TEST FACILITY UNCERTAINTY ANALYSES FOR RBCC SYSTEMS TESTING

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Abstract

The Rocket Based Combined Cycle (RBCC) engine is expected to evolve based upon past combined-cycle propulsion test experience/data and new extensive test data. Currently, it is envisioned that a portion of the component and system testing will be pursued at NASA Stennis Space Center (SSC). To realize the greatest benefit of the test data, uncertainty analyses are being performed on the relevant RBCC components and systems to be tested at NASA SSC to ascertain the needed measurement requirements. These studies pertain to the existing E-Complex test stands as well as a new facility, E-4. This paper describes the approach used in the studies and gives examples to demonstrate the approach and the usefulness of the results. Future work on this project is also described. This work will greatly increase the reliability of the test data while minimizing costs by focusing expenditures in the proper areas that are critical to program success and not allowing resources to be wasted in areas that are not significant relative to overall program goals.

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Nomenclature

B: Systematic uncertainty estimate
C_d: Discharge coefficient
d: Venturi diameter
F: Thermal contraction factor
N: Number of readings
P: Random uncertainty estimate
P: Pressure
r: Result
S: Sample standard deviation
T: Temperature
U: Uncertainty estimate
$\dot{W}$: Mass flow rate
X: Variable
Δ: Change or difference
θ: Sensitivity coefficient
ρ: Density

Subscripts

1: Venturi inlet
2: Venturi throat

Introduction

Combined-cycle propulsion technology is a strong candidate for meeting NASA space transportation goals. Extensive ground testing of integrated air-breathing/rocket systems (e.g., components, subsystems and engine systems) across all propulsion operational modes (e.g., ramjet, scramjet) will be needed to demonstrate this propulsion technology. Ground testing will occur at various test centers based on each center's expertise. Testing at the NASA John C. Stennis Space Center (SSC) will be primarily concentrated on combined-cycle power pack and engine systems at sea level static conditions at a dedicated test facility, E-4. In addition, component testing may occur at the other SSC E-Complex Test Stands (E-1, E-2, and E-3).

To realize the greatest benefit of Rocket Based Combined Cycle (RBCC) engine testing, detailed uncertainty analyses are required. In general, this will encompass defining the measurement uncertainties associated with the current systems resident in the existing SSC E-Complex test stands; defining the measurement uncertainty requirements for RBCC component, powerpack, and full-scale engine testing; and defining measurement systems than can meet the RBCC testing requirements for all of the E-Complex test stands.

This paper describes the methods used for the uncertainty analyses of test stands E-1, E-2, and E-3, and gives examples to illustrate the procedures and their usefulness. More specifically, to obtain the needed uncertainty information, the uncertainties for the test stand measurements are quantified. The complete analysis considers the following measurements:

(1) Temperature
(2) Pressure (Steady-state and Dynamic)
(3) Mass Flow Rate (Gas and Liquid)
(4) Thrust (Load Cell)
(5) Strain
(6) Speed
(7) Accelerometer
(8) Proximity
(9) Level
(10) Valve feedback
(11) Radiometer

This paper will discuss only temperature, steady-state pressure, and mass flow rate to illustrate the methods.

The paper also outlines the direction for future work. For future work, these measurement uncertainties will be used to estimate the uncertainties of test results obtained in the operation of the test facilities. This process can help to identify the critical measurements from an uncertainty standpoint and can be a significant guide in the cost effective use of resources to reduce the test uncertainty. The analyses will also be used to help design the new E-4 test facility for static-sea level testing of the engine system.

E-Complex Test Stands

The E-Complex currently consists of three distinct test stands, E-1, E-2 and E-3, with detailed stand capabilities delineated in Ref. 1. Notably, there are a total of *seven* test positions (or cells) offered within these three stands. The E-1 test stand is comprised of three individual test cells and is shown in Fig. 1. This versatile test stand can accommodate multiple programs and allows for testing of various combustion devices, turbopump assemblies, and other rocket engine components. More specifically, E-1 Cell 1 can handle liquid propellant-based and hybrid-based test articles up to $750\cdot 10^3$ lb_f thrust (horizontal position). E-1 Cells 2 and 3 are designed for various LO_2 and LH_2 turbopump assembly testing. The component testing is enabled here by the ability to supply extremely high-pressure propellants and gases as required.

The E-2 test stand is comprised of Cells 1 and 2 and the stand was originally designed to support materials development for the National Aerospace Plane (NASP) program. The facility, which can handle thrust loads up to $100\cdot 10^3$ lb_f, is being upgraded to support component and engine development.

The E-3 test stand consists of two individual test cells that are primarily designed for component and pilot-scale combustion device testing. E-3 Cell 1 accommodates test articles up to $60\cdot 10^3$ lb_f thrust (horizontal position) and is primarily designed to test pressure-fed LO_2/hydrocarbon, GO_2/hydrocarbon, GO_2/GH_2, and hybrid combustion devices. E-3 Cell 2 is primarily designed to test H_2O_2/hydrocarbon combustion devices up to $10\cdot 10^3$ lb_f thrust. Ongoing upgrades to this facility will allow for the testing of $25\cdot 10^3$ lb_f-thrust test articles.

Coupled with continuous upgrades of the existing E-Complex test stands, a new facility, termed E-4, is being developed at SSC to accommodate Rocket Based Combined Cycle (RBCC) engine development.

Succinctly, the E-4 facility is expected to be a single-cell test stand to be developed in two phases and to be dedicated to the testing of large-scale RBCC test articles at high turnaround rates. Completion of Phase 1 will enable sea-level static testing capability of RBCC test articles up to $50\cdot 10^3$ lb_f thrust, which is consistent with sub-orbital demonstrator vehicle thrust requirements. Propellant capabilities of E-4 will include hydrocarbon, H_2O_2 initially, with LO_2 and LH_2 capability added at a later date. Assuming successful test results and continued engine endorsement, the E-4 test stand will be upgraded during Phase 2 to allow for static sea-level RBCC engine testing up to $500\cdot 10^3$ lb_f thrust, consistent with payload-carrying orbital launchers. In addition, an air blowdown capability may be added to the test stand to allow for testing of the RBCC engine at low Mach numbers ($M < 0.75$) at reduced thrust levels ($20\cdot 10^3 - 50\cdot 10^3$ lb_f).

Measurement Types

The E-Complex Test Facilities use a variety of measurements for data acquisition and control of rocket engine and component testing. The instrumentation types vary depending on the location in the test facility (purpose) and the information required to control or to characterize the facility, engine, or component test article. The objective is to acquire clean, accurate test data within a measure of uncertainty enabling verification of the performance of a test article while maintaining safe operation of the test facility.

