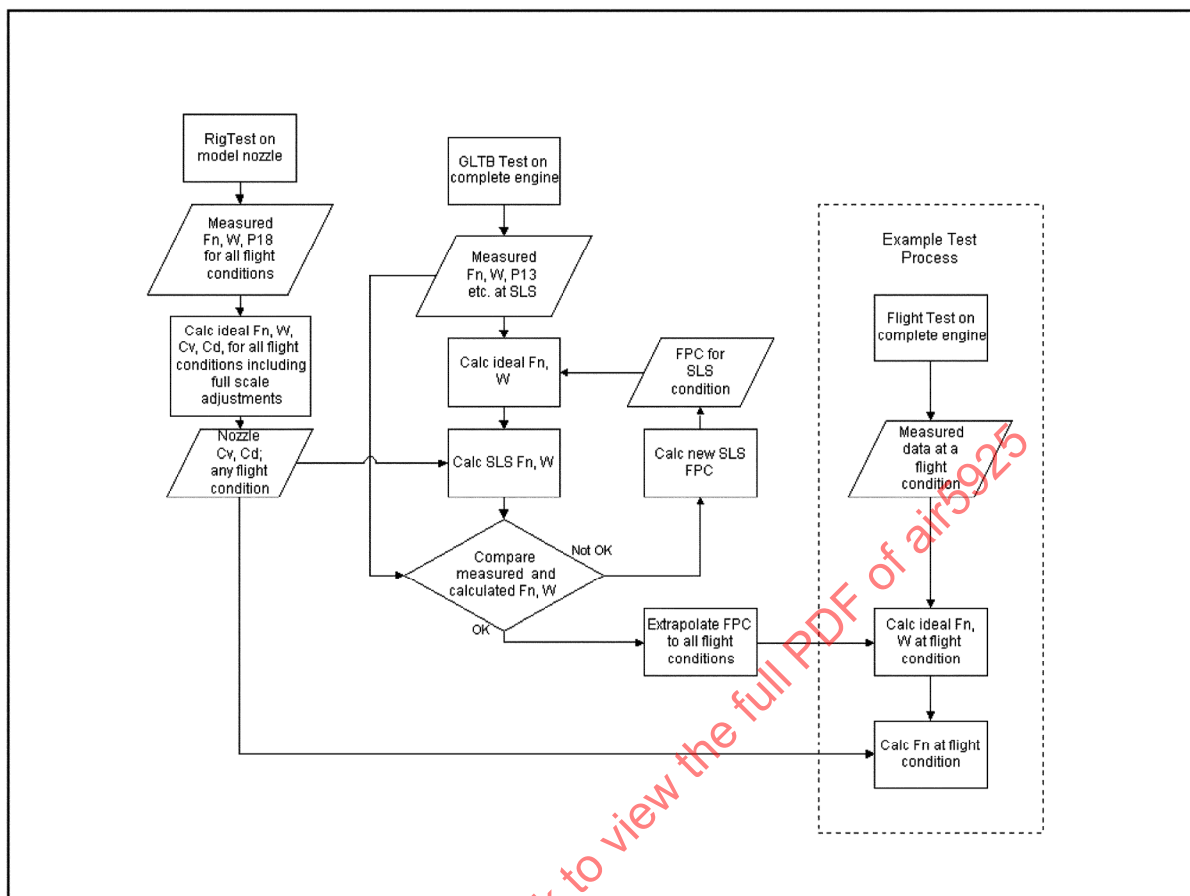


FIGURE 3 - TYPICAL IN-FLIGHT THRUST DETERMINATION PROCESS

Since the thrust of an aircraft engine in-flight is difficult to measure directly through force instrumentation, other measurements are used to derive the thrust indirectly. In this example, fan delivery total pressures are measured in the bypass duct of a turbofan engine using "radial" rakes to provide a defining relation for thrust as a function of fan pressure. Adequate sampling to determine the representative gas path average pressure from such measurements is not always possible. This is especially true in the fan (by-pass) duct where large radial and circumferential variations often exist. One sea level test stand method assumes this known inability to measure the fan duct gas path average pressure to be the primary cause for any disagreements between the calculated versus measured air flow and thrust. The method recognizes that other unknown measurement/modeling errors (Reference 2.1.1.2) could also contribute to the lack of closure.

A ground level test stand calibration is used to define the fan pressure-thrust relation by means of a fan pressure correlation (FPC). Fan pressure correlation is a scalar applied to the average measured fan duct pressure for use in calculating both nozzle thrust and air flow. The calculated values of thrust and air flow are then compared to the equivalent test stand measurements. Typically, errors other than those in fan duct pressure measurement prevent derivation of a unique pressure correlation that simultaneously equates calculated and measured values for both thrust and flow. Instead, the procedure establishes a fan pressure correlation that minimizes the calculated to measured inconsistencies leaving residual errors on both air flow and thrust.

Fan pressure correlation is derived on the ground level test bed using the following procedure. Core nozzle flow is determined from the high-pressure turbine nozzle flow function (HPTFF). This flow along with measured P5 (LPT discharge pressure), calculated T8 (LPT discharge temperature), and core nozzle velocity coefficient are used to determine core nozzle thrust. The difference between the core flow and thrust and the total inlet bellmouth flow and measured thrust is attributable to the bypass exhaust after proper accounting for parasitic flows, fuel flow additions, internal recoups, leakages, scrubbing drags, etc. This provides equivalent measured test stand values for the bypass duct flow and thrust. An iterative solution for the fan duct total pressure that minimizes the root sum squared differences in bypass duct measured and nozzle calculated flow and thrust values (residual error) is then evaluated. The resulting "calibrated" fan duct gas path average pressure is compared to the rake measurement (P13) to establish the pressure correlation at a given test condition. Alternatively, the residual error terms can be defined using overall flow and thrust instead of the bypass values, providing better alignment with the test stand measurements.

A unique pressure correlation characteristic is derived as a function of power for each podded engine. On-wing the individual pressure correlation of each calibrated engine is applied to the fan duct radial rake measured pressure. The resulting fan duct "gas path average pressure" is then used in the determination of nozzle calculated in-flight thrust and air flow.

A spreadsheet can be used to determine the in-flight net thrust measurement uncertainty due to the errors in the process-measured inputs (see 4.3.5). The spreadsheet also calculates the required process sensitivity coefficients. Standard methods, i.e., AIR1678A (Reference 2.1.1.1) or PTC 19.1-1998, Urss 95% coverage (Reference 2.1.2.1), are used to propagate the measurement uncertainties for the flight test ("on-wing") phase to in-flight net thrust uncertainty. This uncertainty would be combined with the calibration and ground test uncertainty to get the total uncertainty of the thrust. For this report, these additional uncertainty components have not been included. Key assumptions in the uncertainty calculations are outlined below:

ASSUMPTIONS:

- a. Separate flow and complete expansion of the (non-mixed) hot and cold jets
- b. Thermodynamic parameters (C_p , specific heat ratio, etc.) remain constant for the small perturbations under consideration
- c. Core nozzle temperature, T8, found from energy balance
- d. Core flow from High Pressure Turbine Flow Function (HPTFF)
- e. Fan exit temperature measured as TT13
- f. Nozzle characteristics assumed constant for small error perturbations

3.2 Defining the Test Objectives and Customer Requirements

3.2.1 Test Subject

The first step is to establish the subject of the test. In the context of this document it is likely that this will be either a complete aero engine or an engine component, but the principles described below are applicable to many other testing activities and technical disciplines.

3.2.1.1 Example Test Subject

The test subject will be a full turbofan aero engine, complete with podded installation nacelle and flight-worthy instrumentation systems. In practice, it is likely that there would be more than one engine to be tested, but for the purposes of this document, only one will be considered.

3.2.2 Test Objectives

It is important to identify and define the principal aim of the test at an early stage, since there may also be supplementary tests which could confuse the plan. It is also necessary to justify the test, both technically and commercially. The justification may be addressed in terms of the risks of not doing the test, since the status quo may be unacceptable. Both of these aspects may be better understood by discussing the actual, sometimes underlying, needs of the customer.

3.2.2.1 Example Test Objectives

The primary objective of the test is to determine the in-flight net thrust of the engine at discrete, nominal flight conditions, expressed as altitude, aircraft Mach number and inlet temperature. A flight test is an expensive exercise and so many other tests will be performed in parallel with the thrust measurement to maximize the investment. Such ride-along tests typically include:

- a. Assessment of thermal transient characteristics
- b. Definition of power management control schedules
- c. Validation of production operating limits.

Such tests are beyond the scope of this document, but are mentioned here to illustrate the need for clarity in the setting of objectives since their inclusion must not impede or displace the primary objective.

3.2.3 Test Requirements and Uncertainty Levels

The critical output parameters or Defined Test Results (DTR) required to meet the stated objectives must be established. These may be either direct physical measurements or derived performance-defining parameters.

The required uncertainty and statistical confidence levels of the defined test results must be established through expert dialogue between the supplier/measurement engineer and the customer/user. The stipulation, "as good as possible" is unacceptable. Current achievable levels of uncertainty of in-flight thrust determination are given in AIR1703 (Reference 2.1.1.2). To stipulate requirements that are unachievable or inappropriate can lead to a test that is not cost-effective.

The application of uncertainty analysis may vary for different types of tests, from demanding some absolute level of accuracy for an engine performance parameter (e.g., thrust) to specifying some level of significance in a comparative (back-to-back) test. Back-to-back tests can benefit from improved uncertainty in their results since, if properly planned, it is likely that many sources of systematic uncertainty are common to both tests and may be reduced.

The uncertainty analysis needs to be developed in such a way that the results are easily understandable and usable. All parties of the test team must coordinate in the definition of key engine and flight conditions for the analysis. Not all test conditions need to be analyzed in the pre-test uncertainty analysis, just those that are critical for the defined measurement process that follows.

3.2.3.1 Example Test Requirements

The primary defined test result is net thrust of the engine at both take off and cruise flight conditions. The total uncertainty of the result is to be no greater than $\pm 1\%$, with 95% confidence.

3.2.4 Limitations

There will be limits on the scope and accuracy of a test. Again, these must be established early in the preparations if unpleasant surprises are to be avoided. Areas that may impose limitations include:

- a. Safety and regulatory issues
- b. Financial constraints
- c. Time limits
- d. Availability of testing facilities, resources and a suitable test subject
- e. Technical shortcomings
- f. Commercial and contractual matters
- g. Politics

3.2.4.1 Example Test Limitations

The test to be worked here is a flight test: this demands certain minimum safety standards to be met regarding the design, construction and installation of instrumentation and these standards must be addressed in the test plan.

The engine to be tested will also have to be run in a ground level test stand, as part of the overall thrust measurement process and, if systematic measurement uncertainty is to be minimized, the ground level tests and the flight tests must utilize the same instrumentation systems. Consequently, the flight-worthy instrumentation systems must be utilized for both tests, even though they are not strictly necessary on the ground.

The test must be performed at minimum cost associated with meeting the requirements. Timescales are constrained by business requirements and deadlines for completion of the tests, or for the production of milestone results, must be agreed between the supplier and the customer.

The test will require ground level tests on both the whole engine and also rig tests on the engine nozzle assemblies prior to flight testing. The availability of facilities for all these tests must be established and included in the test plan.

There may be technical shortcomings in the method used to derive net thrust from the measurements. The existence and impact of these shortcomings must be agreed between the customer and the supplier.

3.2.5 Risks

There are likely to be many risks that prevent meeting the test objectives. These must be identified and assessed for likelihood of occurrence and impact on the outcome of the test. Any of the areas listed as possible limitations above may constitute a risk, since an excursion outside such limits naturally compromises the success of the test. This risk analysis process is in addition to the uncertainty analysis and is not covered in this report. The basic concepts are covered in Reference 2.2.3.

3.3 Defining the Test Process

3.3.1 Outline Test Procedure

The basic steps of the procedure to be adopted for the test need to be established. This preliminary procedure needs to be of sufficient detail to allow conventional project planning techniques to be used to estimate the work involved and resources required. Flexibility will be necessary, since the procedure is likely to be modified once later planning stages have been addressed.

Experience and “lessons learned” from previous similar testing programs should be applied here to optimize the outline test procedure and to highlight vulnerable areas.

3.3.1.1 Example Outline Test Procedure

The outline procedure for the flight test is as shown in Figure 4.

