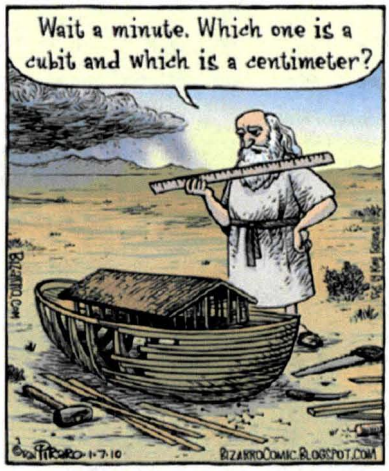
Metrology for Project Development



"What happens when you don't measure up."

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Presentation Topics

1. What is metrology
2. Measurement related risks and their consequences

All measurement decisions have consequences…

You get judged by English Common Law. You are innocent until proven guilty. Your measurements must be judged by Napoleonic Law. They are guilty until proven innocent.

Prof. Emeritus Peter Stein

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Metrology and Measurement Data

Metrology is the *"science of measurement and its application"* (JCGM 200:2008).

- This includes all theoretical and practical aspects of measurement

Measurements = Decisions

Measurement data support decisions to...

- Establish research or investigative fact
- Establish scientific or legal fact
- Accept or reject a product
- Rework or complete a design
- Take corrective action or withhold it
- Continue or stop a process (including a space launch)

*The objective of the design and control of **measurement** processes is to manage the **risks** taken in making **decisions** based on measurement data.*

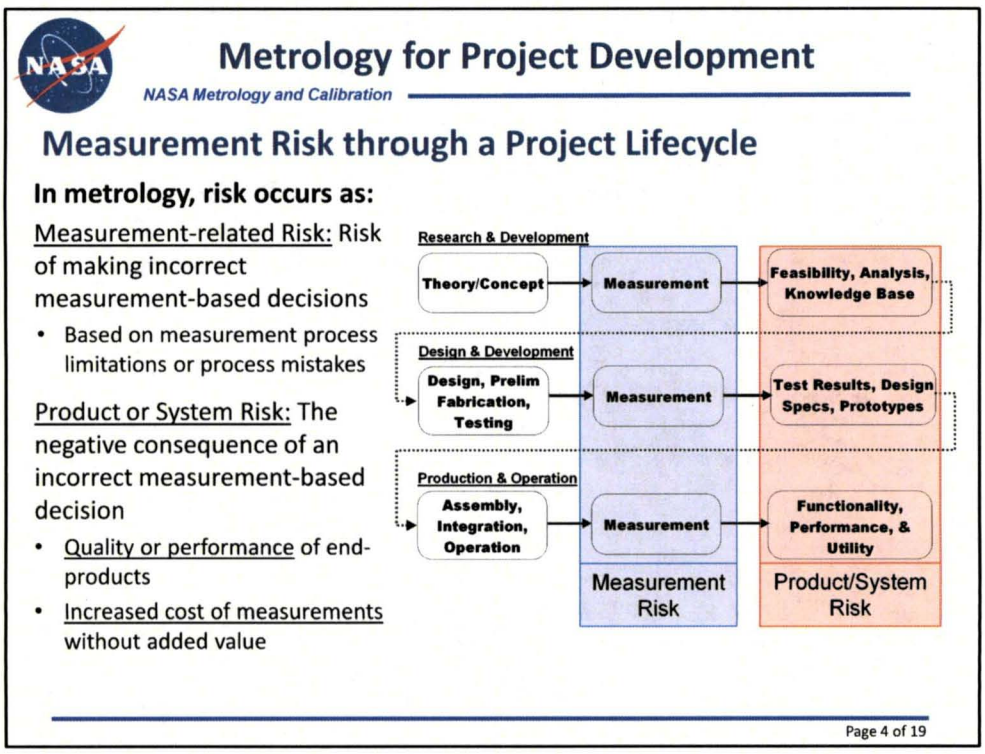
NASA Reference Publication 1342
Metrology — Calibration and Measurement Processes Guidelines

The international definition of metrology is the science of measurement. In the simplest terms, metrology provides the measurement data used to make decisions, and the quality of the decision is directly proportional to the quality of the measurement data.

The old computer adage, "garbage in, garbage out" applies to decision processes where measurement data is involved; bad measurement data can lead to bad decisions.