Each test stand is divided into three major areas (Fig. 2). The facility houses the tanks, piping, valves, structure, and electrical hardware needed to receive, transfer, and store gases, storable liquids, and cryogenics used during test. The facility measurements are used by the control system but are also recorded on the low-speed data acquisition (DAS) system for performance verification.

The Special Test Equipment (STE) comprises the equipment essential for bridging the differences between the facility and the test article. The fluids (including cryogenic) in the facility must be delivered to the test article at the pressures, flows, and temperatures that meet the test article's inlet design conditions. As with the facility area, STE measurements are brought back to the control system and also are recorded on the low-speed DAS. Sometimes high flow rates and pressures create conditions that can result in undesirable test conditions. Dynamic measurements of acceleration and strain are used in the STE area to identify these conditions for corrective action.

The Test Article is a customer-supplied system that may or may not require control but always requires data acquisition of the instrumentation installed to measure the numerous parameters needed to characterize the system. The various sensor signals are distributed to the low-speed and high-speed data acquisition systems.

Figure 2 is a general list of the many types of measurements required in the E-Complex. Temperatures, pressures, and mass flow rate measurements are taken at all of the E-Complex test facilities. Together, they comprise some of the most important measurements needed to control and characterize a test article. They are addressed in further detail below.

Temperature

Temperatures are quite often measured with thermocouples—typically Type E for cryogenics and Type K for ambient and higher. Resistance temperature detectors (RTDs) are also occasionally used. Thermocouples respond faster than RTDs but lack the accuracy. RTDs are much more useful when determining a steady-state temperature since the thermal time constant can reach 500 milliseconds or even greater depending on the manufacturer and model.

Additionally, aerospace testing requires temperature instrumentation to be robust to survive the extreme environments of rocket engine testing. In many cases, temperature instrumentation must withstand pressures measured in thousands of PSI and cryogenic flow rates of hundreds of lb_m/sec. Often engineers are saddled with a dilemma—the greater the structural integrity of a temperature sensor, the slower it is to respond to changing temperature due to its physical design.

Pressure

Measuring pressure, including differential pressure, can be accomplished using transducers with signal conditioning for bridge excitation, gain, and signal filtering. These devices typically have a 0-30 mV output.

Pressure is also measured by another device called a transmitter. It combines a pressure transducer with a 4-20 mA output signal but does not require the same level of signal conditioning as the transducer.

End-to-end data system check capabilities of transducers using resistance calibration (R_{Cal}) play a large part in guaranteeing data quality and determining the instrument's health prior to test. Transmitters do not have the same ability to provide the end-to-end R_{Cal} checks but fit rather nicely into the existing test facilities control schemes that use programmable logic controllers (PLCs). Efforts are underway in the E-Complex to test transmitter prototypes providing a similar calibration capability to transducers.

Response times of pressure transducers and transmitters are similar provided the transmitters are not "smart" transmitters incorporating an internal processor for linearization and conversion. "Dumb" transmitters have passive electronics that lack the time delay created by the processor thus giving them a much faster response time. The transducers and fast transmitters are always used for performance-based measurements.

Mass Flow Rate

Historically, flow rates have been a challenge to measure accurately, especially in the case of cryogenics. Numerous methods exist to accommodate the diverse flow conditions and mediums found in rocket engine testing. Issues such as materials compatibility, high-pressure with high flow rates, two-phase flow, low flow rates, etc., play a very large part in how a specific flow parameter is acquired. Venturis, cavitating venturis, and orifices are the most common types of mass flow devices in use in the E-Complex. V-Cone devices have just begun to be investigated and used in the E-complex test area at SSC. Turbine flowmeters have also been used in the E-Complex and may be used in the future. Coriolis flowmeters are another possibility for future use.

Other Sensors

Naturally, rocket engine and component testing require a range of the other devices to capture the physical phenomena such as dynamic pressure, thrust, strain, speed, accelerometer, proximity, level, valve feedback, and radiometer. This instrumentation will be reserved for a future presentation on the uncertainty analysis study being performed at Stennis Space Center.

Uncertainty Analysis Overview

Only a brief overview of the methodology to obtain uncertainty estimates and how they propagate through a given data reduction equation is given here. The reader is referred to Coleman and Steele for a detailed discussion of uncertainty analysis techniques.[2]

The word accuracy is generally used to indicate the relative closeness of agreement between an experimentally determined value of a quantity and its true value. Error is the difference between the experimentally determined value and the truth; therefore, as error decreases, accuracy is said to increase. Only in rare instances is the true value of a quantity known. Thus, it is necessary to estimate error, and that estimate is called an uncertainty, U. Uncertainty estimates are made at some confidence level—a 95% confidence estimate, for example, means that the true value of the quantity is expected to be within the $\pm U$ interval about the experimentally determined value 95 times out of 100.

Total error can be considered to be composed of two components: a random (precision) component, ε, and a systematic (bias) component, β. An error is classified as random if it contributes to the scatter of the data; otherwise, it is a systematic error. As an estimator of β, a systematic uncertainty or bias limit, B, is defined. A 95% confidence estimate is interpreted as the experimenter being 95% confident that the true value of the systematic error, if known, would fall within $\pm B$. A useful approach to estimating the magnitude of a systematic error is to assume that the systematic error for a given case is a single realization drawn from some statistical parent distribution of possible systematic errors. Or, in other words, the systematic error could be treated as a random variable, but with only a single realization, its variance cannot be measured and must be estimated. As an estimator of the magnitude of the random errors, a random uncertainty or precision limit, P, for a single reading is defined. A 95% confidence estimate of P is interpreted to mean that the $\pm P$ interval about the single reading of X_i should cover the (biased) parent population mean, μ, 95 times out of 100.

In nearly all experiments, the measured values of different variables are combined using a data reduction equation (DRE) to form some desired result. A general representation of a data reduction equation is

$$r = r(X_1, X_2, \ldots, X_J) \qquad \textbf{(1)}$$

where r is the experimental result determined from J measured variables X_i. Each of the measured variables contains systematic errors and random errors. These errors in the measured values then propagate through the DRE, thereby generating the systematic and random errors in the experimental result, r. Uncertainty analysis is used to estimate the random and systematic uncertainties of the result, P_r and B_r respectively, and the corresponding total uncertainty of the result, U_r.