3.3.2 Outline Measurements

A list of the measurements needed to achieve results of the required uncertainty must be drawn up. This should only be in sufficient detail to allow visibility of the general level of instrumentation and calibration standards necessary. In doing this, it must be acknowledged that there will be a minimum number of instruments, of some known standard of calibration, to achieve the uncertainties demanded by the Test Objectives. This minimum instrumentation regime can only be estimated through the Defined Measurement Process, so this aspect will be subject to modification before the test plan can be finalized.

Again, experience of previous testing is valuable in identifying the most important measurements. For example, it has been established (Reference 2.1.1.2) that for in-flight thrust measurements, pressure measurement errors are dominant in determining the accuracy of the results. With this knowledge, the DMP may be designed to ensure that the pressure measurements are particularly well engineered. Furthermore, the DMP may be used to confirm that such examples of previous experience are indeed applicable.

While the precise algorithms for derived output parameters may not be required at this stage, they must be specified before the final Defined Measurement Process (DMP) can be completed. Assumptions need to be explicitly defined.

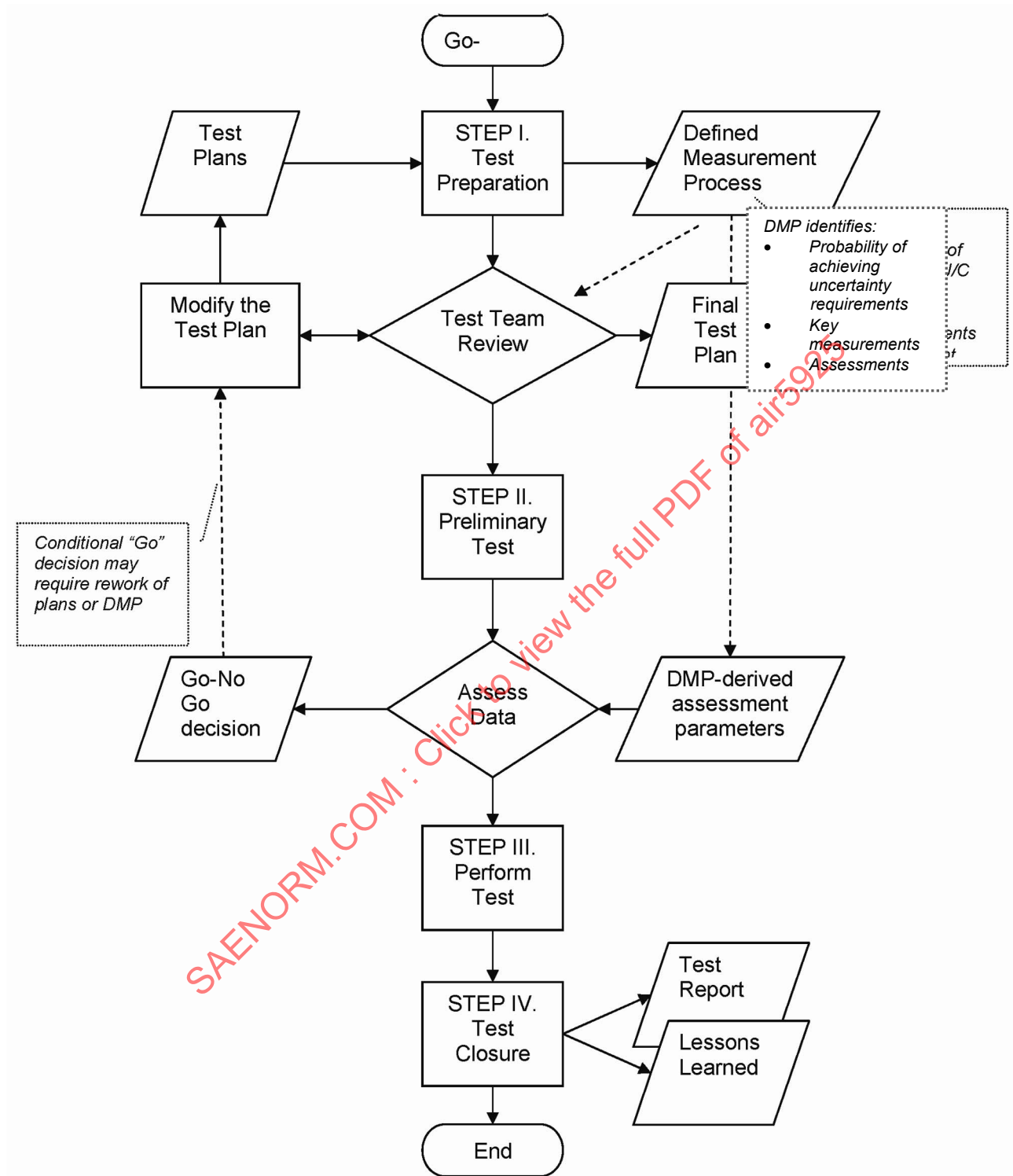


FIGURE 4 - PRELIMINARY TEST PLAN DIAGRAM

3.3.2.1 Example Outline Measurements

The in-flight thrust is derived from the following measurements and inputs:

- a. Ambient pressure, P_0
- b. Free stream total pressure, PT_2
- c. Free stream total temperature, TT_2
- d. Fan discharge pressure, PT_{13}
- e. Low pressure turbine discharge pressure, PT_5
- f. Compressor discharge pressure, PT_3
- g. Compressor discharge temperature, TT_3
- h. Fan nozzle area, A_{18}
- i. Velocity coefficient on fan nozzle stream, CV_{18}
- j. Flow coefficient on fan nozzle stream, CD_{18}
- k. Velocity coefficient on core nozzle stream, CV_9
- l. Fan discharge temperature, TT_{13}
- m. High Pressure Turbine Flow Function, $HPTFF$
- n. Fuel flow, WF
- o. Nozzle discharge suppression factor, CD_{18SUP}
- p. Fan Pressure Correlation Extrapolation Factor, $FPCEX$

Typical ranges and accuracies of measurement may be defined using knowledge of the flight conditions to be used, the design of the engine (and hence pressure, temperature ratios, fuel flows, turbine capacity, etc.) and previous experience. For example, reference to standard atmospheric tables will show the range of P_0 to be expected at the maximum and minimum altitudes specified and the instrumentation must be selected to cover this range. Likewise, knowledge of the flight Mach numbers to be flown will allow the range of PT_2 to be easily found. The engine performance model is used to determine internal engine conditions.

The specification of accuracy is more difficult without prior experience of the test to be undertaken. In this example, it has been assumed that such information is readily available.

3.3.3 Initial Uncertainty Analysis

Known or estimated values for instrumentation uncertainty should be combined with the known or estimated influence coefficients to produce an initial estimation of uncertainty for the results. Clearly, if this preliminary estimate of uncertainty is greater than the required level, then the plans must be immediately reviewed. If it is acceptable then the plan may proceed.

3.3.3.1 Example Initial Uncertainty Analysis

In this example, the test methodology is well established and previous analyses have determined the typical levels of systematic and random uncertainties and also the non-dimensional influence coefficients. These are summarized in Table 1 for the take-off condition and Table 2 for the cruise. The methodology used for the combination of these uncertainty estimates is presented in Section 4 of this document. Also shown are Pareto charts for the two conditions, indicating the relative contributions of errors in the parameters to the overall uncertainty of the result.

It may be seen from the Pareto charts that some parameters have a high contribution to errors in thrust measurement at both flight conditions (e.g., CV18, CD18 and FPCEX), while others do not (P0). Knowledge of these characteristics allows informed expenditure on instrument numbers, types and calibration requirements.

TABLE 1 - UNCERTAINTY ANALYSIS FOR IN-FLIGHT THRUST DETERMINATION
(ON-WING PHASE - TAKEOFF CONDITION)

	Parameter Description	Parameter	Influence Coeff.	Systematic Uncert. % RDG	Random Uncertainty %RDG
1	Ambient Pressure	P0	2.905	0.067	0.029
2	Fan Inlet Total Pressure	PT2	-3.971	0.046	0.008
3	Fan Inlet Total Temperature	TT2	0.157	0.153	0.038
4	Fan Discharge Pressure	PT13	1.974	0.052	0.017
5	Turbine Discharge Pressure	PT5	0.276	0.155	0.058
6	Compressor Discharge Pressure	PT3	0.181	0.159	0.124
7	Compressor Discharge Temp.	TT3	-0.038	0.163	0.160
8	Fan Nozzle Area	A18	0.731	0.260	0.000
9	Velocity Coefficient (Fan Noz)	CV18	1.094	0.224	0.000
10	Flow Coefficient (Fan Noz)	CD18	0.731	0.316	0.000
11	Velocity Coefficient (Core Noz)	CV9	0.275	0.224	0.000
12	Fan Discharge Temperature	TT13	-0.161	0.285	0.149
13	HPT Flow Function	HPTFF	0.181	1.000	0.000
14	Fuel Flow	WF	0.090	0.300	0.220
15	Flow Coeff (Suppression)	CD18SUP	0.731	0.150	0.000
16	FPC Extrapolation	FPCEX	1.974	0.100	0.000

Name	Code	PERCENTAGE		
		Systematic	Std Dev	Uncertainty
Net Thrust	FN	0.570%	0.105%	0.607%

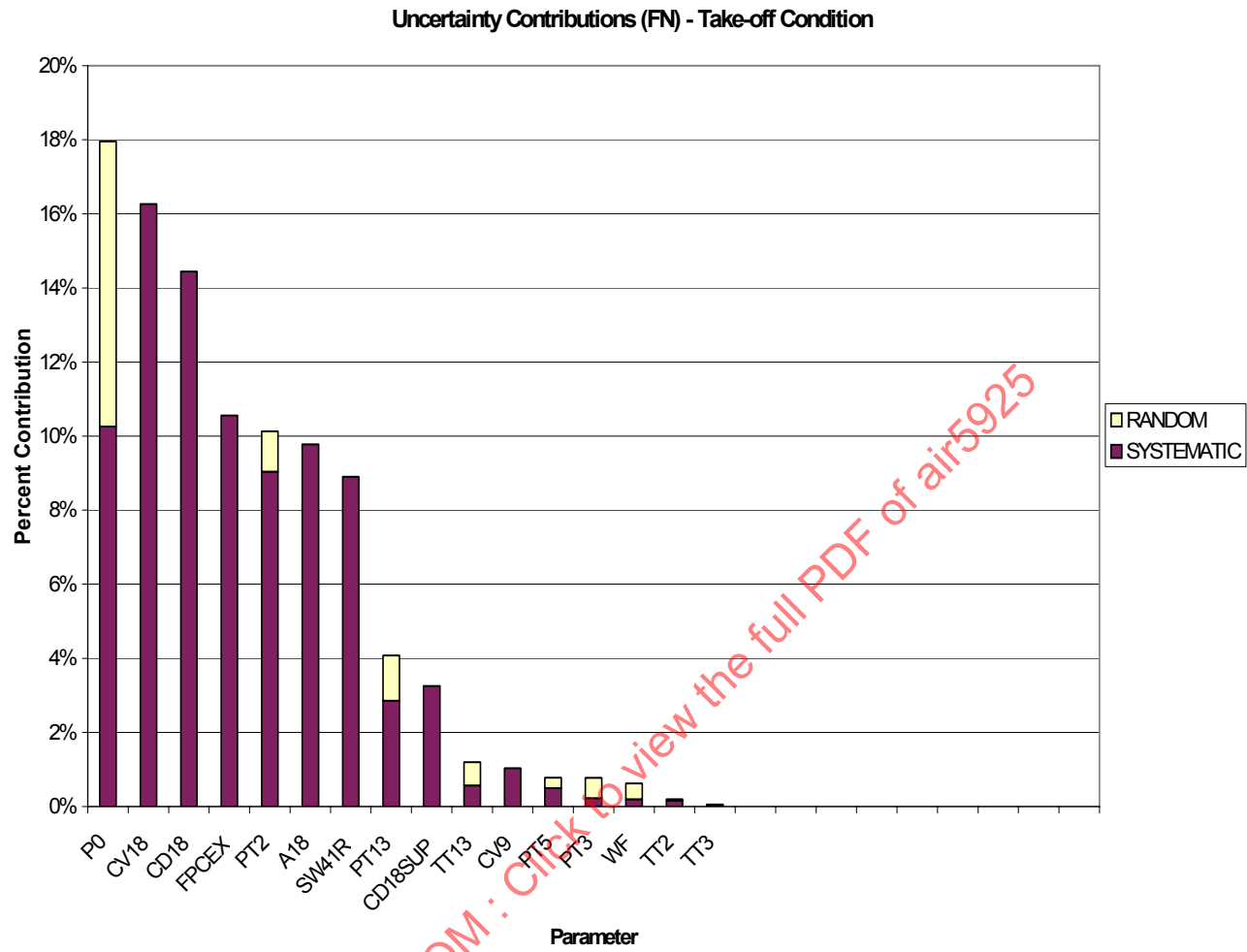


FIGURE 5 - UNCERTAINTY FOR TAKE-OFF CONDITION

TABLE 2 - UNCERTAINTY ANALYSIS FOR IN-FLIGHT THRUST DETERMINATION
(ON-WING PHASE - CRUISE CONDITION)