The measurement data used by NASA can be critical to decisions which affect everything from a program's economic success, to its mission success. Measurement data influences design decisions, acceptance or rejection decisions, and even launch decisions.

Before measuring, there are two important questions that need to be answered: How good does the measurement need to be? How good can the measurement be made?



This figure illustrates measurement versus product/system risk through a lifecycle. The negative impact of measurement decisions can carry through the entire lifecycle; therefore, managing measurement-based risks during each phase of the lifecycle is an essential part of a quality system.

NPR 7120.5D, **NASA Space Flight Program and Project Management Requirements**

2.3.1.1 Project formulation consists of two sequential phases, traditionally denoted as Phases A (*Concept & Technology Development) and B (Preliminary Design & Technology Completion). The primary activities in these phases are to develop and* define the project requirements and cost/schedule basis and to design a plan for implementation (including an acquisition strategy, contractor selection, and long-lead procurement). While not formally a part of formulation, some formulation-type activities will naturally occur as part of earlier advanced studies. These fall into a part of the project life cycle known as Pre-Phase A (*Concept Studies).*

2.3.1.2 Project implementation consists of Phases C, D, E, and F. Approval marks the transition from Phase B of formulation to Phase C of implementation. During Phases C (*Final Design and Fabrication) and D (System Assembly, Integration and Test, and Launch), the primary activities are developmental in nature, including acquisition contract execution. Phase C includes the* fabrication and testing of components, assemblies, and subsystems. All activities are executed as per the Project Plan developed during formulation. The transition from Phase C to Phase D is uniquely a "soft gate," in which the project may initiate Phase D work immediately upon completion of the Phase C work products, absent a notice of discontinuance by the Program Manager (rather than waiting for affirmative direction from the Program Manager to begin Phase D). The start of Phase E (*Operations and Sustainment) marks the transition from system development and acquisition activities to primarily systems operations and* sustainment activities. In Phase F (*Closeout), project systems are taken out of service and safely disposed, although scientific and* other analyses might still continue under project funding. Independent evaluation activities occur throughout all phases.

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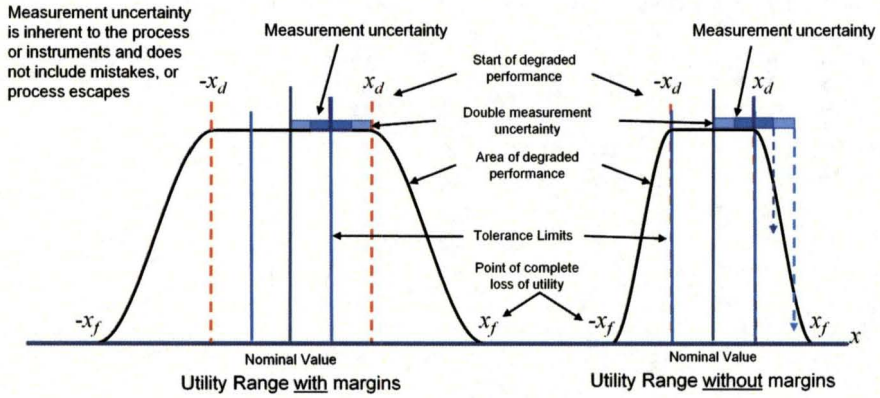
Measurement Risk and End-item Performance



- Over specification of requirements costs money…
- However, under specification can be hazardous

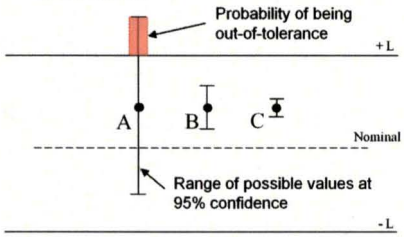
Probability of Incorrect Measurement Decisions

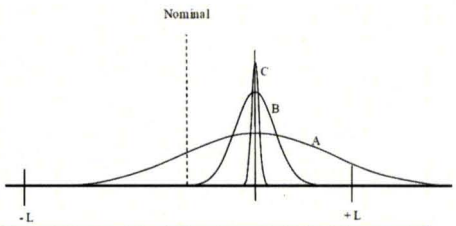
Measurement Uncertainty: The doubt that exists about a measurement's result

- Every measurement—even the most careful—always has a margin of doubt
- Uncertainty is the inherent limitation of a measurement process, due to instrumentation and process variation
- Measurement uncertainty does not include mistakes or process escapes

The **probability of an incorrect decision** is determined by:

- The amount of uncertainty in the measurement process
- Where the measurement result lies with respect to the tolerance limit (e.g., $\pm L$)
- Knowledge acquired from previous measurements of similar items (i.e., *a priori* distribution)





Decision rules, such as the 10:1 and 4:1 are designed around this concept.