If it is assumed that the degrees of freedom for the result is large (>10), which is very appropriate for most engineering applications, then the "large sample assumption" applies[2] and the 95% confidence expression for U_r is

$$U_r^2 = B_r^2 + P_r^2 \qquad \textbf{(2)}$$

The systematic uncertainty (bias limit) of the result is defined as

$$B_r^2 = \sum_{i=1}^{J} \theta_i^2 B_i^2 + 2 \sum_{i=1}^{J-1} \sum_{k=i+1}^{J} \theta_i \theta_k B_{ik} \qquad \textbf{(3)}$$

where

$$\theta_i = \frac{\partial r}{\partial X_i} \qquad \textbf{(4)}$$

The systematic uncertainty estimate for each X_i variable is the root sum square combination of its elemental systematic uncertainties

$$B_i = \left[\sum_{j=1}^{M} \left(B_i\right)_j^2 \right]^{1/2} \qquad (5)$$

The second term in Eq (3) accounts for systematic errors that have the same source and are correlated. The factor B_{ik} is the 95% confidence estimate of the covariance appropriate for the systematic errors in X_i and X_k and is determined from[3]

$$B_{ik} = \sum_{\alpha=1}^{L} \left(B_i\right)_\alpha \left(B_k\right)_\alpha \qquad (6)$$

where variables X_i and X_k share L identical systematic error sources.

The random uncertainty (precision limit) of the result is defined as

$$P_r^2 = \sum_{i=1}^{J} \theta_i^2 P_i^2 + 2 \sum_{i=1}^{J-1} \sum_{k=i+1}^{J} \theta_i \theta_k P_{ik} \qquad (7)$$

where P_{ik} is the 95% confidence estimate of the covariance appropriate for the random errors in X_i and X_k. The 95% confidence large sample (N≥10) random uncertainty for a variable is estimated as

$$P_i = 2S_i \qquad (8)$$

where S_i is the sample standard deviation.

Typically, correlated random uncertainties have been neglected so that the P_{ik}'s in Eq (7) are taken as zero. These covariance terms account for correlation between the time varying errors in different measurements. If the time varying errors are assumed to be random, the correlation between them is zero. That assumption is generally true; however, there are some cases where the random (precision) errors are correlated and the covariance terms are important.[4]

Two types of terms are used to evaluate the contributions of the various terms to the uncertainty of the result: Uncertainty Magnification Factor (UMF) and Uncertainty Percentage Contribution (UPC). These terms can provide great insight for improving the test results.

The UMF values are defined as

$$UMF_i = \frac{X_i}{r} \frac{\partial r}{\partial X_i} \qquad (9)$$

The UMF for a given measured variable indicates the influence of the uncertainty in that variable on the uncertainty in the result. A UMF greater than 1 indicates that the uncertainty in that variable is magnified as it propagates through the DRE. A UMF of less than 1 indicates that the uncertainty in that variable is diminished as it propagates through the DRE. Since the UMF values are squared to calculate the uncertainty of the result, the sign is not important. The UMF values indicate the potential of specific terms to have a significant impact on the uncertainty of the result based solely on the DRE since uncertainty values are not a part of the UMF. UMF calculations can be extremely beneficial for evaluating different possible DRE's, measurement methods, etc., in the early planning stage of an experiment.

The Uncertainty Percentage Contribution (UPC) values are used to evaluate the sensitivity of the uncertainty of the result to the uncertainty of the various measured quantities. The UPC is defined as

$$UPC_i = \frac{\left(\theta_i U_i\right)^2}{U_r^2} * 100 \qquad (10)$$

with θ defined in Eq (4). The UPC illustrates the influence of each variable and its uncertainty as a percent of the result uncertainty squared for each term in the uncertainty equation. The sum of the UPC values total 100% of the uncertainty in the result. This approach shows the sensitivity of the squared uncertainty of the result to the squared uncertainty effect of each of the variables for a particular situation where values for the variables are known and the uncertainties for each variable have been estimated. UPC calculations are extremely useful from the later planning phase throughout the experiment.

This work concentrates on estimating the measurement uncertainties for each measurement type in the E-1, E-2, and E-3 test stands. For direct measurements, elemental error sources are being evaluated to obtain an overall systematic uncertainty estimate for each measurement type. The random uncertainties can be calculated for the measured variables for each specific test. These uncertainties are then combined according to equation (2) to obtain the overall uncertainty of measurements of interest for particular tests. For parameters calculated using a DRE, the uncertainties of the measured variables are propagated through the DRE using the techniques described to determine the uncertainty of the calculated parameter (result).

E-Complex Measurement Uncertainties

The calibration and test procedures greatly impact the uncertainty determination for the various measurements since the elemental error sources depend on these procedures. These procedures are being studied and used to establish a method to estimate the uncertainties for the range of values and measurement methods used in the E-complex for each type of measurement. These calculated uncertainty values will then be available to potential customers to use to evaluate their specific test requirements. The details of the calculations and results cannot be provided in this paper; however, examples of the elemental error sources considered for the temperature and pressure measurements will be given to supply the reader with the general idea of how the uncertainty values will be determined from the elemental error sources. Also, the measurement uncertainty estimates will be used for sample mass flow rate uncertainty calculations. These calculations will give sample UMF and UPC values to show their usefulness. It is important to note that the examples used in the following paragraphs do not follow the exact procedures used in any one instance at SSC but combine possible measurement scenarios simply to demonstrate the uncertainty procedure. The uncertainty numbers produced from these examples should not be taken as valid uncertainty estimates for SSC measurements.

Temperature

As stated previously, temperature measurements are made in the E-Complex using type E and type K thermocouples as well as RTD's. The type E thermocouples are typically used for room temperature and below (down to 36° R) whereas the type K thermocouples are used for room temperature and above (up to 3460° R). The thermocouples can be used with a Uniform Temperature Reference (UTR) or a temperature transmitter. RTD's can also be used with the temperature transmitters.

As an example, consider a type K thermocouple used along with a UTR in the test facility to obtain a temperature measurement (Fig. 3). Standard temperature versus millivolt curves are used to obtain temperature based on the facility voltage measurement. (The thermocouple is not calibrated in the calibration laboratory to provide these curves.) The test facility calibration involves a voltage input downstream of the UTR with a voltage tolerance for the data acquisition system (V_{Cal}). An RTD is used to measure the UTR temperature.