	Parameter Description	Parameter	Influence Coeff.	Systematic Uncert.	Random Uncert.
				% RDG	%RDG
1	Ambient Pressure	P0	0.425	0.067	0.029
2	Fan Inlet Total Pressure	PT2	-2.024	0.046	0.008
3	Fan Inlet Total Temperature	TT2	-0.248	0.153	0.038
4	Fan Discharge Pressure	PT13	1.901	0.052	0.017
5	Turbine Discharge Pressure	PT5	0.325	0.155	0.058
6	Compressor Discharge Pressure	PT3	0.142	0.159	0.124
7	Compressor Discharge Temp.	TT3	-0.031	0.163	0.160
8	Fan Nozzle Area	A18	0.630	0.260	0.000
9	Velocity Coefficient (Fan Noz)	CV18	2.521	0.224	0.000
10	Flow Coefficient (Fan Noz)	CD18	0.630	0.316	0.000
11	Velocity Coefficient (Core Noz)	CV9	0.550	0.224	0.000
12	Fan Discharge Temperature	TT13	0.156	0.285	0.149
13	HPT Flow Function	HPTFF	0.142	1.000	0.000
14	Fuel Flow	WF	0.231	0.300	0.220
15	Flow Coeff (Suppression)	CD18SUP	0.630	0.150	0.000
16	FPC Extrapolation	FPCEX	1.901	0.250	0.000

Name	Code	PERCENTAGE		
		Systematic	Std Dev	Uncertainty
Net Thrust	FN	0.828%	0.073%	0.841%

Uncertainty Contributions - Cruise Condition

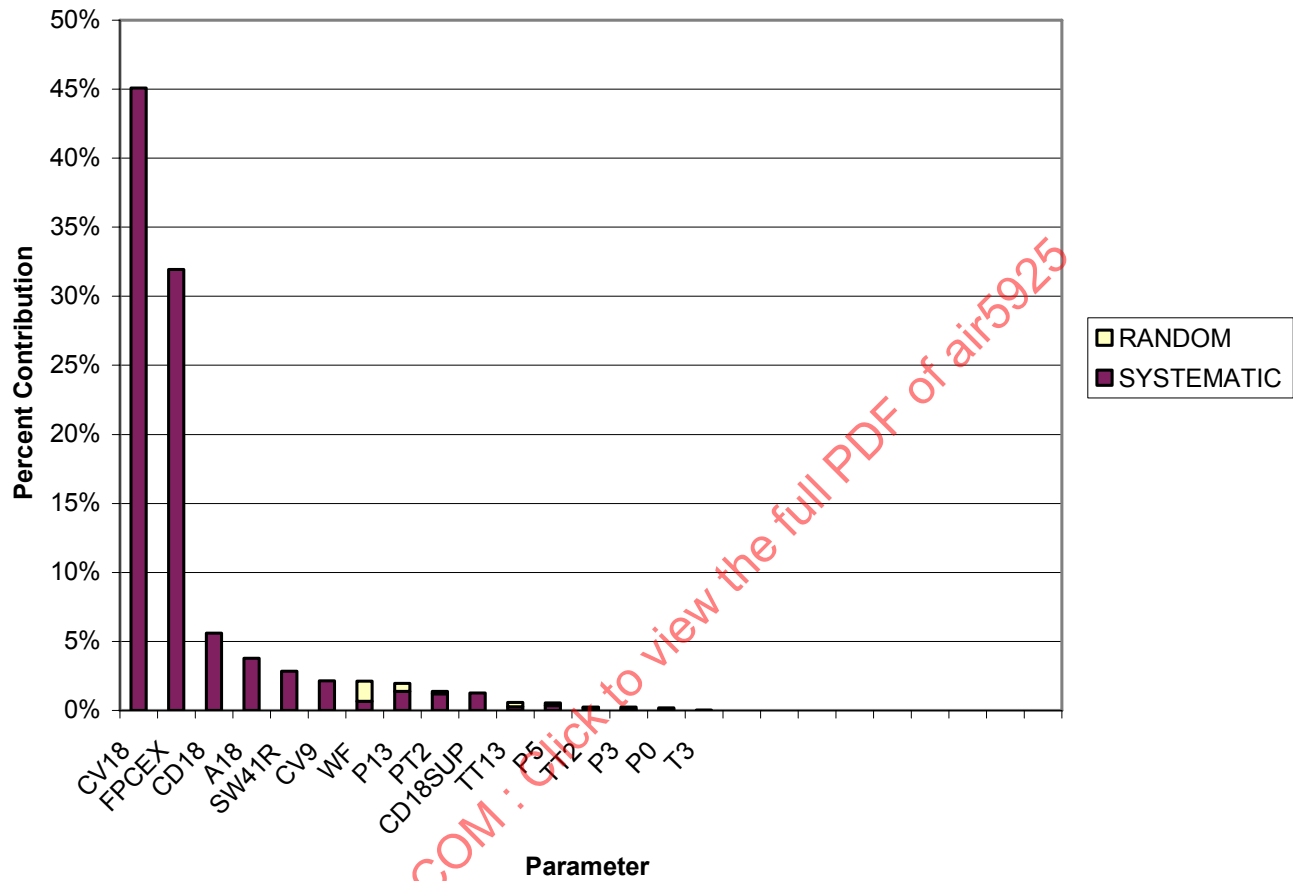


FIGURE 6 - UNCERTAINTY FOR CRUISE CONDITION

3.3.4 Presentation of Results

The method and format of presenting the test results both during the test and as a final report should be established. Typically the type and layout of graphs and tabular data need to be agreed along with the engineering units to be used. The digital transmission of test data via networks or internet-based systems can improve uncertainty since it allows numerical data to be transferred directly from the test bed data acquisition system to the post-test analysis system, then to the customer, without the need for manual transcription. Technical issues to be considered are: data file format (including parameter-identifying names, numbers or co-ordinates), transmission speed (since there may be large quantities of data) and security.

3.3.4.1 Example Results Presentation

During the test, a facility will be required to display and record all measurements relevant to the test. Plots showing all measurements from any one instrument rake against radial position are essential for quick and effective fault diagnosis.

It must also be possible to display and record selected calculated parameters for data validation purposes. Specifically, it must be possible to display plots of any combination of net thrust, shaft speeds, various engine pressure ratios, fuel flow, etc. If possible, such plots should be overlaid with model plots, previous data and/or acceptance limits.

The post-test analysis of the results must be done using data downloaded from the test bed via digital data transmission. The uncertainty analysis must be reported in detail using a formal technical report style. It must include a full description of the testing procedures, assumptions and calculations, and also a full report on difficulties/shortcomings, etc. and how they were solved. Graphical representations should be used where possible. The final report must be circulated to the customer and also to those for whom the lessons learnt will be of benefit in the future.

3.3.5 Resources

In a broad sense, the resources required to achieve the objectives of the test include such things as a suitable organization and infrastructure for carrying out the sophisticated testing described here. The actual demands will depend upon the scope of the test, its impact in terms of safety and other crucial aspects. Regardless, the organization employed for the test must be well ordered and have administrative systems capable of maintaining proper records of project details, instrumentation matters, etc., preferably within an accredited quality management system.

In order to minimize errors due to poor practice and human failings, a test team must be selected from adequately trained and/or experienced personnel. Adequate funding must be secured for the test, although the exact amounts required will be known only when the final test plan is complete. Conventional project management techniques should be applied to the estimation of human resources and costs. Compromises made in order to reduce cost and/or timescales must be assessed for impact on the uncertainty using the DMP.

A suitable laboratory or other testing facility must be sought. Since the facilities used for testing aero engines and components thereof are often large scale, complex and expensive, it is likely that the actual test plan may need to be matched to the capabilities of some existing facility. If the test plan demands that a new facility is necessary then costs and timescales must be reviewed and the justification for the test reconfirmed.

The list of measurements drawn up in 3.3.2 must be used to estimate instrumentation and calibration resources. Common sense dictates that allowance for redundancy be made in this estimation and so the minimum instrumentation regime must not be used for the estimation process. If the facility selected does not normally use instrument calibrations which are traceable to national standards, the additional associated work, delay and cost must be recognized in the plans.

The test will require a data acquisition and storage system, as well as computing and analysis tools. Again, the precise requirements will be developed as the measurement process is defined, but intelligent estimations should be made. Desk top personal computers and reprographic facilities are necessary for report preparation to an agreed standard or format.

Cost, time and measurement uncertainty are often in conflict when estimating resources. The parties involved in the test program must agree how these aspects are to be balanced. Subsequent changes to the test plan can alter this equilibrium and frequent reviews may be necessary to keep all three aspects under control.

3.3.5.1 Example Resources

- a. An engine, suitably instrumented, and previously calibrated on a ground-level test bed to measure thrust and air flow directly and to develop the fan pressure correlation data necessary to derive in-flight thrust.
- b. An aircraft of suitable type to mount the engine and to be capable of flying the envelope demanded by the test requirements.
- c. Instrumentation, data acquisition and analysis systems to support the tests, both installed inside the aircraft and on the ground for later analysis.
- d. Controlled documentation systems for instrumentation schedules, test schedules, fault reporting and project control (cost, timescales, etc.)
- e. Adequate numbers of properly trained and equipped personnel to carry out the work required.
- f. An organization and infrastructure capable of operating such facilities safely and successfully, utilizing recognized Quality Assurance systems and with traceability to national measurement standards where necessary.

3.4 Summary

The Benefits of Measurement Uncertainty Analysis:

The foregoing describes the initial work required to define a preliminary test plan. It introduces the concept of measurement uncertainty at an early stage, since decisions over instrumentation and testing procedures may be directly affected. By introducing uncertainty this early in the planning, maximum benefit may be obtained from the work.

The customer requirements, the test objectives and the uncertainties associated with them, predicate the defined measurement process described in the next section. This task has to be done at some stage of the project and is, therefore, not additional work. Traditionally, it has been done after testing is complete, however it is more effectively employed in the pre-test stage where the benefits of having a defined measurement process may be maximized.

4. DEFINED MEASUREMENT PROCESS (DMP) (FIGURE 7)

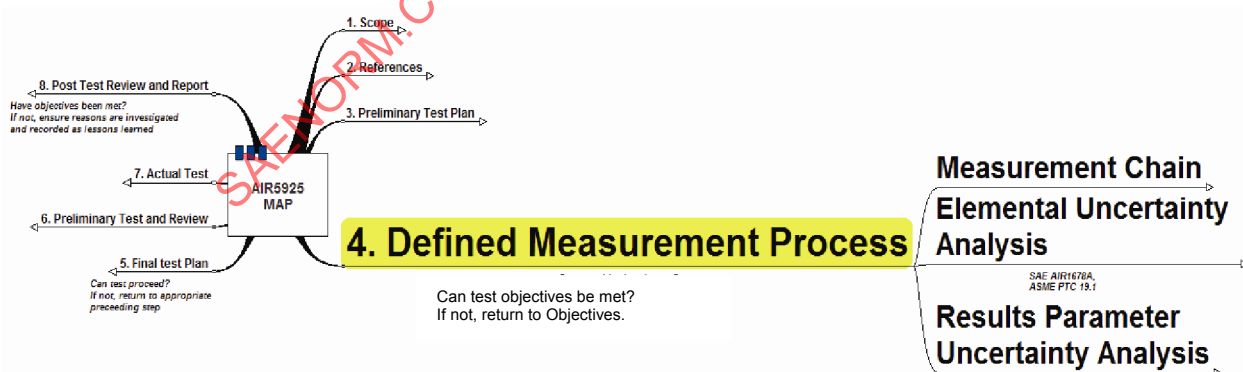


FIGURE 7 - DEFINED MEASUREMENT PROCESS

This section discusses the Defined Measurement Process (DMP), consisting of a measurement chain definition, an analysis of the elemental uncertainties, and the propagation of elemental errors to a result, all of which should be included in the test plan. To illustrate each of these steps, a measurement uncertainty analysis of in-flight thrust calculation is provided as an example. Sections 4.1 through 4.3 are designed to give the reader an overview of uncertainty analysis. They summarize the determination of systematic and random uncertainties of the parameters and of the test result. Section 4.4 gives examples of how the uncertainty analysis information can be used to save money, whilst assuring the quality of the results.