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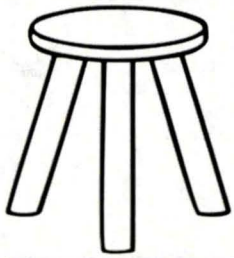
Essential Components of "Good" Measurement Data

Three essential components are required for measurements to adequately support decisions in a cost-effective manner

1. "Good requirements" - Reasonable measurement tolerances that are based on system performance
2. "Good equipment" - Measuring and test equipment that is properly calibrated
3. "Good measurements" - End-user measurement processes/procedures that adequately support the end-product performance requirements



Like the legs of a three-legged stool, all three components are necessary.
If one leg is missing, the risk that the stool will fall over increases; likewise, the risk of an incorrect decision increases dramatically if one of these components is missing.

NASA's metrology policy is to *"Control measurement processes to ensure the accuracy of measurement results affecting safety and mission success."* Traditionally, *"measurement control"* has focused on the calibration of instruments, and although vital, instrument calibration alone does not ensure accurate measurement data. A "perfect" instrument does not guarantee a "good" measurement. Such assurance can only come from the proper and appropriate application of measurement controls. Measurement controls fall into three basic categories.

Measurement requirements – Establishing reasonable measurement requirements that are based on system performance is the foundation for making good measurement-based decisions. Without this link, the cost of verifying the measurement requirements can increase without adding value, or worse, verification of the design performance may not be adequate. In the absence of specified measurement requirements (e.g., research), it is imperative to document the quality of the measurement. (link to AS9100, 7.3.3 & 8.2.4)

Measuring Instruments – In addition to the proper selection, care, and use of measuring instruments, it is vital to periodically verify that measuring instruments are performing to their specifications. Calibration is the measurement control for ensuring instrument accuracy. Calibration establishes the link for a given measurement to the national or international standard for that unit of measure. Calibration provides traceability, ensuring that measurements made at a particular place and time can be meaningfully compared with those made at other places and/or at other times. There are three basic forms of calibration:

Laboratory calibration

In-situ calibration

Instrument verification, also called "user calibrations,"

(link to AS9100, 7.6)

Measurement Processes - Adequate measurement processes/procedures are necessary to control errors which could lead to incorrect decisions based on measurement data. Even with a properly calibrated instrument, there are other factors that can introduce errors into the measurement process larger than the instrument accuracy. To ensure accuracies sufficient to support quality decisions, measurement procedures must be developed which adequately account for, or manage all relevant error sources in the measurement process. Examples of potential error sources are:

Environmental

Instrument resolution,

Operator competency and bias

Repeatability

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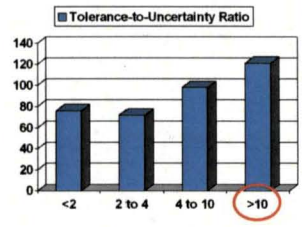
Case Study 1 – Space Shuttle Measurement Assessments

Two measurement-related Independent Assessments

1. Shuttle Discovery's 2nd post-Columbia return to flight
2. Ground Support Equipment (GSE) follow-on

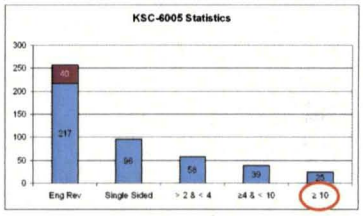


Shuttle Discovery (STS-121) Assessment

- 67.0% non-compliant with Program requirement
- 40.3% non-compliant with "good" measurement practices
- **Components 1 & 3**

GSE Follow-on Assessment

- 97.4% non-compliant with Program requirement
- 86.4% non-compliant with "good" measurement practices
- **Components 1 & 3**



Engineering review indicated all measurements were acceptable due to large margins built into the Shuttle systems

Page 8 of 19

During a walk-down of Kennedy Space Center Shuttle processing areas by Safety and Mission Assurance personnel, it became apparent there was a general lack of awareness of the Shuttle requirements for measurement assurance. NSTS 5300.4 (1D-2) requires that measurement uncertainty be no more than ten percent of the required tolerance of a measurement. The lack of knowledge of this requirement raised questions about whether required measurement assurance had been maintained for the STS-121 hardware. A short-term assessment was conducted to review measurements accomplished, and to estimate the degree of non-compliance and the potential implications for the STS-121 mission.