For the sample procedure described above, the uncertainty in the test temperature measurement must consider elemental error sources from the test procedure. Elemental error sources to consider include the manufacturer's specifications on the accuracy of the thermocouple, sources related to the UTR, and sources related to the facility voltage calibration. Sources related to the UTR include the uniformity of the block temperature and the uncertainty of the RTD used to measure the block temperature. Sources related to the voltage calibration include the voltage input device, the tolerance of the voltage calibration, and the possible system drift. These uncertainty sources are combined using the uncertainty analysis techniques described previously to give the overall uncertainty of the test temperature measurement.

In contrast, now consider the same type K temperature measurement made with a temperature transmitter rather than a UTR (Fig. 4). Again, standard temperature versus millivolt curves are used to obtain temperature based on the facility voltage measurement. When used in the test facility, a resistor is placed in the circuit to convert the current output of the transmitter to a voltage for the data acquisition system. The test facility calibration involves a voltage input downstream of the resistor with a voltage tolerance for the data acquisition system (V_{Cal}).

For the sample procedure described above, the uncertainty in the test temperature measurement must again consider elemental error sources from the test procedure. Elemental error sources to consider include the manufacturer's specifications on the accuracy of the thermocouple, sources related to the transmitter, the circuit resistor, and sources related to the facility voltage calibration. Sources related to the transmitter can be obtained from the manufacturer's specifications. Sources related to the voltage calibration are the same as those given in the above example. These uncertainty sources are combined using the uncertainty analysis techniques described previously to give the overall uncertainty of the test temperature measurement.

Pressure

Pressure measurements are made in the E-complex with a broad range of pressure transducers and pressure transmitters. Typically, the transmitters are used more for facility measurements, and the transducers are used more for performance-based measurements for the STE and test articles.

As an example, consider a 2500 psi pressure transducer. The transducer has an internal shunt resistor. The transducer is calibrated in the calibration laboratory over the 2500 psi range. A pressure standard is used to set and measure equal increments of pressure between 0 and 2500 psi. The mV output of the pressure transducer is recorded. A curve-fit of the pressure versus mV data is then produced. The calibration also provides the output resistance for 0% and 80% for the internal shunt resistor. The transducer is then used in the test stand for a performance test. An end-to-end calibration of the transducer is done prior to testing using the internal shunt resistor (R_{Cal}). This end-to-end calibration is used to match the output of the test data acquisition system to the data from the calibration laboratory.

For the sample procedure described above, the uncertainty in the test pressure measurement must consider elemental error sources from the calibration laboratory procedure and the test facility procedure. Sources of error for the calibration include the pressure standard, the voltage measurement, the resistance measurement, and the curve-fit of the data. These sources must be combined using the uncertainty analysis techniques described previously to give the overall uncertainty of the calibration. For the test facility calibration procedure, the uncertainties associated with the shunt resistance, the tolerances allowed in matching the calibration laboratory data, and the possible system drift with time must be considered. These uncertainty estimates are combined with the calibration laboratory uncertainty using the uncertainty analysis techniques described previously to give the overall uncertainty of the test pressure measurement.

In contrast, now consider the same 2500 psi pressure measurement made with a pressure transmitter. The transmitter is calibrated in the calibration laboratory over the 2500 psi range. A pressure standard is used to set and measure equal increments of pressure between 0 and 2500 psi. The mA output of the pressure transmitter is recorded. A curve-fit of the pressure versus mA data is then produced. When the transmitter is used in the test stand, a resistor is used to convert the mA output signal to voltage. The data acquisition system is then calibrated to a certain voltage tolerance to match the calibration laboratory data.

For the sample procedure described above, the uncertainty in the test pressure measurement must again consider elemental error sources from the calibration laboratory procedure and the test facility procedure. Sources of error for the calibration include the pressure standard, the current measurement and tolerance, and the curve-fit of the data. These sources must be combined using the uncertainty analysis techniques described previously to give the overall uncertainty of the calibration. For the test facility calibration procedure, the uncertainties associated with the input resistance, the tolerances allowed in matching the calibration laboratory data voltage, and the possible system drift with time must be considered. These uncertainty estimates are combined with the calibration laboratory uncertainty using the uncertainty analysis techniques described previously to give the overall uncertainty of the test pressure measurement.

Any changes in the procedures described above for the pressure measurements will change the elemental error sources that need to be considered. This, in turn, will change the uncertainty estimate for the measurement. Therefore, it is vital that the correct procedure be evaluated to determine the uncertainty value. The exact procedures used at SSC are being evaluated to determine the uncertainty values for the various types of measurements and ranges of these measurements in the E-complex test stands. The uncertainty information will then be available to potential customers.

Mass Flow Rate

As stated previously, a broad range of mass flow rate measurements is required in the E-complex, and these measurements are made with a variety of devices. Devices used to measure mass flow rate include turbine flowmeters (volumetric flow), subsonic venturis, cavitating venturis, V-cone flow meters, orifices, and Coriolis flow meters. Since mass flow rate is not a direct measurement like pressure or temperature, the correct data reduction equation must be used to evaluate the uncertainty of the mass flow rate depending on the device, measurement procedures, and calculation procedure. The data reduction equation must be written in terms of the measured variables. Changes in the measured variables, calculation method, etc., change the DRE and hence affect the uncertainty calculation for the mass flow rate measurement.

The procedures for calculating mass flow rate for the various devices used in the E-complex are being studied and used to establish a method to calculate the uncertainties for the range of values in the E-complex. Mathcad calculation files will be provided to SSC for each of the mass flow rate measurement methods so that uncertainty values can be calculated for specific test situations. Again, the details of the calculations and results cannot be provided in this paper; however, examples will be given to supply the reader with the general idea of the usefulness of the uncertainty analyses. These calculations will give sample UMF and UPC values defined previously.

First, consider a subsonic venturi used to calculate the mass flow rate of an incompressible fluid. This type of device may be used for a cryogenic fluid such as liquid oxygen. The equation to calculate mass flow rate for an incompressible fluid in a subsonic venturi can be found in reference 5. For this example, consider that the mass flow rate is a function of the following variables:

$$\dot{W} = f(C_d, F, d_1, d_2, \rho_1, \Delta P) \qquad \textbf{(11)}$$

This analysis assumes that the discharge coefficient, thermal contraction factor, inlet and throat diameters, and the inlet density are constant input values. It also assumes that ΔP is measured directly (as opposed to P_1 and P_2).

Based on the DRE defined above, the UMF values can be calculated. These values are given in Table 1 and Fig. 5 and show the potential impact of certain variables on the uncertainty of the mass flow rate. Only the throat diameter has a UMF value greater than 1. The discharge coefficient and thermal contraction factor have values of 1, while the other variables have values less than 1.