4.1 Measurement Chain Definition

The measurement chain definition is a complete description of the elements that make up a measurement. The measurement definition should consider measurements from “end to end,” to include all potential error sources. It is helpful to draw a block diagram showing all of the major elements of how a measurement is made, starting from the field of measurement, and proceeding through sensing devices, data acquisition equipment, data reduction processes, and system calibration techniques associated with the selected test facility. If the desired parameter is not measured directly, each individual quantity associated with the derived result must be identified and defined similarly.

Mapping of the measurement chain helps to identify potential systematic and random error sources. It is sometimes helpful to identify elemental errors in the following categories:

- a. Calibration hierarchy
- b. Data Acquisition
- c. Data Reduction
- d. Real Effects (Errors of Method or other non-instrumentation effects)

4.1.1 Calibration

Calibration is the process of transferring measured results from an instrument of higher quality to the acquired response of a lower quality instrument. The purpose of calibration is to economically eliminate large, known systematic errors. What is left is then the systematic uncertainty associated with the calibration standard. When calibration data is used to convert measured data into engineering units, all random uncertainty of higher-level calibration standards is treated as a “fossilized” systematic uncertainty and combined with other higher-level calibration systematic errors. Calibration laboratories are required to provide the uncertainties associated with their transfer standards. Measurements shall be traced back to a national standards laboratory according to the following example hierarchy:

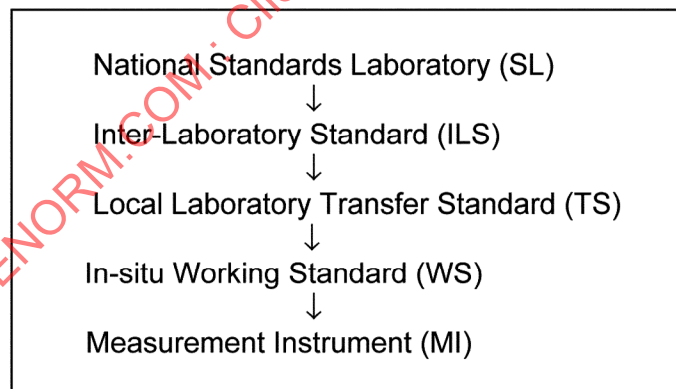


FIGURE 8 - CALIBRATION HIERARCHY

Each level in the calibration hierarchy contributes to the overall uncertainty of the measurement. In practice, the contributions of the higher level calibration sources can sometimes be ignored if they have uncertainties that are significantly less than lower level instruments. Traceability to a national standard must be demonstrated.

4.1.2 Data Acquisition

Data Acquisition involves a sensor that transfers a physical property to some other form, typically an electrical signal with a proportionate voltage level or frequency. Often this signal is altered, or “conditioned,” to filter out unwanted frequency components, or to sharpen a frequency transition. Then, the signal is converted to a digital value, usually through an analog to digital converter, or a frequency to digital converter. Since sensors, signal conditioning, and signal conversion all affect measurement uncertainty, the process definition and its graphical depiction should include all of these elements, as well as any environmental affects associated with temperature, humidity, barometric pressure, etc. Elemental systematic and random uncertainties are sometimes estimated from manufacturer’s specifications. Often, however, it is better to estimate these uncertainties based on special end-to-end tests to capture error sources that are difficult to estimate, such as environmental and installation affects.

4.1.2.1 Sensors

Sensors convert a variable physical property to another property, typically either a voltage level or a frequency. This transformation is rarely completely linear, and care must be taken to capture the appropriate transfer characteristics. This may be done through in-situ calibrations or perhaps a lab calibration. Sensors can exhibit both systematic and random errors in their ability to convert the desired physical properties. Also, the installation effects of the sensor must be considered if “truth” is defined as the value of the property if a sensor were not present.

4.1.2.2 Signal Conditioning/Conversion

Signal conditioning elements such as filters, multiplexers, and amplifiers all add uncertainty to a measurement, and should be captured by the measurement process description. Signal conversion elements include analog to digital converters and frequency to digital converters, each with systematic and random error components. The uncertainties associated with these elements can be determined through special tests, calibration data, or manufacturer’s specifications. The latter must be used with caution, and the basis for manufacturer’s specifications should be clearly understood. Otherwise, these errors may be captured by special end-to-end tests.

4.1.2.3 Environmental Effects

Environmental effects to each of the above measurement elements must be considered. Often, signal conditioning and data acquisition equipment are subject to additional uncertainties due to temperature, humidity, and other environmental effects. Test requirements may drive the user toward expensive environmental control procedures. If special tests are performed to estimate instrument error sources, environmental errors may be captured. If this is not possible, environmental errors may be estimated separately.

4.1.3 Data Reduction

Conversion of raw binary data to an engineering unit value results in various uncertainties. The test plan should define how this engineering unit conversion will be done. The DMP should define the source of engineering unit conversion method routines, such as thermocouple tables, lab calibrations, and in-situ calibrations. Typically, computer resolution is not an issue in modern computer systems. However, if the test plan includes use of an older system, this should be noted in the DMP. Computer resolution could also be an issue if older conversion programs are used that do not take advantage of double-precision calculation techniques. Though most modern computer systems have negligible uncertainty due to resolution, curve fit techniques and other engineering unit conversion methods can result in significant uncertainties, and should henceforth be listed in the test plan. In the engineering unit conversion process, various correction factors are used that have associated uncertainties. Various properties that are obtained from reference sources may be a significant source of measurement uncertainty. Care and rigor should be exercised in estimating their uncertainty contribution.

4.1.4 Real Effects (Errors of Method and Other Non-Instrumentation Effects)

Other measurement elements that do not fit well in the above categories can be captured in the method category. Some common examples include:

- a. A factor that is used to correct thrust measured in an indoor test cell to a value that would be obtained in an outdoor stand has systematic error associated with it.
- b. Other calculated quantities such as fuel flow measurement and air flow measurement that have calibration factors.
- c. Instrumentation installation effects on probes such as conduction, convection, and radiation.
- d. Spatial or profile uncertainty in the conversion from discrete point measurements to station averages.
- e. Instability, non-repeatability, and hysteresis of the test process.
- f. Effect of instrumentation on engine performance.

These are estimated from experience and assumed to be repeatable when based on one-time tests.

4.1.4.1 Instrumentation Installation Effects

Errors due to the installation of probes and other instrumentation may be significant. Thermocouple errors due to conduction, radiation, and recovery are beyond the scope of this document, but have been estimated in a variety of texts.

4.1.4.2 Probe Sampling and Spatial Nonuniformity

If the test plan demands a non-homogenous spatial quantity that is estimated by spatial sampling, significant error contributions may result. Treatment of this is described in detail for pressure measurement sampling in Reference 2.1.2.1.

4.1.4.3 Instability, Non-repeatability, and Hysteresis of the Test Process

Measurement system variation and instability in the quantity being measured cause variation of acquired data. Post-test analysis from previously run similar tests will indicate the level of test article instability. If possible, preliminary analysis of the data may help define the amount of sampling needed to produce acceptable uncertainties, without unnecessarily increasing test cost.

4.1.5 Example

Measurement Chain Definition: Consider the example of measuring the amount of thrust produced by an engine in flight. In the in-flight thrust determination example, the following measurements must be made that affect the calculated quantity of interest:

- a. Ambient pressure, P0
- b. Free stream total pressure, PT2
- c. Free stream total temperature, TT2
- d. Fan discharge pressure, PT13
- e. Low pressure turbine discharge pressure, PT5
- f. Compressor discharge pressure, PT3

- g. Compressor discharge temperature, TT3
- h. Fan nozzle area, A18
- i. Velocity coefficient on fan nozzle stream, CV18
- j. Flow coefficient on fan nozzle stream, CD18
- k. Velocity coefficient on core nozzle stream, CV9
- l. Fan discharge temperature, TT13
- m. High Pressure Turbine Flow Function, HPTFF
- n. Fuel flow, WF
- o. Nozzle discharge suppression factor, CD18SUP
- p. Fan Pressure Correlation Extrapolation Factor, FPCEX

A measurement chain for each of these measured parameters should be defined in the test plan. For this example, the measurement of PT2, fan inlet pressure is considered. Initially, an individual transducer with a measurement uncertainty of 0.25% was proposed. A comprehensive measurement uncertainty analysis will show that this level of uncertainty is unacceptable in the overall measurement of in-flight thrust, which requires an overall uncertainty of less than 1%. An alternate, high-accuracy pressure measurement system was proposed to bring the overall in-flight uncertainty levels within the 1% desired by the test customer. The following example is a detailed analysis of the elemental uncertainty for PT2 obtained using the alternate system.

The first step is to consider the measurement from flow field, back to the national standards laboratory definition of "truth." See the block diagram below that illustrates the Defined Measurement Process for the measurement of PT2. Note that the diagram shows the measurement of PT2 in terms of its potentially significant error sources; calibration hierarchy, data acquisition, data reduction, and real effects.

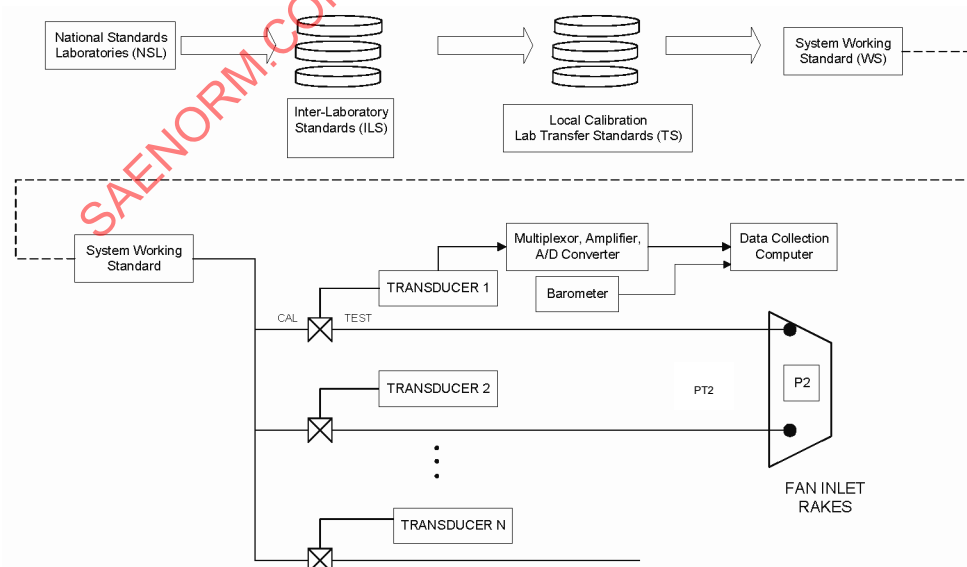


FIGURE 9 - EXAMPLE PRESSURE MEASUREMENT SYSTEM

4.2 Elemental Uncertainty Analysis

The Defined Measurement Process analysis proceeds with an analysis of the uncertainty of all elements identified in the measurement chain. To do this on a pre-test basis, the analysis will require the following information for each element:

- Full Scale Range of Measurement
- Measurement Units
- Estimated Parameter Values at points of interest
- Systematic and Random error estimates of error sources

The full-scale range of measurement is the calibrated range of the measurement instrument. Obviously it is best if instrumentation, transducers, and signal conditioning are selected so that the full-scale range of measurement is only slightly higher than the highest expected measured value. Hence, full-scale measurement information is required to verify proper instrumentation selection and to analyze elemental error sources that are defined as a percent of full scale.

Measurement units are identified in terms of their input to the calculated parameter of interest. A pressure, for example, may be measured by a transducer that is referenced to atmosphere, yielding a measurement in psig. The derived result parameter may be expressed in units of psia, requiring addition of the barometric pressure. Thus, uncertainties due to the measurement of barometric pressure must also be considered.

Estimated parameter values at the point of interest are required if elemental error estimates are characterized as a percent of reading value.