The assessment was conducted by developing a catalog of over 28000 precision measurements made for STS-121 flight hardware. From this list, a statistically relevant sample of 367 randomly-selected measurements was developed. For these items, the specified tolerance and the measurement uncertainty were recorded. The tolerance-to-uncertainty ratio was then calculated. Those with a ratio less than 10:1 (NSTS requirement) were analyzed to determine the likelihood of the measurement being out of tolerance. Of the 367 sampled measurements, 76 or 21% were found to have ratios of 2:1 or less. These measurements were judged to have a significant likelihood of being out of tolerance and were sent to engineering for an evaluation of the possible impact to Shuttle safety.

Engineering evaluations on the 76 items determined that margins built into the Shuttle hardware would absorb the risk posed by the possible out of tolerance measurements. While this report indicated that no immediate threats to Shuttle safety were found, not all measurements were checked, and the assessment results cannot be used as a guarantee that threats do not exist. Consequently, there is some risk in using the results as justification for continuing with the current measurement process. At the same time, the fact that no measurement accuracies raised concerns from engineering indicates that the universal application of the 10:1 ratio requirement may be overly restrictive.

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Case Study 1 – Space Shuttle Measurement Assessments

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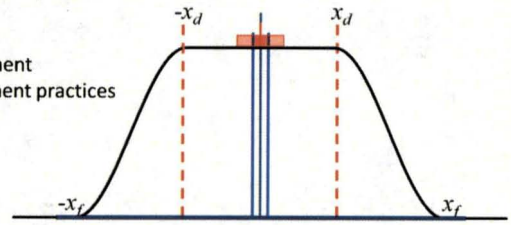
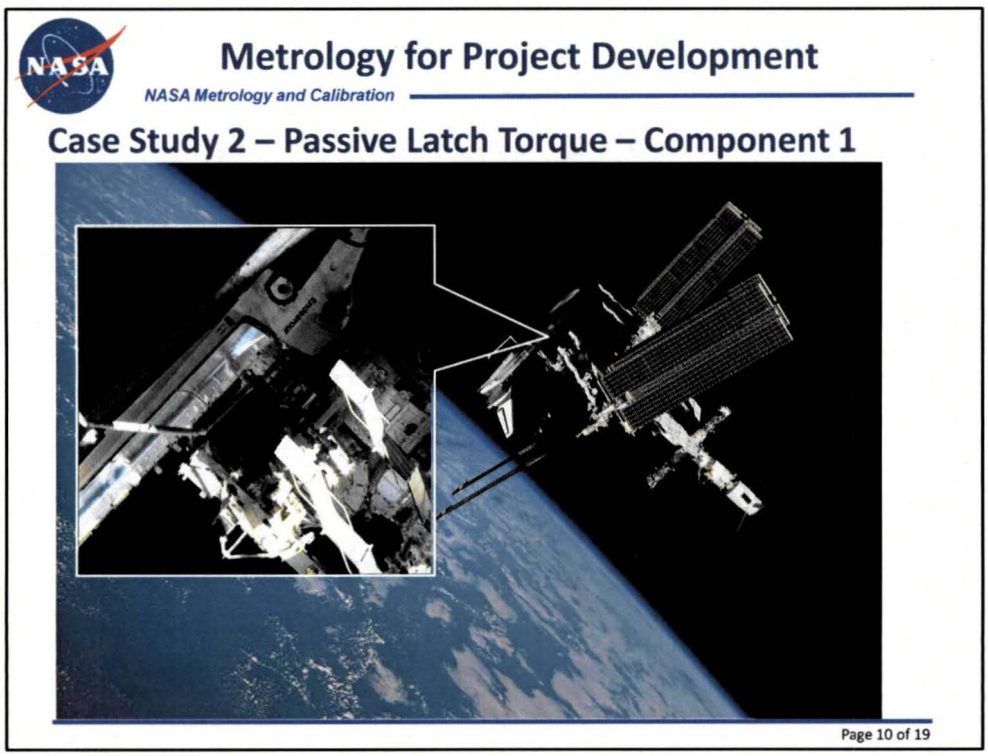