Now consider the uncertainty estimates for the variables given for case 1 in Table 1. These are realistic estimates for the uncertainty values of these variables. With these uncertainty estimates, the UPC terms can be calculated (Table 1 and Fig. 5). The results show that, for these uncertainty estimates, C_d and F are the driving factors accounting for 80% of the uncertainty in mass flow rate. For case 2, the uncertainty of the discharge coefficient was increased from 1% to 2%, which again is realistic depending on the calibration procedure. The results (Table 1 and Fig. 6) now show that the uncertainty in the mass flow rate has greatly increased, and the uncertainty in C_d is responsible for 72% of the uncertainty in the mass flow rate. Thus, the mass flow rate calculation can be greatly affected by the discharge coefficient although the UMF value was 1. For case 3, the uncertainty in C_d was set back to 1%, but the uncertainty in the ΔP measurement was increased to 2%. This resulted in a UPC value of 30% for the ΔP measurement (Table 1 and Fig. 7). This calculation shows that, although the UMF value for ΔP was less than 1, it can be important depending on the uncertainty values of the other variables. Note that the UPC values for the throat diameter are relatively small even though the UMF was greater than 1. This is due to the fact that the throat diameter can usually be determined very precisely. Therefore, although the variable had the potential to be extremely important based on the DRE, it did not turn out to be a critical variable when its uncertainty was considered. This shows the importance of extending the UMF analysis to a UPC analysis in later stages of the experiment.

Next, consider the same subsonic venturi used to calculate the mass flow rate of an incompressible fluid, but assume that P_1 and P_2 are measured directly (as opposed to ΔP). For this example, the mass flow rate is a function of the following variables:

$$\dot{W} = f(C_d, F, d_1, d_2, \rho_1, P_1, P_2) \qquad \textbf{(12)}$$

Based on the DRE defined above, the UMF values can be calculated. These values are given in Table 2 and Fig. 8. Now the throat diameter, inlet pressure, and throat pressure have UMF values greater than 1. The discharge coefficient and thermal contraction factor have values of 1, while the other variables have values less than 1.

Now consider the uncertainty estimates for the variables given for case 1 in Table 2. These are the same estimates used for case 1 in the previous example with 1% used for the uncertainty of all pressure measurements. The uncertainty of the mass flow rate has increased by an order of magnitude purely due to the change in the measurement method. With these uncertainty estimates, the UPC terms can be calculated (Table 2 and Fig. 8). The results show that the two pressure measurements account for 99% of the mass flow rate uncertainty. This example shows the importance of properly accounting for the measurement methods and calculation procedures as well as the importance of evaluating the possible methods in an uncertainty sense. The mass flow rate calculation depends on the difference in pressure between the inlet and throat of the venturi. Therefore, measuring the two pressure values independently greatly increases the uncertainty of the mass flow rate calculation. It is important to note that no correlation has been considered between the two pressure measurements in this calculation. In a situation where a ΔP measurement was not possible, the uncertainty of the mass flow rate calculation could be diminished by forcing correlation between the two pressure measurements (Eqs. (3) and (6)). This could be accomplished by calibrating the two pressure measurements at the same time against the same standard, etc. Then a part of the systematic shift of both transducers would be the same. Although both absolute pressure values may differ from the true value, the difference in the two pressures would be close to the true value. And the pressure difference is the critical parameter.

At the conclusion of this study, results such as those given in the examples above will be available for all types of mass flow rate measurement devices over the range of conditions for the E-Complex. Mathcad files will be provided so that calculations can be made for specific conditions of interest to aid in test planning and posttest evaluation of test data.

Summary and Future Work

The Rocket Based Combined Cycle (RBCC) engine is expected to evolve based upon past combined-cycle propulsion test experience/data and new extensive test data. Currently, it is envisioned that a portion of the RBCC component and full-scale engine testing will be pursued at NASA SSC. The powerpack system and full-scale engine tests will take place at the newly designed E-4 test facility, while the balance of the other tests will likely occur at the other existing E-Complex test stands (i.e., E-1, E-2 and E-3).

To realize the greatest benefit of the new test data, uncertainty analyses are being performed on the relevant RBCC components and systems to be tested at NASA SSC to ascertain the needed measurement requirements. These studies pertain to the existing E-Complex test stands as well as the new E-4 facility. This paper describes the approach used in the studies and gives examples to demonstrate the approach and the usefulness of the results.

Future work on this project involves completing the measurement uncertainty analyses for the measurement types listed in the introduction for the existing E-Complex test facilities. The analyses will cover the range of measurements required for each device. The results will be documented in a comprehensive report to SSC. A customer report will also be produced. Computer files and training for their use will also be provided to SSC so that the uncertainty calculations can be performed for new systems or changes to existing systems.

Future work also pertains to evaluating results of interest for RBCC testing. For each RBCC component and system to be tested, the performance, life, and operability goals will be determined. From these goals, an uncertainty analysis will be performed to establish the measurement requirements to meet the stated goals. A comparison will then be made to determine if the designated test facility can meet the measurement requirements. If the RBCC test measurement requirements exceed the present capability of the facility, recommendations will be made on measurement systems and methodologies that should be employed to achieve the desired RBCC test measurement goal. Recommendations will also be made for the E-4 test facility since the associated data acquisition and controls system is currently being designed. Hence, for this facility, a measurement system can be specifically tailored around the RBCC engine measurement requirements. This work will greatly increase the reliability of the test data while minimizing costs by focusing expenditures in the proper areas that are critical to program success.

Acknowledgments

The authors would like to recognize the support and contributions of those associated with the NASA Propulsion Test Directorate (PTD) Operations and Engineering Divisions. This work is being performed under contract NAS13-98033 Delivery Order #160.