4.2.1 Random Uncertainty

Random errors are estimated by inspection of the measurement scatter during special tests, or by combining known or estimated elemental random errors. Typically, it is better to determine random variations from actual measurements provided that the test is representative of all typical error sources. If the random uncertainty is to be estimated from test data, the sample standard deviation, S_x is as follows:

$$S_x = \sqrt{\frac{\sum_{k=1}^N (x_k - \bar{x})^2}{N - 1}} \quad (\text{Eq. 1})$$

where:

N = Number of independent measurements

x_k = Individual measurements

$$\bar{x} = \frac{\sum_{k=1}^N x_k}{N} \quad (\text{Eq. 2})$$

If the averages of repeated samples are used to characterize the measurand, then the standard deviation of the distribution of the averages is:

$$S_{\bar{x}} = \frac{S_x}{\sqrt{N}} \quad (\text{Eq. 3})$$

Sometimes, all random error cannot be captured during the special test. Therefore, elemental contributions to random error must be estimated. If elemental error sources S_k are known or estimated, the random uncertainty is calculated to be:

$$S_{\bar{X}} = \frac{1}{\sqrt{N}} \sqrt{\sum_{k=1}^n S_k^2} \quad (\text{Eq. 4})$$

where:

S_k = Standard deviation for elemental error source k

N = Number of measurements made to determine $\bar{X}$

n = Number of error sources

4.2.2 Systematic Uncertainty

The systematic uncertainty B is an estimate of the true systematic error evaluated at a specified confidence level (usually 95%). Systematic errors are often more difficult to estimate than random error, and are usually based on engineering judgment and/or special tests. Examples of estimates include (Reference 2.2.3):

- inter-laboratory or inter-facility tests
- comparison of standards with instruments in the actual test environment
- special calibrations
- manufacturers' reports
- engineering judgment

As the test progresses, better information regarding the systematic error sources may become available, and certain elemental error sources may need to be updated. For example, the systematic error for a transducer may be estimated to be the manufacturer's specifications, but updated when in-situ calibrations are performed by a secondary standard.

Error sources are grouped into the proper measurement chain categories, and then combined to give the overall systematic uncertainty:

$$B = \sqrt{\sum_{i=1}^n B_i^2} \quad (\text{Eq. 5})$$

where:

B_i = Elemental systematic uncertainty for error source i

n = Number of error sources

4.2.3 Uncertainty of Empirical Data

Uncertainties for empirical data corrections must also be estimated if they are part of the measurement chain. An example would be an empirically derived factor to correlate measurement of jet engine thrust in an indoor test facility to the amount of thrust produced if the engine were outdoors. Other correction factors may include the test result if the environmental conditions were normalized to sea level static pressure and standard day temperature. Uncertainties are derived for these constants from the tests used to produce them, and are typically classified as systematic error.

4.2.4 Example: Elemental Uncertainty Analysis

Figure 9 shows the improved pressure measurement method proposed for in-flight thrust measurement. In this system, an in-situ working standard, calibrated in a lab traceable to a national standards laboratory is used to produce a calibration table for each of a number of individual gage pressure transducers in the measurement system. A pressure rake with two immersions will measure pressures between 0 to 5 psig. This value is then added to the barometric pressure measured with an instrument of the same quality as the pressure system working standard. The reported value is in units of psia.

Elemental uncertainties will be shown as $(B)_{ij}$ for systematic uncertainties, and $(S)_{ij}$ for standard deviation estimates where:

i = error source within a category

j = category

Categories:

1 = Calibration

2 = Data Acquisition

3 = Data Reduction

4 = Real Effects (Errors of Method)

Data are summarized in Table 3.

TABLE 3 - EXAMPLE ELEMENTAL UNCERTAINTY SUMMARY TABLE

PARAMETER: PT2		TYPE OF SENSOR: Silicon Pressure Transducer		MEASUREMENT RANGE: 14 – 19		UNITS: psia	
TEST CONDITIONS: Power Cal N2 = 9000 - 9500 RPM							
ELEMENTAL ERROR SOURCE Sub-Script			Systematic Uncertainty (B) _{ij} +/- unless indicated	Standard Deviation (S) _{ij} +/- unless indicated	Substantiation Source and Notes		
CALIBRATION							
11	ILS – TS		.00025	-	.005% on 5 psia Range		
21	TS – WS		.0023	-	.01% on 23 psia Range		
31	Barometer		.0015	.0075	Review of Calibration Lab Data		
DATA ACQUISITION							
12	Data Acquisition		.006	.0023	Historical Data, Many in-situ calibrations		
DATA REDUCTION							
13	Calibration Curve Fit		.005	-	Evaluation of non-linearity of in-situ calibrations		
	Resultant Error Components (RSS)		.0083 .044%	.0014 .008%			

4.2.4.1 Calibration Errors

The Local Laboratory Transfer Standard is an air dead weight tester with uncertainty of .005% of reading, or ± 0.0001 psi; whichever is greater, over a pressure range of 0.2 to 725 psig. Therefore, the uncertainty component due to calibration transfer is as follows:

$$(B)_{11} = .00005 * 5 \text{ psi} = .00025 \text{ psi}$$

$$(S)_{11} = \text{N/A (all error is fossilized as systematic)}$$

The in-situ working standard in this example is a 23 psia vibrating quartz crystal transducer that has a digital output to the data acquisition system. Estimates based on many calibrations over many ranges are as follows:

$$(B)_{21} = .0023 \text{ psi}$$

$$(S)_{21} = \text{N/A (all error is fossilized as systematic)}$$

A 15 psia transducer of like quality is used to reference the measurement to barometer:

$$(B)_{31} = .0015 \text{ psi}$$

$$(S)_{31} = .0075 \text{ psi}$$

4.2.4.2 Data Acquisition Errors

The data acquisition process will contribute uncertainty due to signal excitation, signal conditioning, transducer effects, and environmental effects. Since the working standard is used to calibrate each of the transducers in place, many effects due to signal conditioning are calibrated out. Through many calibrations the remaining errors may be estimated. Estimates of the error contribution due to data acquisition are as follows:

$$(B)_{12} = .006 \text{ psi}$$

$$(S)_{12} = .0023 \text{ psi}$$

4.2.4.3 Data Reduction Errors

During system calibration, pressures are applied to the individual transducers, and the corresponding output is recorded for each of approximately 10 calibration points evenly distributed through the range of the transducer. During data acquisition, the response of the transducer is used to interpolate this calibration table, resulting in an engineering unit quantity. The linear interpolation of the table assumes perfect linearity between points. Therefore, any non-linearities result in a data reduction contribution to uncertainty. The estimate of this error is as follows:

$$(B)_{13} = .005 \text{ psi}$$

$$(S)_{13} = \text{N/A (SAME CALIBRATION ASSUMED)}$$

4.2.4.4 Real Effects (Errors of Method)

In this example, errors of method include installation effects and spatial non-uniformity. Since these effects are estimated based on the average pressure measured at the cross section, and not on the individual pressure taps, real effects will be analyzed in the results parameter analysis section.

4.2.4.5 Combined Pressure Error

Note that the standard deviation estimates in Table 3 represent the random uncertainty for 1-second samples of the measurement. Since the uncertainty of a 30 second average is desired, the sample standard deviation of the mean is used, with N=30.

Equations 4 and 5 are used to combine all elemental error sources, resulting in the following:

$$B = \sqrt{\sum_{i=1}^n B_i^2} = \sqrt{.00025^2 + .0023^2 + .0015^2 + .006^2 + .005^2}$$

$$S_{\text{Pt2}} = \frac{1}{\sqrt{N}} \sqrt{\sum_{k=1}^n S_k^2} = \frac{1}{\sqrt{30}} \sqrt{.0075^2 + .0023^2}$$

$$= .0014 \text{ psi } (.008\% \text{ of full scale})$$

4.3 Results Parameter Uncertainty Analysis

4.3.1 Influence Coefficients

Influence coefficients are the ratios of the change in a result to a unit change in each input parameter. Influence coefficients are sometimes referred to as sensitivity coefficients or exchange rates. They are determined either analytically from the data reduction equation or numerically by perturbing the input parameter by a unit close to the estimated uncertainty level. The latter is typically used if the data reduction equation is complex, or if it is implemented in a series of computer programs that are difficult to dissect. The test plan should specify all inputs and assumptions.

The influence coefficients, θ , of a result, r , where $r=f(X_1, X_2, \dots, X_j)$, are evaluated by the partial derivative,

$$\theta_i = \frac{\partial r}{\partial X_i} \quad (\text{Eq. 6})$$

or by perturbing the input parameters one at a time and evaluating the change in the output:

$$\theta_i = \frac{\Delta r}{\Delta X_i} \quad (\text{Eq. 7})$$

Care should be taken to choose a perturbation interval that is appropriate for the test. This can be checked by calculating the influence coefficient for two different intervals, such as 1% and 0.5%, and ensuring the results are consistent.

It is helpful to express the influence coefficients in a non-dimensional form as relative influence coefficients, θ' :

$$\theta'_i = \frac{X_i}{r} \frac{\partial r}{\partial X_i} \quad (\text{Eq. 8})$$

A value greater than 1 indicates that the influence of the uncertainty in the variable is magnified as it propagates through the data reduction equation into the result. A value of less than 1 indicates that the influence of the uncertainty in the variable is diminished as it propagates through the data reduction equation into the result.

4.3.2 Overall Uncertainty of Result

As previously stated, it is often desired to determine the overall uncertainty of a quantity not measured directly, but derived from a number of measured quantities, each with its own systematic and random error estimates. These estimates must be correctly propagated to yield an estimate for overall uncertainty. The following information is needed from the test plan in order to perform this analysis:

- Elemental systematic and random error estimates
- Influence coefficients of the measured quantities with respect to the results parameter
- An analysis of any correlated systematic errors (see 4.3.3)
- The type of testing being proposed (back-to-back, multiple tests, etc.)

The Results Parameter Uncertainty analysis may then be used to determine if the proposed test plan will adequately answer the question being proposed. The analysis will also show which measurements should be improved to yield a lower result uncertainty.

For a large sample, the uncertainty of the derived parameter is given by

$$U_r^2 = B_r^2 + (2S_r)^2 \quad (\text{Eq. 9})$$

where

$$B_r^2 = \sum_{i=1}^J \theta_i^2 B_i^2 + 2 \sum_{i=1}^{J-1} \sum_{k=i+1}^J \theta_i \theta_k B_{ik} \quad (\text{Eq. 10})$$

and

$$S_r^2 = \sum_{i=1}^J \theta_i^2 S_i^2, \quad (\text{Eq. 11})$$

where:

B_R = Resultant systematic uncertainty

S_R = Random standard deviation of the result

θ_i = Influence coefficients

B_{ik} = Correlated systematic uncertainty terms between any of the J measurements

4.3.3 Correlated Systematic Uncertainties

Correlated uncertainties must be carefully considered in an uncertainty analysis, since they may improve or degrade the resultant uncertainty. Correlated systematic uncertainties are those that are not independent of each other, typically a result of different measured variables sharing some identical error sources.

Table 3 shows a summary of all the error sources for a PT2 measurement. PT2, however, is an average of 2 rake element measurements that share some common systematic error terms. Each pressure measurement shares common calibration hierarchy terms ((B)₁₁, (B)₂₁, (B)₃₁). All other systematic terms are not considered correlated.

Equation 10 contains a term for correlated systematic uncertainties, B_{ik}, where

$$B_{ik} = \sum_{\alpha=1}^L (B_i)_{\alpha} (B_k)_{\alpha} \quad (\text{Eq. 12})$$

where:

L = Number of correlated elemental uncertainties

α = Elemental uncertainties common to B_i and B_k

4.3.3.1 Example: Correlated Systematic Uncertainty for PT2 Measurement

The following example will show treatment of correlated systematic error sources for the 2-element PT2 system, where

$$\overline{PT2} = \frac{PT2_1 + PT2_2}{2}$$

The systematic uncertainty for each element of PT2 from Table 3 is

$$B_{PT2(1)} = B_{PT2(2)} = .0083 \text{ psi}$$

Since the elemental systematic errors associated with the pressure transducer calibration hierarchy are the same for each pressure sensor, the correlated systematic uncertainty term B_{PT1PT2} is the sum of the products of the common systematic uncertainties determined from Table 3 as

$$B_{PT1PT2} = (0.00025)^2 + (0.0023)^2 + (0.0015)^2 = 0.0000138 \text{ psi}^2$$

Using Equation 10 with influence coefficients of 0.5 and assuming correlated systematic uncertainties:

$$B_{\overline{PT2}}^2 = \left(\frac{1}{2}\right)^2 (0.0083)^2 + \left(\frac{1}{2}\right)^2 (0.0083)^2 + 2\left(\frac{1}{2}\right)\left(\frac{1}{2}\right) 0.0000138$$

$$B_{\overline{PT2}}^2 = 0.000041$$

$$B_{\overline{PT2}} = 0.0064 \text{ psi} = .033\% \text{ of F.S.}$$

4.3.4 Example: Real Effects for PT2 Measurement

As stated in 4.2.4, the real effects (or errors of method) for the PT2 example are based not on the individual pressure measurements, but on the average, therefore these effects are combined with the uncertainties of the PT2 average.