- Non-compliance to measurement requirements is a **Component 3** issue
- Although large design margins seemed to compensate for non-compliance, lack of documentation (**Component 1**) fostered complacency and left a potential for hidden threats



The International Space Station and the Docked Space Shuttle Endeavour

ISS027-E-036793 (23 May 2011) --- This image of the International Space Station and the docked space shuttle Endeavour, flying at an altitude of approximately 220 miles, was taken by Expedition 27 crew member Paolo Nespoli from the Soyuz TMA-20 following its undocking on May 23, 2011 (USA time).

In the close-up, the Endeavour's docking module is visible.

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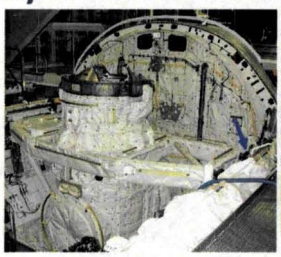
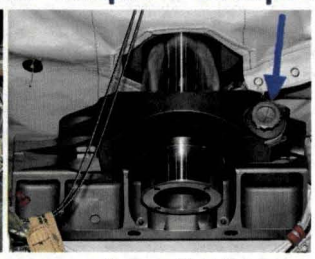
Case Study 2 – Passive Latch Torque – Component 1



4 Latches Secure Airlock to Shuttle



Close up of Latch Bolt

Over specification of original Shuttle measurement design requirements led to an expensive redesign of a failed torque system

1. Measurement requirement for latch bolt torque: 8,000-8,500 inch-lbs
   - Only lower torque limit linked to design requirements (maximum flight load)
2. Permissible bolt torque range per NASA standards: 8,000-10,200 inch-lbs
3. Acceptable latch bolt torque for typical flight loads: 6,580-10,200 inch-lbs

Application of existing NASA or Industry standards would have allowed the use of off-the-shelf torque systems that were readily available

Failure of the specially designed torque multipliers required a complete redesign and flight waivers for three Space Shuttle missions

Excerpt from **A70-1051 Torque Multiplier S063385A Waiver Extension** , March 23, 2007, to add extension effectivity to include STS-118

The V073-340177-013/14 passive latch is certified for a design limit +Z trunnion load of 121,000 pounds at a design flight torque of 8000-8500 inch-pounds.

The A70-1051 torque multipliers may not produce correct flight torque in passive latch bolts. CAR KG0077 was taken to document the absence of verified repeatable output torque. The A70-1051 serial number 004 was used to torque all four External Airlock latches installed in OV-105 for flight 20 for STS-118.

An analysis of variance test conducted on 3/8/2006 indicates a 99.7% probability that the output torque from the serial number 004 torque multiplier was between 6780 and 10,900 inch-pounds.

Per Design Center Loads and Dynamics Verification Loads Analysis, STS-118 calculated maximum External Airlock trunnion flight load will be 13,714 pounds.

Per Design Center Stress assessment, a passive latch torqued to 6580 inch-pounds will restrain a trunnion load 62,400 pounds.

Per Design Center M&P fastener assessment, a high torque of 10,900 inch-pounds is permissible.

Therefore, the torque applied to the External Airlock latches is sufficient to ensure the latches will function per design intent for STS-118.

Rationale has been coordinated with the Payload Accommodations PRT.