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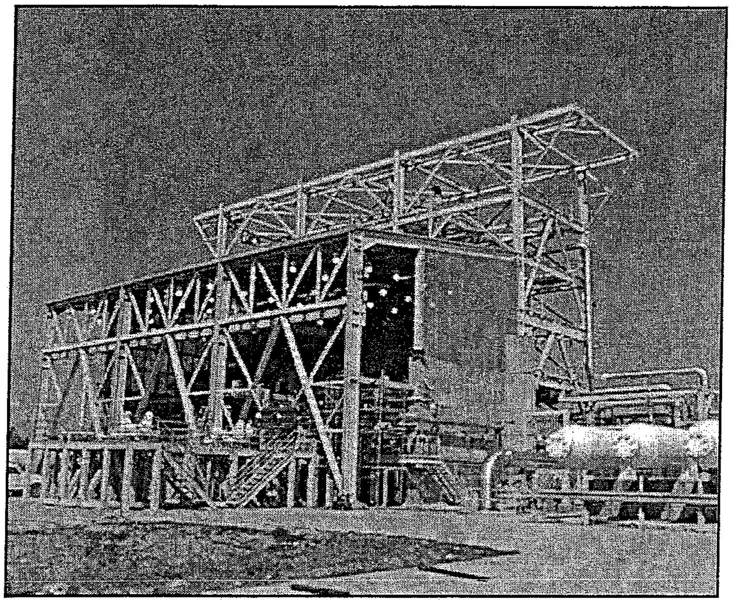

Fig. 1. **E-1 Test Stand comprised of Cells 1, 2 and 3**

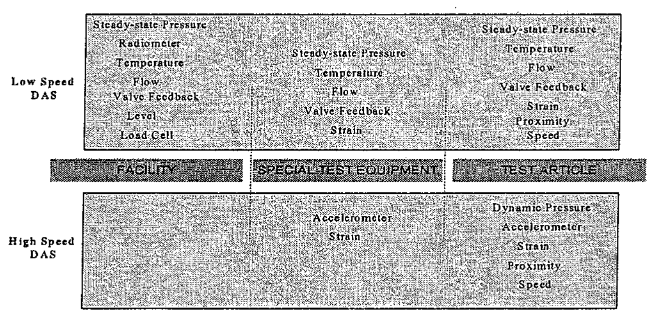

Fig. 2. Facility, Special Test Equipment (STE) and Test Article Measurement Types