Tests on many rake installations using similar rakes in wind tunnel calibrations shows the following distribution of expected error due to rake installation and spatial non-uniformity:

Installation Effects:

$$(B)_{14} = .005 \text{ psi} \quad (S)_{14} = \text{N/A (SAME CALIBRATION ASSUMED)}$$

Spatial Non-uniformity:

$$(B)_{24} = .007 \text{ psi} \quad (S)_{24} = .003 \text{ psi}$$

The combined uncertainty for the PT2 average is, therefore, as follows:

$$B_{PT2} = \sqrt{.0064^2 + .005^2 + .007^2} = .011 \text{ PSI (0.058\% full scale error)}.$$

$$S_{PT2} = \sqrt{\left(\frac{.0014}{\sqrt{2}}\right)^2 + .003^2} = .0032 \text{ PSI (.017\% full scale error)}.$$

NOTE: The first term is divided by the square root of 2 because there are two rake elements in the PT2 probe.

4.3.5 Test Type Considerations

The type of test needs to be considered to determine if correlated systematic uncertainties exist that will affect the uncertainty of the derived parameter. For example, measurements made in a back-to-back test with the same instrumentation and same calibration are considered correlated and will affect the systematic portion of that parameter's uncertainty.

Another significant test type consideration exists if the required result is a relationship between two measured values. For example, if a test is to result in an X-Y relationship of two measured parameters, the influence of the X parameter uncertainty must be propagated to the uncertainty reported for the Y value. Reference 2.2.2, chapter 7, and Reference 2.1.2.1, Appendix D, give additional information on the treatment of this situation.

4.3.6 Pareto Analysis of Uncertainty Contributions

At this point in the analysis, it is helpful to review the contribution of each error source in relation to the total estimated uncertainty. If there are multiple error sources, a Pareto chart can be assembled to assess the relative impact of each elemental error source. It is a common problem to focus resources on insignificant error sources. This analysis should take place with respect to the uncertainty sources combined with the influence coefficients. Analysis such as this will maximize the efficiency of limited resources.

4.4 Example: Results Parameter Uncertainty Analysis

4.4.1 Example: Results Parameter Uncertainty Analysis at Takeoff Condition

Tables 4 and 5 summarize the uncertainty analysis for the on-wing test portion of in-flight thrust determination, prior to the PT2 measurement improvement. The relative influence coefficients were derived by perturbing inputs one at a time through the data reduction program by 1%. Systematic and random error components were estimated based on analyses similar to that used to derive the uncertainties for PT2 in our example.

The overall uncertainty of this portion of in-flight thrust measurement is higher than the desired 1%. Tables 6 and 7 summarize in-flight thrust measurement uncertainty changing only the uncertainty estimate for the improved PT2 measurement. Using the alternate pressure measurement system, the overall uncertainty of in-flight thrust is .635%, well within the customer requirements.

TABLE 4 - UNCERTAINTY ANALYSIS FOR IN-FLIGHT THRUST DETERMINATION
(ON-WING PHASE - TAKEOFF CONDITION)

	Parameter Description	Parameter	θ'	SYS % RDG	STDEV %RDG
1	Ambient Pressure	P0	2.905	0.067	0.029
2	Fan Inlet Total Pressure	PT2	-3.971	***0.250	0.008
3	Fan Inlet Total Temperature	TT2	0.157	0.153	0.038
4	Fan Discharge Pressure	PT13	1.974	0.052	0.017
5	Turbine Discharge Pressure	PT5	0.276	0.155	0.058
6	Compressor Discharge Pressure	PT3	0.181	0.159	0.124
7	Compressor Discharge Temp.	TT3	-0.038	0.163	0.160
8	Fan Nozzle Area	A18	0.731	0.260	0.000
9	Velocity Coefficient (Fan Noz)	CV18	1.094	0.224	0.000
10	Flow Coefficient (Fan Noz)	CD18	0.731	0.316	0.000
11	Velocity Coefficient (Core Noz)	CV9	0.275	0.224	0.000
12	Fan Discharge Temperature	TT13	-0.161	0.285	0.149
13	HPT Flow Function	HPTFF	0.181	1.000	0.000
14	Fuel Flow	WF	0.090	0.300	0.220
15	Flow Coeff (Suppression)	CD18SUP	0.731	0.150	0.000
16	FPC Extrapolation	FPCEX	1.974	0.100	0.000

*** Prior to improvement

TABLE 5 - ON-WING MEASUREMENT UNCERTAINTY SUMMARY FOR
IN-FLIGHT THRUST DETERMINATION

Name	Code	PERCENTAGE		
		Systematic	Std Dev	Uncertainty
Net Thrust	FN	1.130%	0.105%	1.149%

TABLE 6 - UNCERTAINTY ANALYSIS FOR IN-FLIGHT THRUST DETERMINATION
(ON-WING PHASE - TAKEOFF CONDITION - IMPROVED PT2)

	Parameter Description	Parameter	θ'	SYS % RDG	STDEV %RDG
1	Ambient Pressure	P0	2.905	0.067	0.029
2	Fan Inlet Total Pressure	PT2	-3.971	***0.058	0.017
3	Fan Inlet Total Temperature	TT2	0.157	0.153	0.038
4	Fan Discharge Pressure	PT13	1.974	0.052	0.017
5	Turbine Discharge Pressure	PT5	0.276	0.155	0.058
6	Compressor Discharge Pressure	PT3	0.181	0.159	0.124
7	Compressor Discharge Temp.	TT3	-0.038	0.163	0.160
8	Fan Nozzle Area	A18	0.731	0.260	0.000
9	Velocity Coefficient (Fan Noz)	CV18	1.094	0.224	0.000
10	Flow Coefficient (Fan Noz)	CD18	0.731	0.316	0.000
11	Velocity Coefficient (Core Noz)	CV9	0.275	0.224	0.000
12	Fan Discharge Temperature	TT13	-0.161	0.285	0.149
13	HPT Flow Function	HPTFF	0.181	1.000	0.000
14	Fuel Flow	WF	0.090	0.300	0.220
15	Flow Coeff (Suppression)	CD18SUP	0.731	0.150	0.000
16	FPC Extrapolation	FPCEX	1.974	0.100	0.000

*** Using improved pressure measurement system

TABLE 7 - IMPROVED ON-WING MEASUREMENT UNCERTAINTY
SUMMARY FOR IN-FLIGHT THRUST DETERMINATION

Name	Code	PERCENTAGE		
		Systematic	Std Dev	Uncertainty
Net Thrust	FN	0.587%	0.121%	0.635%

The Pareto chart for the uncertainty determination using the improved measurement system is given in Figure 10.

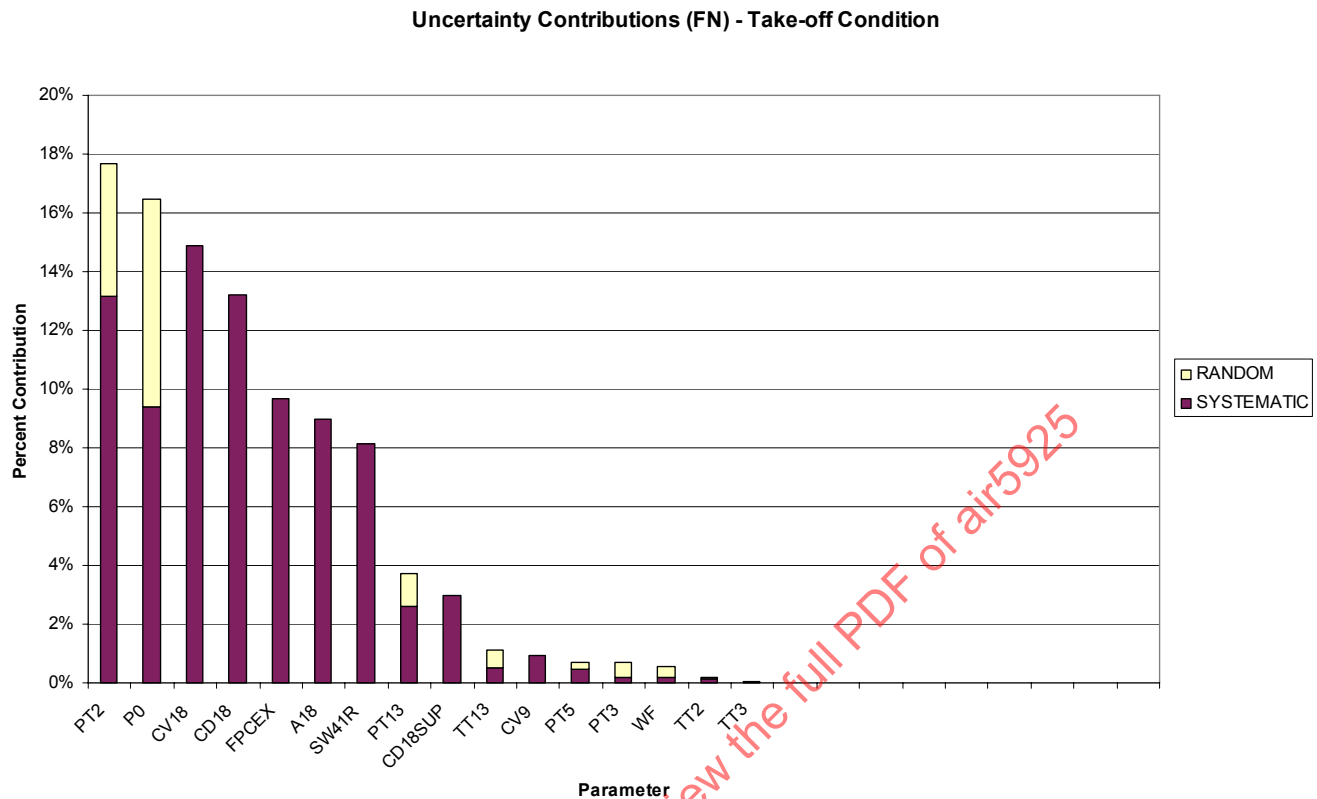


FIGURE 10 - PARETO ANALYSIS OF IN-FLIGHT THRUST PARAMETER UNCERTAINTIES (TAKE-OFF CONDITION)

4.4.2 Example: Results Parameter Uncertainty Analysis at Cruise Condition

The above analysis was repeated at cruise conditions, instead of takeoff power. Note below how the changes in the relative influence coefficients and the uncertainty estimates cause a change in both the overall uncertainty estimate as well as the distribution of error contributors.