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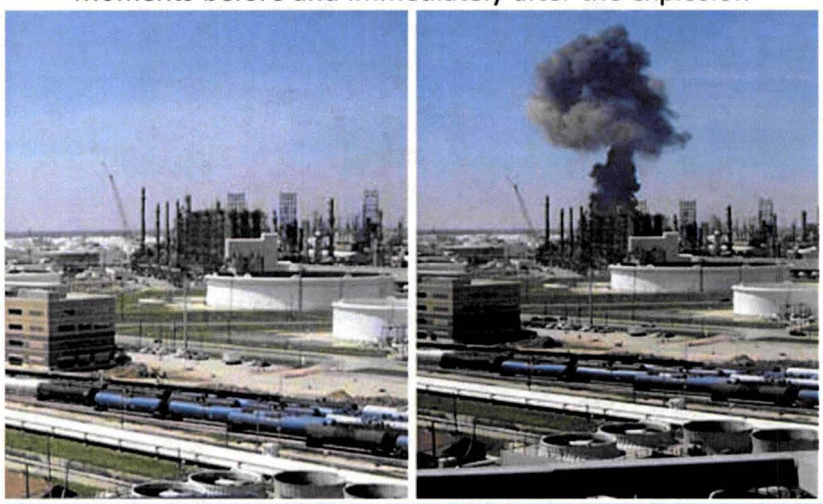
Case Study 3 – BP's Texas City Refinery - March 23, 2005

Moments before and immediately after the explosion



Houston, Texas, March 20, 2007 - In a 335-page final report released today, federal investigators from the U.S. Chemical Safety Board (CSB) conclude that "organizational and safety deficiencies at all levels of the BP Corporation" caused the March 23, 2005, explosion at the BP Texas City refinery, the worst industrial accident in the United States since 1990. The report calls on the U.S. Occupational Safety and Health Administration (OSHA) to increase inspection and enforcement at U.S. oil refineries and chemical plants, and to require these corporations to evaluate the safety impact of mergers, reorganizations, downsizing, and budget cuts.

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Case Study 3 – BP's Texas City Refinery (continued)

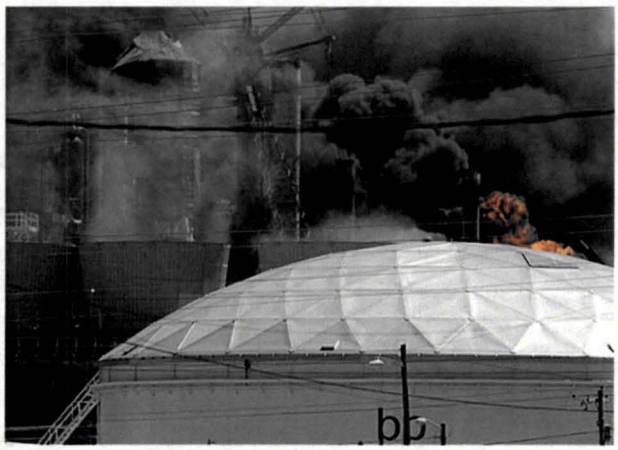
The Accident:

- Distillation tower and attached blowdown drum overfilled
- ~7600 gallons flammable liquid released
- Liquid ignited by an idling diesel truck

Proximate cause:

- High-level alarm malfunctioned
- Level transmitter miscalibrated
  - Outdated 1975 data sheet
  - Level transmitter indicated liquid level falling
  - Level actually rising rapidly

Component 2



CSB Investigator Mark Kaszniak, who led the CSB's vapor and blast modeling effort, stated, "The CSB was able to calculate that approximately 7,600 gallons of flammable liquid hydrocarbons - nearly the equivalent of a full tanker truck of gasoline - were release from the top of the blowdown drum stack in just under two minutes." The ejected liquid rapidly vaporized due to evaporation, wind dispersion, and contact with the surface of nearby equipment. High overpressures from the resulting vapor cloud explosion totally destroyed 13 trailers and damaged 27 others. People inside trailers were injured as far as 479 feet away from the blowdown drum, and trailers nearly 1000 feet away sustained damage.

Although a high tower liquid level alarm did activate in the control room in the early morning hours, a second highlevel alarm malfunctioned and the faulty tower level transmitter later indicated that the liquid level was below nine feet and falling. The normal liquid level in the tower was six-and-a-half feet. Unknown to operators, the level was actually rising rapidly, reaching 158 feet by 1 p.m. on March 23, twenty minutes before the explosion. The CSB determined that the level transmitter was miscalibrated, using a setting from outdated data sheets that likely had not been updated since 1975.