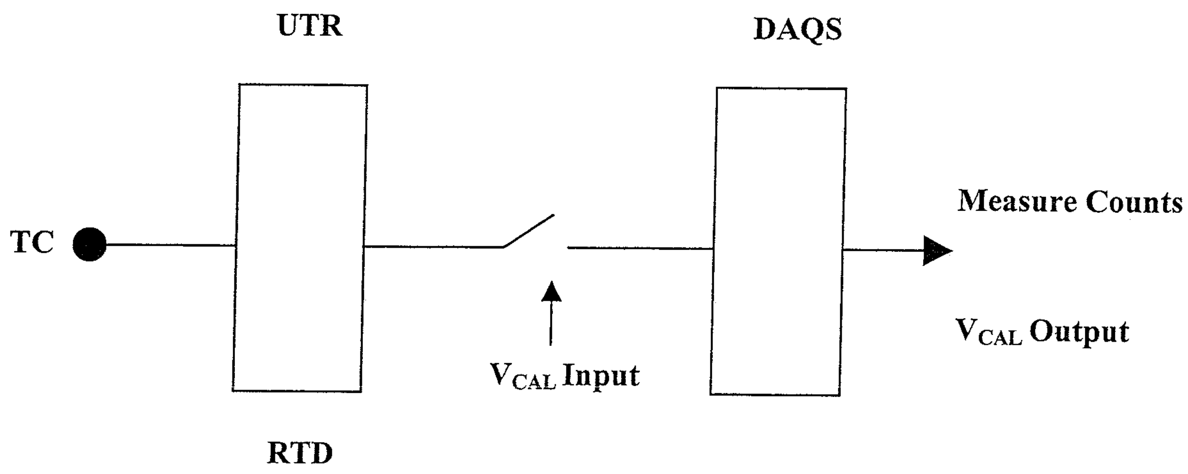

Fig. 3. Thermocouple Measurement with UTR

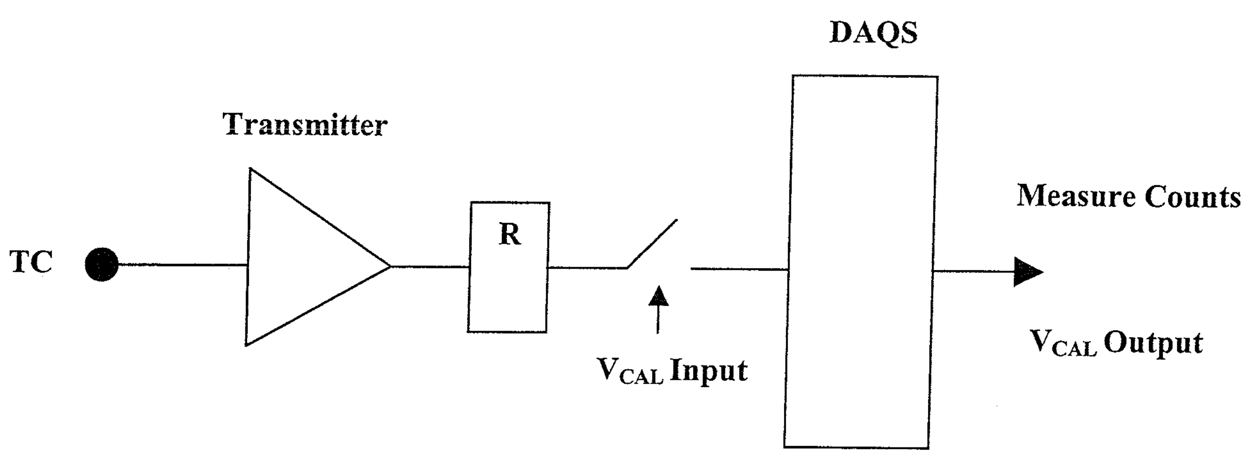

Fig. 4. Thermocouple Measurement with Transmitter

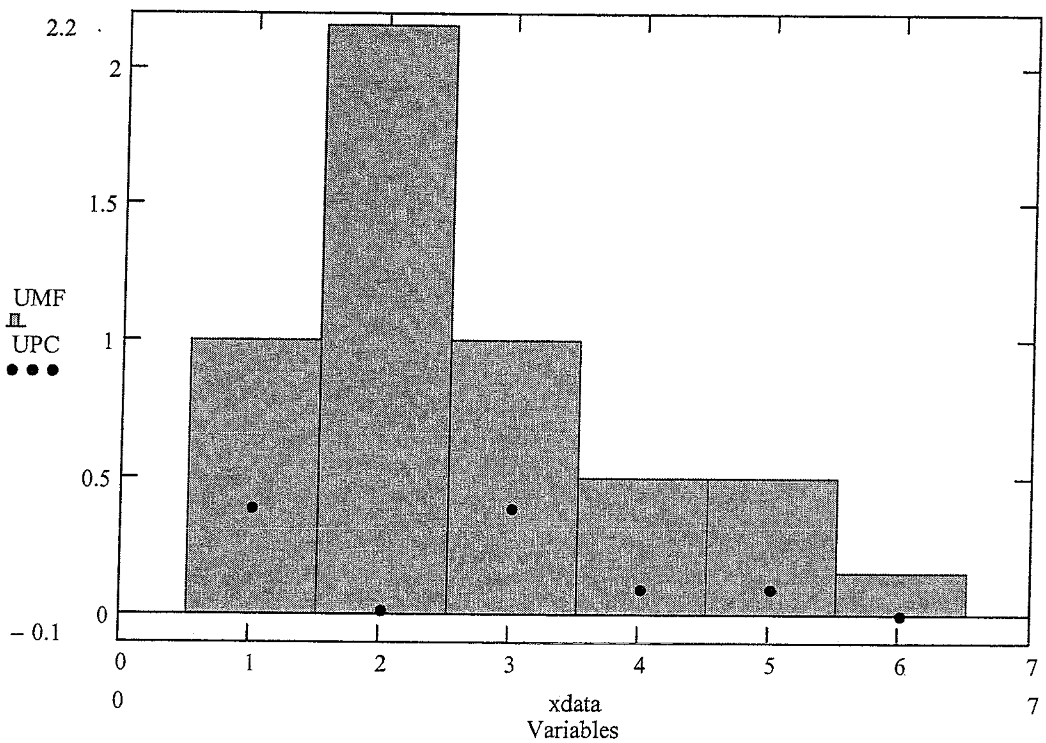

Fig. 5. Subsonic Venturi with ΔP Measurement—Case 1 UMF and UPC Values
1=C_d, 2=d_2, 3=F, 4=ρ1, 5=Δp, 6=d_1

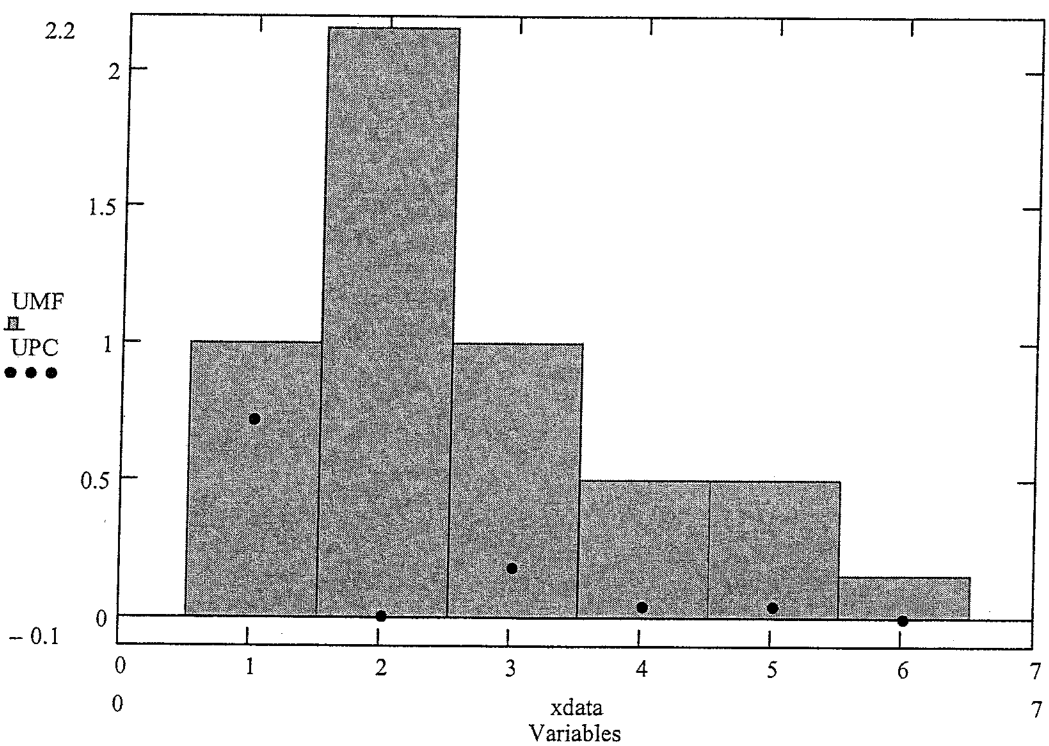

Fig. 6. Subsonic Venturi with ΔP Measurement—Case 2 UMF and UPC Values
1=C_d, 2=d_2, 3=F, 4=ρ1, 5=Δp, 6=d_1

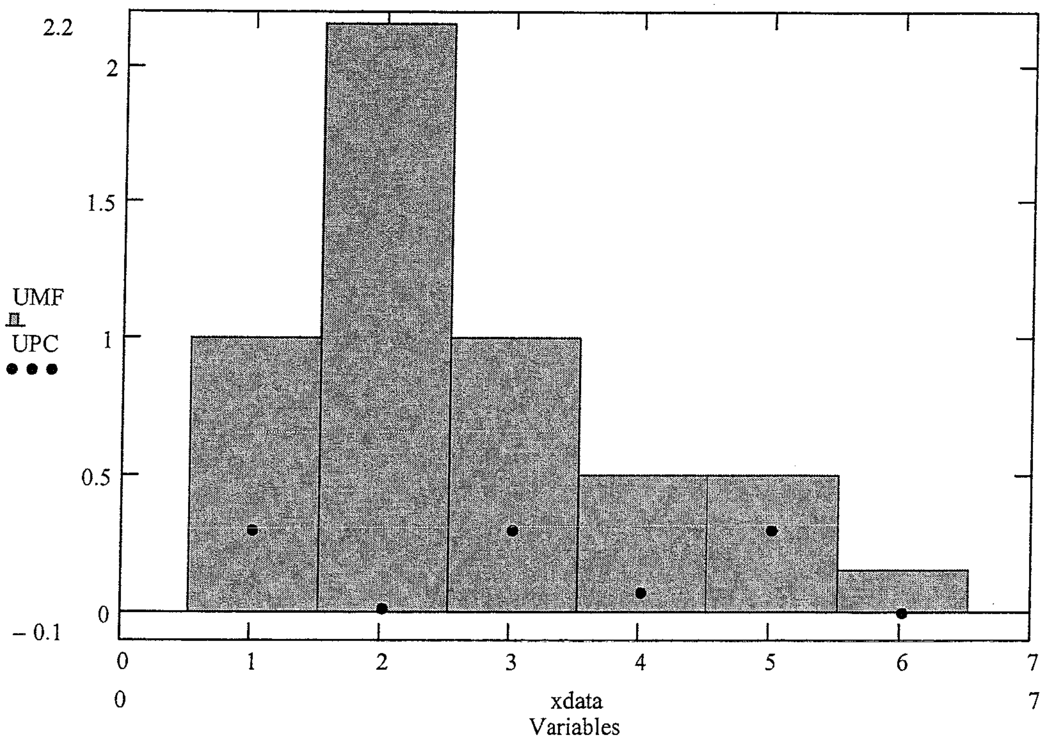

Fig. 7. Subsonic Venturi with ΔP Measurement—Case 3 UMF and UPC Values
1=C_d, 2=d_2, 3=F, 4=ρ1, 5=Δp, 6=d_1