TABLE 8 - UNCERTAINTY ANALYSIS FOR IN-FLIGHT THRUST DETERMINATION
(ON-WING PHASE - CRUISE CONDITION)

	Parameter Description	Parameter	θ'	SYS % RDG	STDEV %RDG
1	Ambient Pressure	P0	0.425	0.067	0.029
2	Fan Inlet Total Pressure	PT2	-2.024	0.058	0.017
3	Fan Inlet Total Temperature	TT2	-0.248	0.153	0.038
4	Fan Discharge Pressure	PT13	1.901	0.052	0.017
5	Turbine Discharge Pressure	PT5	0.325	0.155	0.058
6	Compressor Discharge Pressure	PT3	0.142	0.159	0.124
7	Compressor Discharge Temp.	TT3	-0.031	0.163	0.160
8	Fan Nozzle Area	A18	0.630	0.260	0.000
9	Velocity Coefficient (Fan Noz)	CV18	2.521	0.224	0.000
10	Flow Coefficient (Fan Noz)	CD18	0.630	0.316	0.000
11	Velocity Coefficient (Core Noz)	CV9	0.550	0.224	0.000
12	Fan Discharge Temperature	TT13	0.156	0.285	0.149
13	HPT Flow Function	HPTFF	0.142	1.000	0.000
14	Fuel Flow	WF	0.231	0.300	0.220
15	Flow Coeff (Suppression)	CD18SUP	0.630	0.150	0.000
16	FPC Extrapolation	FPCEX	1.901	0.250	0.000

TABLE 9 - ON-WING MEASUREMENT UNCERTAINTY SUMMARY FOR
IN-FLIGHT THRUST DETERMINATION (CRUISE CONDITION)

Name	Code	PERCENTAGE		
		Systematic	Std Dev	Uncertainty
Net Thrust	FN	0.831%	0.079%	0.846%

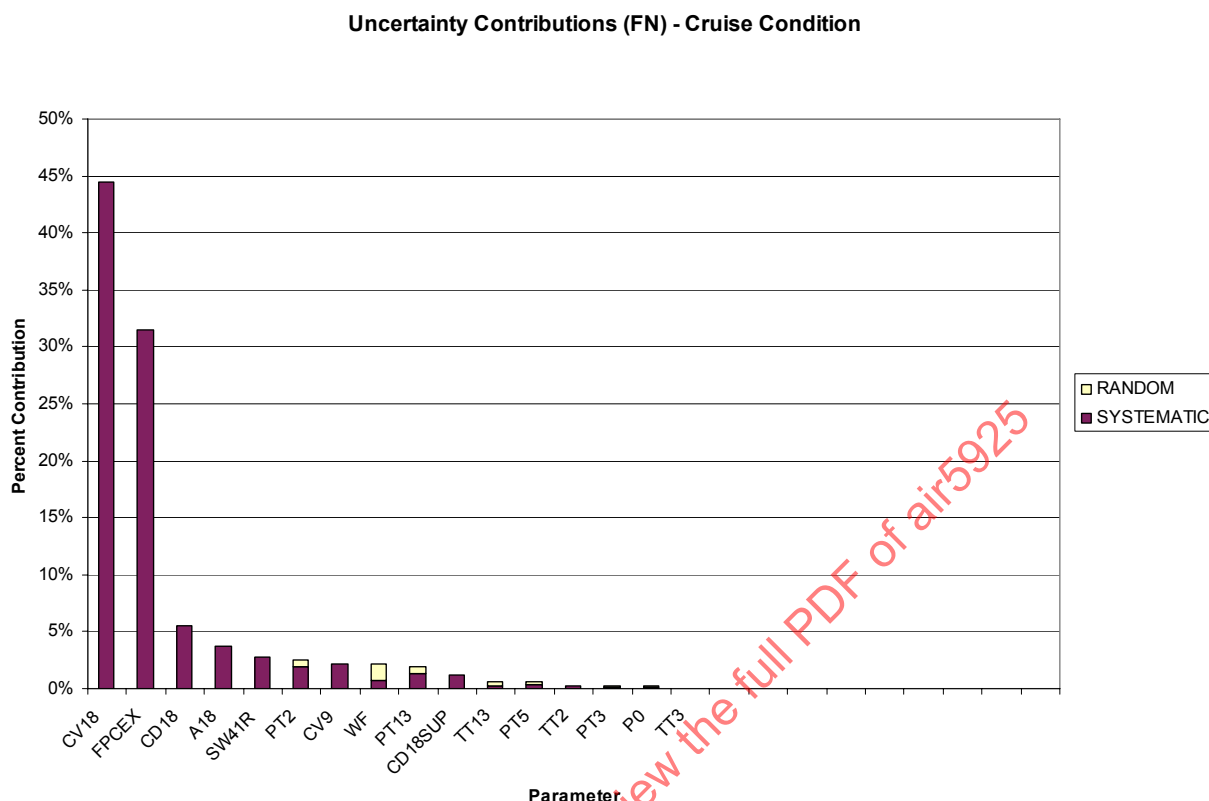


FIGURE 11 - PARETO ANALYSIS OF IN-FLIGHT THRUST PARAMETER UNCERTAINTIES (CRUISE CONDITION)

4.5 Summary

Benefits of Uncertainty Analysis: In the Defined Measurement Process of a test program the measurement chain is defined, the elemental uncertainties are determined for each parameter, and an estimate is made of the expected random, systematic, and total uncertainties in the test result. This information feeds into the development of the Final Test Plan (Section 5). If the level of expected uncertainty in the result meets the test requirements, then the test plan can be completed in preparation for preliminary testing. If the level of expected uncertainty in the result is too large for the result to meet the test objectives, then the objectives will have to be reconsidered. Either the limits on the objectives will have to be redefined or an improved instrumentation system will have to be designed. Identifying problems with meeting the test objectives at the DMP stage can help prevent the costly discovery of these problems later in the test program.

5. FINAL TEST PLAN (FIGURE 12)

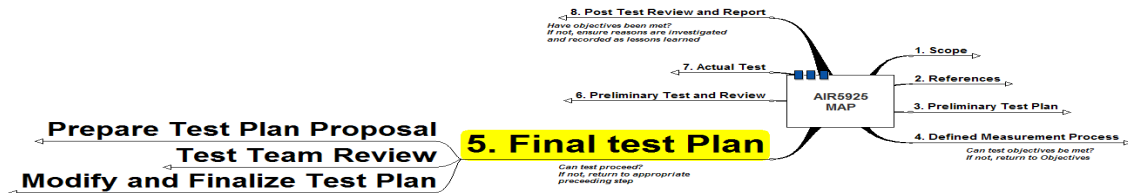


FIGURE 12 - FINAL TEST PLAN

5.1 Introduction

This stage completes the preparation phase of the program and reviews all aspects of the testing, with reference to the defined measurement process. It lays the foundations for a rational decision to proceed to the testing phase of the program. The outcomes are

- A Final Test Plan that is understood and supported by all parties.
- A decision on whether to proceed on the basis of that plan, to return to an earlier stage of the planning process, or to abandon the test.
- The cost-effectiveness has been optimized.

5.2 Prepare Final Test Plan Proposal

A Final Test Plan must be developed from the Preliminary Test Plan, using the information from the defined measurement process to specify instrumentation numbers, calibration requirements, etc. and also the critical measurements for health and safety, performance and accuracy. It must develop and describe the design of the test to optimize the range and number of test points for the preliminary test phase and the main test program, as well as the sample size and statistical tests to be used. Contingency plans must be drawn up for all major risks.

Parameters to be monitored and the checks used to monitor them during testing must be identified.

The Final Test Plan must review the resources, limitations, risks and assumptions associated with the program. The cost and timescales must also be re-established. When this has been done and compliance with the customer requirements is assured, the Final Test Plan may be presented to the Test Team to propose moving on to the preliminary test phase of the program.

If compliance with the requirements cannot be achieved, the proposal to the Test Team must be to return to the very first steps of the planning process so that new measurement processes and Test Plans may be defined.

5.3 Test Team and Customer Review

The decision to proceed to testing should be taken at a Test Team review meeting, including the customer if applicable. The Final Test Plan should be presented including a review of the uncertainty analysis, the state of readiness of test vehicle, instrumentation and all other test management systems.

It is possible that shortfalls in meeting the original requirements may be accepted by the customer. Depending upon the real implications to the results of the test caused by the shortfalls, contractual implications of such compromises must be assessed.

The Pre-test Uncertainty Analysis must be reviewed and accepted as good by the customer. It is critical that all team members understand and agree upon any modifications to be made to the Test Plan and DMP, why these modifications are to be made, and how all test team members' work may be affected by such modifications.

The customer should have a clear understanding as to what the test team's approach will be in meeting all stated performance requirements. The customer should also feel assured that the Test Plan and DMP will allow all performance requirements to be achieved within the cost and schedule constraints established at the initiation of the test program.

5.4 Modify and Finalize Test Plan

The proposed Test Plan and DMP, having been presented to the customer for approval, may now be modified as agreed in the Test Team Review and finalized.

Representatives from the team which installed the test vehicle and instrumentation should confirm that those tasks are complete and to the Plan. Quality and safety documentation, checklists, etc. should be audited at this point. Likewise, the configuration of data acquisition and on-line analysis systems should be confirmed as complete.

Other work required at this time includes finalization of the data analysis algorithms and preparation of Quality Assurance plans, including instrumentation connection and calibration lists, documentation controls and fault management. The parameters to be used for test data quality checks must be established and agreed.

With approval being granted by the customer, the test team must be prepared to adopt the test plan in full. Further Test Team reviews may be required to complete this. Notwithstanding that the Test Plan has been formally accepted at this stage, it may continue to be modified once testing begins: it is important that Test Plan change controls continue to be maintained also.

5.5 Benefits of Uncertainty Analysis to Final Test Plan

Conscientious use of the pre-test uncertainty analysis will keep the test team focused on the relative importance of each measurement to the achievement of the customer requirements and give guidance to setting priorities for remedial activity.

The uncertainty analysis may have profoundly affected the design of the test, e.g., details of each test run, order of testing and even selection and design of test apparatus. Clearly the uncertainty analysis is not just a luxury or useful aid to meeting the customer requirements; it is an essential part of defining those requirements and is crucially important in controlling the outcome of the test.

5.6 Example: Final Test Plan

The DMP described in Section 4 clearly indicated that the uncertainty of the thrust measurements taken from the test program would fulfill the customer's requirements, provided certain details of the instrumentation are changed as recommended. Specifically, it showed how the measurement of PT2 and ambient pressures must be made using instruments of adequate accuracy, if the overall aim of the test is to be achieved. The final test plan for the example test program will therefore incorporate the outcome of the DMP and state the instrumentation requirements clearly.

Those measurements that have the greatest influence on the uncertainty of the thrust measurement have been identified in the DMP; the test plan must make clear the steps to be taken to monitor these during the tests and also lay out contingency plans for dealing with any difficulties that do arise. Such actions should be discussed at the Test Team Review to ensure that test team members are aware of their specific responsibilities.

Ultimately the Final Test Plan, as ratified by the Test Team Review, will be distributed to all relevant parties according to the requirements of the document control system.

6. PRELIMINARY TEST AND REVIEW (FIGURE 13)

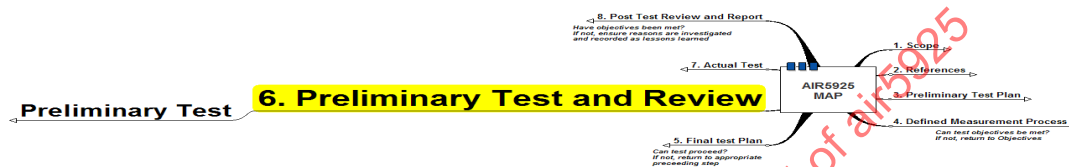


FIGURE 13 - PRELIMINARY TEST AND REVIEW

6.1 Introduction

Once the final preparations and review has been completed the preliminary part of the test program can be started. This is known as the test shakedown run. The shakedown run is used to test out the complete measurement and processing system including facility, instrumentation, performance calculations and the test article itself. A shakedown run is considered particularly important if any part of the total system has not been used before, or if the different parts of the system are being combined for the first time. Since the life of the test article may be a risk factor the length of the shakedown run should be minimized. However, it must be long enough to allow the total system to be checked and collect enough data for the performance of the test article to be analyzed. It is a very important part of the test.

6.2 Check Out Test Plant and Instrumentation Performance

6.2.1 Test Article

One of the most important aspects of the shakedown run is the checking of the validity of the data being obtained, or, in other words examining the performance of the measurement system. This should be done by applying the on-line data checks, specified in Section 5. It is generally during the shakedown run when most instrumentation faults will be found. Instrumentation faults can be many and varied, but can include damage during transportation, instrument lines not connected and incorrect calibrations being applied to instruments. It is at this stage that the comprehensive Instrument Schedule created during Section 5 of the project can be used to minimize the problems associated with instrument identities, misconnections and calibrations. For example, the Instrument Schedule can be used to check that the correct pressure channels have been connected to the pressure rakes. Any changes to the Instrument Schedule due to these problems must be properly documented using the QA system set up earlier. It is also at this stage that the instrument fault control system (which should be as fully automated as possible) is used for the first time. The instrument fault control system will have been designed during Section 5 and constructed as to cross-reference to the Instrument Schedule for ease of use and commonality. Note that each fault should be individually identified and include information on the originator of the fault sheet, the instrument that has failed, an indication of the nature of the fault, the priority that should be given to this instrument and a reply detailing the repair or stating the fact that the instrument is not repairable.

Once identified by the shakedown run, as many as possible of the instrumentation faults should be corrected before the test program continues. Priority must be given to those faults that directly impact the quality of the defined test result. The amount of time and effort required to resolve such instrumentation faults may be reduced by building some redundancy into the measurement system. This would allow some substitution of instrumentation, instead of having to attempt to repair every instrument which could lead to an unacceptable delay in the test program.