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Case Study 3 – BP's Texas City Refinery (continued)

Root causes:

- Cost-cutting, production pressures, and failure to invest
- Lack of preventative maintenance and safety training
- Procedural workarounds to compensate for the deteriorating equipment

Component 3

The Cost:

- 15 deaths,
- 180 injured
- Over $2 billion, including lawsuits

The aftermath

BP acquired the Texas City refinery when it merged with Amoco in 1999. The CSB report found that "cost-cutting in the 1990s by Amoco and then BP left the Texas City refinery vulnerable to a catastrophe." Shortly after acquiring Amoco, the BP Group Chief Executive ordered an across-the-budget 25% cut in fixed spending at the corporation's refineries. The impact of the cost cuts is detailed in many of the more than 20 key investigative documents the CSB made public today, including internal BP safety audits, reviews, and emails. Among other things, cost considerations discouraged refinery officials from replacing the blowdown drum with a flare system, which the CSB previously determined would have prevented or greatly minimized the severity of the accident.

Chairman Merritt said, "The combination of cost-cutting, production pressures, and failure to invest caused a progressive deterioration of safety at the refinery. Beginning in 2002, BP commissioned a series of audits and studies that revealed serious safety problems at the Texas City refinery, including a lack of necessary preventative maintenance and training. These audits and studies were shared with BP executives in London, and were provided to at least one member of the executive board. BP's response was too little and too late. Some additional investments were made, but they did not address the core problems in Texas City. In 2004, BP executives challenged their refineries to cut yet another 25% from their budgets for the following year."

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Case Study 4 – Air Force B-2A Crash

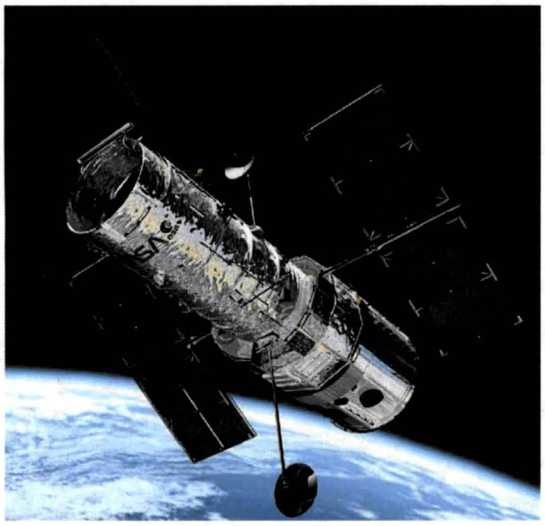
The loss of the U.S. Air Force B-2 bomber in February 2008 is a dramatic example of measurement-based decisions leading to catastrophe.
Performance requirement: Altimeter ± 75 feet of field elevation.
Actual reading: + 136 feet of field elevation at take-off.

- The proximate cause of the crash was moisture in the Air Data System (ADS) which introduced large errors during a field calibration of several Port Transducer Units onboard the aircraft
- The measurement procedure did not account or mitigate for moisture **Component 3**
- There was a lack of understanding regarding how the ADS affects the aircraft flight safety **Component 1**
- Although the calibration procedure was followed, an incorrect measurement-based decision led to the loss of a $1.4 billion asset, fortunately without loss of life

"Moisture in the MA port transducer unit (PTUs) during an air data calibration caused an unnecessarily large 'bias' or correction to the air data system. Using this "moisture distorted" data, the MA flight computers calculated inaccurate airspeed and a negative angle of attack (AOA) which contributed to an early rotation and uncommanded pitch-up on takeoff. Loss of all air data resulted in degraded flight controls response and stability of the MA."

"Three factors contributed to ineffective communication of critical information. First, the increased requirement for air data calibrations was intermittent, only surfacing as an issue during deployments that lasted only a few months a year. Second, a requirement for an air data calibration never caused an aircraft to miss a takeoff. While maintenance supervisors were concentrating on issues that grounded jets, air data calibrations never made it to their "Top 10" items of concern. **Third, maintenance and operations personnel interviewed had a functional understanding of the air data system, but lacked an appreciation for the potential to induce catastrophic errors into air data sensors. Most of the individuals interviewed by the board viewed the air data calibration as a mechanism to correct the aircraft altimeters and nothing more. The board had to consult aircraft design engineers who had not been associated with the B-2 program for over 10 years to find a level of understanding in the system that raised concerns over a need to calibrate PTUs on the aircraft.**"

Case Study 5 - Hubble Space Telescope



- Hubble Space Telescope (HST) launched aboard the Space Shuttle Discovery, April 24, 1990
- During on-orbit checkout, the telescope could not be properly focused
- Ensuing investigation revealed the primary mirror was not built to specifications
- The optical test used to manufacture mirror was set-up incorrectly **Component 3**
- Error was ten times the specified tolerance

NASA Technical Memorandum TM-103443, "The Hubble Space Telescope Optical Systems Failure Report", November 1990.