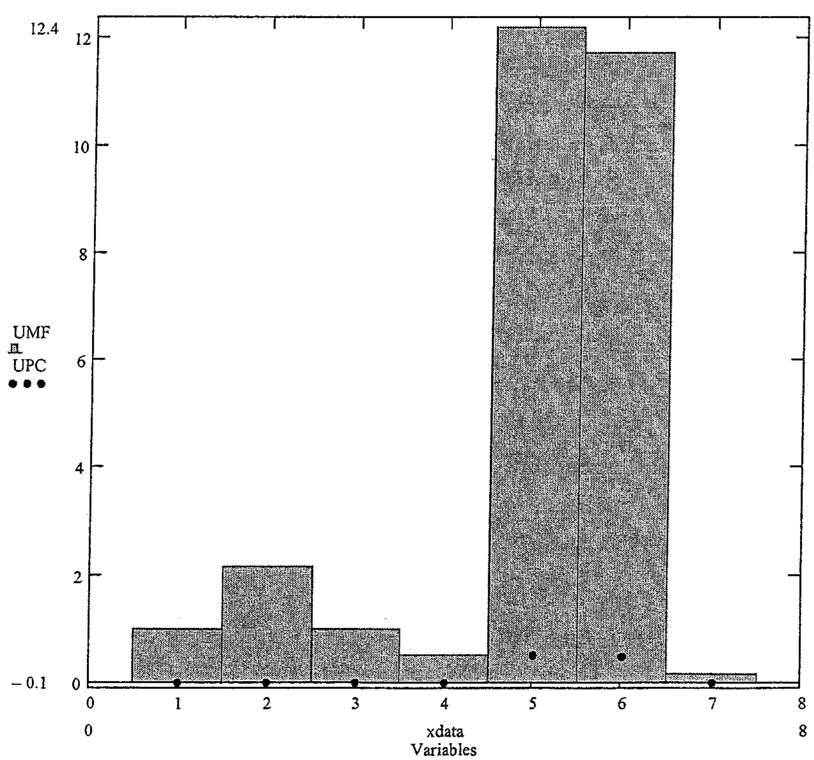

Fig. 8. Subsonic Venturi with P_1 and P_2 Measurements—Case 1UMF and UPC Values
1=C_d, 2=d_2, 3=F, 4=ρ1, 5=P_1, 6=P_2, 7=d_1

Table 1. Subsonic Venturi Incompressible Flow—ΔP Measurement

	Cd	F	d_1	d_2	ρ1	ΔP	$\dot{W}$	$U\dot{w}$	$U\dot{w}$ %
UMF	1	1	0.152	2.152	0.5	0.5			
Nominal Values	0.9773	0.99474	5.295	2.7277	41.327	42.04	164.18		
Uncertainty Estimates									
Case 1	1%	1%	0.005 in	0.005 in	1%	1%		2.62	1.6
Case 2	2%	1%	0.005 in	0.005 in	1%	1%		3.87	2.4
Case 3	1%	1%	0.005 in	0.005 in	1%	2%		2.98	1.8
UPC Values									
Case 1	39.3	39.3	Negligible	1.6	9.8	9.8			
Case 2	72.2	18.0	Negligible	Negligible	4.5	4.5			
Case 3	30.4	30.4	Negligible	1.2	7.6	30.4			

Table 2. Subsonic Venturi Incompressible Flow—P_1 and P_2 Measurements

	Cd	F	d_1	d_2	ρ1	P_1	P_2	$\dot{W}$	$U\dot{w}$	$U\dot{w}$ %
UMF	1	1	0.152	2.152	0.5	12.21	11.71			
Nominal Values	0.9773	0.99474	5.295	2.7277	41.327	1026.35	984.31	164.18		
Uncertainty Estimates										
Case 1	1%	1%	0.005 in	0.005 in	1%	1%	1%		27.88	17.0
UPC Values										
Case 1	Negl.	Negl.	Negl.	Negl.	Negl.	51.7	47.5			

REPORT DOCUMENTATION PAGE	*Form Approved* *OMB No. 0704-0188*

1. REPORT DATE *(DD-MM-YYYY)*	2. REPORT TYPE	3. DATES COVERED *(From - To)*
19-06-2002		

4. TITLE AND SUBTITLE
Test Facility Uncertainty Analysis for RBCC System Testing

5a. CONTRACT NUMBER
NAS13-98033

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
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5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Propulsion Test Directorate

8. PERFORMING ORGANIZATION REPORT NUMBER
SE-2002-06-00051-SSC

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSORING/MONITOR'S ACRONYM(S)

11. SPONSORING/MONITORING REPORT NUMBER

12. DISTRIBUTION/AVAILABILITY STATEMENT
Public Available STI per Form 1676

13. SUPPLEMENTARY NOTES
Conference - 38th AIAA/ASME/SAE/ASEE Joint Propulsion Conference

14. ABSTRACT
The Rocket Based Combinec Cycle (RBCC) engine is expected to evolve based upon past combined-cycle propulsion test experience/data and new extensive test data. Currently, it is envisioned that a portion of the component and system testing will be prused at NASA Stennis Space Center (SSC). To realize the greatest benefit of the test data, uncerainty analyses are being perfomred on the relevant RBCC components and systems to be tested at NASA SSC to ascertain the needed measurement requirements. These studies pertain to the exisiting E-Complex test stands as well as a new facility, E-4. This paper describes the approach used in the studies andgives examples to demonstrate the aproach and the usefulness of the results. Future work on this project is also described. This work will greatly increase the reliability of the test data while minimizing costs by focusing expeditures in the test data while minim izing cost by focusing expenditures in the proper areas that are critical to program success and not allowing resources to be wasted in areas that are not significant relative to overall, program goals.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19b. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			Harry Ryan
					19b. TELEPHONE NUMBER *(Include area code)*
U	U	U	UU	14	(228) 688-2757