It is usual to look for instrumentation faults during the shakedown run, and it is normal to use "engineering judgment" as well as computer programs to spot problems. It is important to take into account the number and impact of faulty instruments discovered during the shakedown run. The agreed DMP should define the instruments that cannot be lost before testing continues.

6.2.2 Facility

It is important to check that the shakedown run does not adversely affect the test facility in some unforeseen manner, even though the test program has been designed to avoid foreseeable problems with the test facility integrity. For an altitude, or other specialized environmental facility, it is also necessary to check that the test facility actually achieved the test conditions required by the test program, otherwise the results from the shakedown run may be considered invalid. A pre-agreed "next best" position may be adopted.

It is also important to check analysis software operation. Although the software should have been tested as part of the software QA system before the beginning of the shakedown run (by breaking the software down into modular form, confirmation can be made much simpler and quicker), the whole analysis package should be subjected to trial input data representative of real test data. Where schedule constraints prevent a complete check out of programs beforehand, full authentication must be carried out during the running of the preliminary test phase. This is often the only way to authenticate the performance of "legacy" software or programs imported from other systems.

At this time, the results of the shakedown run should they be considered valid and can be used to verify the pre-test measurement uncertainty levels.

6.3 Review

6.3.1 Assess Results

Only after all software has been authenticated and all instrumentation has been checked for faults and assuming that none of the faulty instruments are critical to the performance calculations does it become possible to verify the performance of the test article. It should be noted that this is another advantage for having some redundancy built into the measurement system. Checking performance validity of the test article can be carried out in a number of ways, although all of these techniques must use some sort of comparative methodology. If the test article had been tested successfully elsewhere then comparison could be made against that test. Alternatively, the comparison may be against a computer model prediction. In any case, the comparison should be kept as simple as possible, whilst ensuring that the results are as expected by the customer with uncertainty bands set out in the test plan.

Analysis should be made of the scatter of the data with the most likely source being "test article instability." If the scatter of the data is relatively small then it can be considered as a component of the random uncertainty, however, if it is large, then other considerations should be examined. If the instability is caused by the test article, then its control system should be examined in concert with the test article owner. From the investigation, it may be necessary to modify/change the control system, replace the test article with another unit or even to abandon the test series if the level of the random uncertainty is unacceptable. If the instability is caused by the facility, then its control systems will need investigation and the appropriate action taken. Note should be made here that any changes will almost certainly cause a delay in the project.

Lastly, it is important to hold a post shakedown run meeting for all relevant parties to discuss the results of the shakedown run. This meeting should be used to discuss in general terms the instrumentation, the software and the performance of the test article. This meeting allows all interested groups to raise individual concerns and to prioritize the required workload before the main body of the test program can be started. However, this meeting should not be used to discuss whether or not the test program should be continued, as a separate meeting would be required for such a discussion.

6.3.2 Compare Actual Uncertainty with Predictions

The review of the preliminary testing should be carried out with the customer. If the measurement uncertainty levels produced at this stage are greater than those predicted at the pre-test stage, or if the test article does not produce the results expected and all outside influences have been taken into account, then a decision to modify or abandon the test program has to be made here.

Examples of how the data comparison is used are shown in Figures 14 through 16.

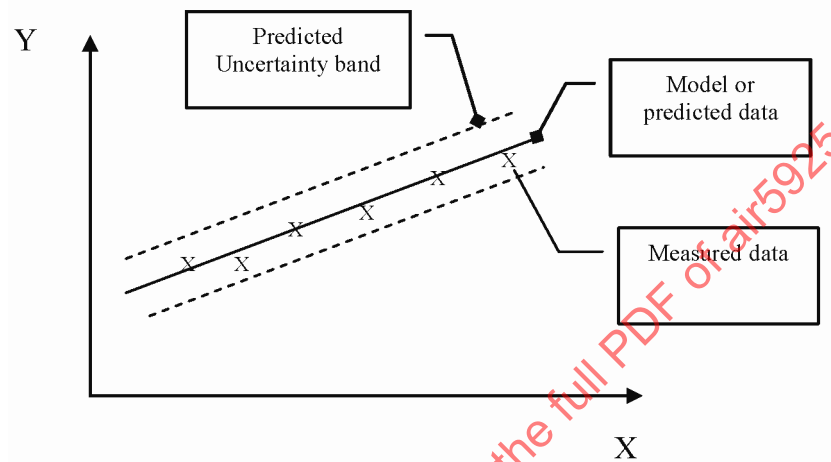


FIGURE 14 - MEASUREMENTS FALL WITHIN UNCERTAINTY PREDICTION

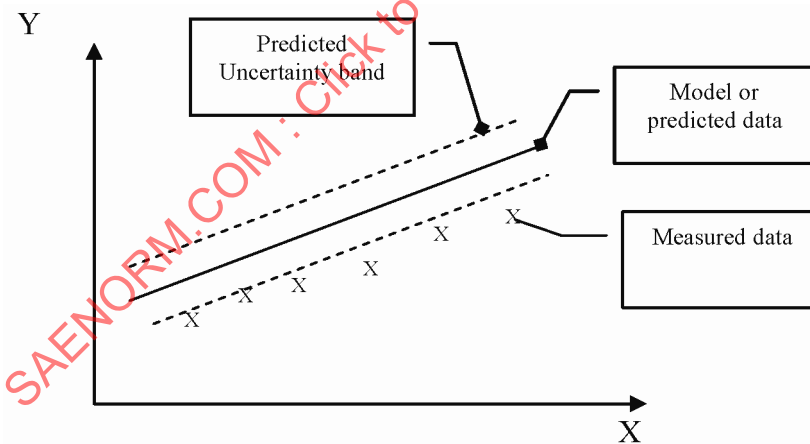


FIGURE 15 - MEASUREMENTS EXHIBIT SYSTEMATIC ERRORS FROM PREDICTION

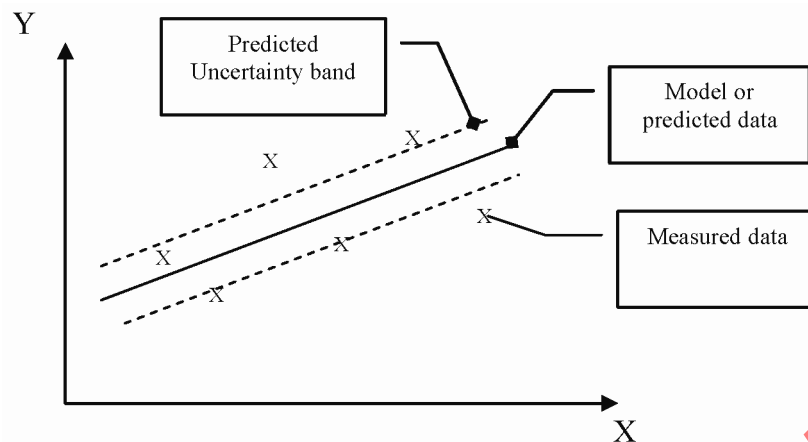


FIGURE 16 - MEASUREMENTS EXHIBIT RANDOM ERRORS FROM PREDICTION

Once the preliminary testing has been completed, reviewed and approved and any resulting modification or repair work has been carried out, then the process can enter the main part of the test program.

6.4 Application to Example

As noted in 6.2 the quality of the data needs to be checked before it can be used to verify the performance of the test article. A good example would be the analysis of instrumentation rakes fitted into various planes of an engine. There are two aspects to this. Firstly, are any of the instruments out of position in comparison with the rest, and secondly, is the general instrument profile as expected both in shape and in level. Both of these aspects could have serious consequences if not corrected (or at least taken account of).

The compressor discharge pressure (PT3) is measured by a five-arm rake with each arm fitted with six individual probes, giving a total of thirty instrument channels. Given below in tabular form (Table 10) are the results from one data point for these pressure readings.

TABLE 10 - EXAMPLE OF PRESSURE RAKE MEASUREMENTS (PSIA)

Radial Position	Circumferential Position				
	0°	72°	144°	216°	288°
1	360.3	372.4	372.8	371.6	370.7
2	371.5	371.1	372.1	371.9	371.5
3	371.1	373.0	371.8	371.6	371.3
4	370.4	369.1	369.9	368.5	369.6
5	367.7	364.0	366.4	363.3	365.6
6	364.0	362.7	363.6	362.4	363.9

This converts in graphical form into Figure 17.

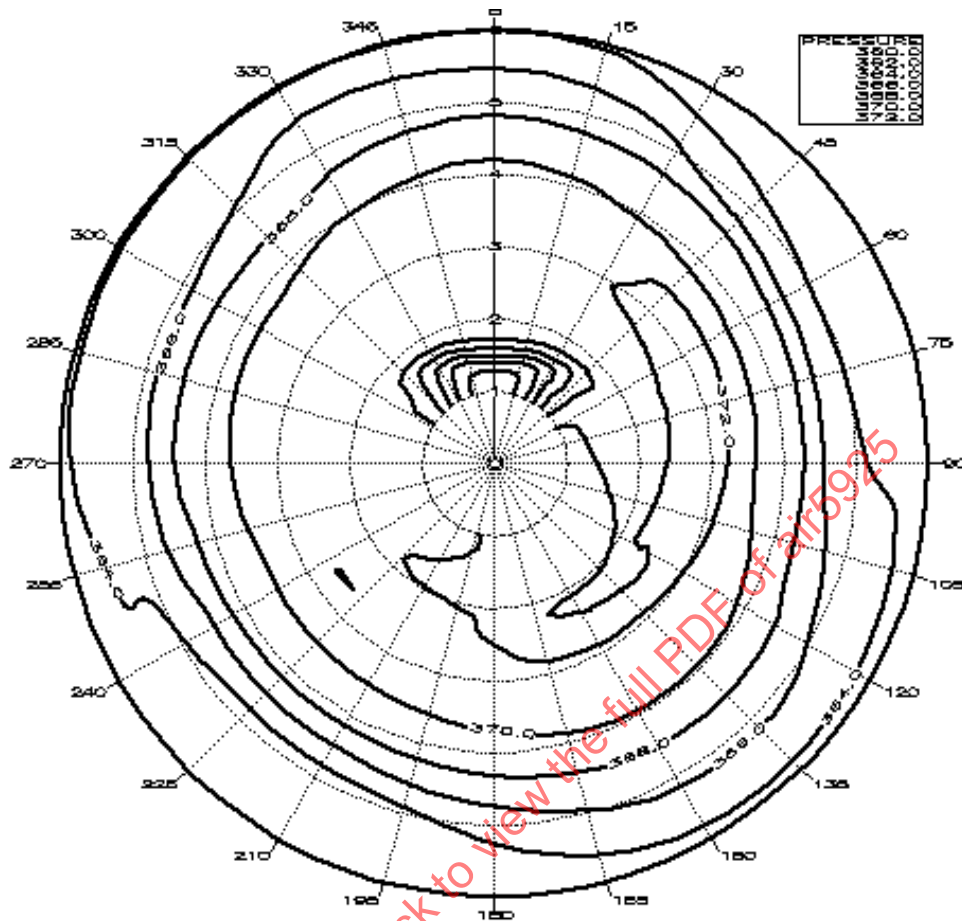


FIGURE 17 - PLOT OF COMPRESSOR DISCHARGE PRESSURE PROFILE

Examination of the figure indicates a distinct pattern across the profile, with the pressure level at Radial Position 6 being low and the pressure level at Radial Position 1 being high. Discussion with the engine owner suggests that this is the expected profile as Radial Position 6 is close to the wall and Radial Position 1 is near the centre-line of the flow. However, it is also clear from the figure that one of the pressure probes looks out of place, that being Radial Position 1 on Rake Arm at 0°. It is agreed that this instrument channel is faulty, but because of the difficulty of actually physically reaching the probe, it is agreed that this instrument be deleted from the calculation of the compressor discharge pressure (PT3). Therefore the average compressor discharge pressure will be based on the mean of the remaining 29 probes. Thus, this instrument set is passed for further use during the main part of the testing.

Note that examination of the DMP confirmed that the loss of a single instrument in this rake was not a problem. Maximum allowable instrument failure for PT3 was three in total or two on any one radial/circumferential position.

6.5 Benefits of Uncertainty

Uncertainty analysis at the preliminary testing phase can provide a great deal of useful information to the relevant personnel. Although obviously not providing information on the total testing regime, it should be possible to partially validate the uncertainty results from the pre-test phase. This should particularly be the case with the random uncertainty, as for the first time the program has gained "real" data. Therefore, the new uncertainty information from the preliminary tests can be used to give the go ahead for the continuation of the testing or to require remedial action to solve problems which could invalidate the test program.