The Hubble Space Telescope (HST) was launched aboard the Space Shuttle Discovery on April 24, 1990. During checkout in orbit, it was discovered that the telescope could not be properly focused because of a flaw in the optics. The HST Project Manager announced this failure on June 21, 1990. Both of the high resolution imaging cameras (the Wide Field planetary Camera and the Faint Object Camera) showed the same characteristic distortion, called spherical aberration, that must have originated in the primary mirror, the secondary mirror, or both.

The National Aeronautics and Space Administration (NASA) Associate Administrator for the Office of Space Science and Applications then formed the Hubble Space Telescope Optical Systems Board of Investigation on July 2, 1990, to determine the cause of the flaw in the telescope, how it occurred, and why it was not detected before launch. The Board conducted its investigation to include interviews with personnel involved in the fabrication and test of the telescope, review of documentation, and analysis and test of the equipment used in the fabrication of the telescope's mirrors. The information in TM-103443 is based exclusively on the analyses and tests requested by the Board, the testimony given to the Board, and the documentation found during the investigation.

Continued analysis of images transmitted from the telescope indicated that most, if not all, of the problem lies in the primary mirror. The Board's investigation of the manufacture of the mirror proved that the mirror was made in the wrong shape, being too much flattened away from the mirror's center (a 0.4-wave rms wavefront error at 632.8 nm). The error is ten times larger than the specified tolerance.

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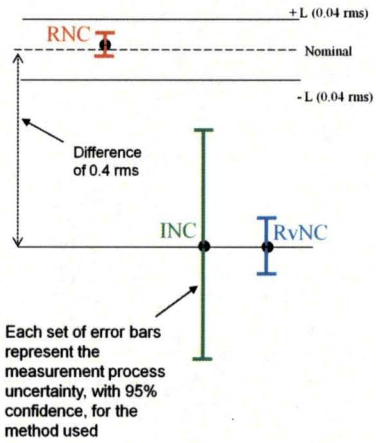
Case Study 5 - Hubble Space Telescope – Measurements



Data from three different measuring techniques were available

1. RNC: ±0.01 rms (*Reflective* Null Corrector)
2. RvNC: ±0.02 rms (*Refractive* Null Corrector)
3. INC: ±0.14 rms (*Inverse* Null Corrector)

- RNC was a high accuracy measurement system developed specifically for the HST
- The INC and RvNC are less accurate, standard mirror measurement systems
- Both clearly showed the RNC error, although both were discounted

High confidence was placed in Method #1. The other two methods were dismissed (lower confidence). They should not have been dismissed because they had adequate accuracy to reveal the error. This situation mandates investigation before an "Acceptance Decision" is made.

"The consistency of the data from the INC and the RvNC indicates the presence of the error in the RNC."

NASA TM-103443 HST Optical Systems Failure Report

Although it seems impossible for less accurate measurement processes to be correct over an extremely accurate process, the lessons from the Hubble investigation can be summed up in a movie quote (also from Sherlock Holmes fame).

"Once you have eliminated the impossible, whatever remains, however improbable, must be the truth. "

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Case Study 5 - Hubble Space Telescope

- According to the HST failure report, project decision makers did not understand the accuracy of critical measurements
- The report also noted a mindset existed to discount any independent measurements with less accuracy than the RNC
- Discounting the INC and RvNC data was, in essence, "shopping for the answer they wanted"
- A servicing mission to correct the error was flown by the Space Shuttle Endeavor in December 1993
- Cost of servicing mission was ~$1 billion USD

While it is true that, *"a perfect instrument cannot fix a bad measurement process"*, a properly designed and executed Quality Assurance (metrology) program should reveal the bad measurement process before it is placed into use and accepted as "good".

NASA TM-103443, *"The Hubble Space Telescope Optical Systems Failure Report"*, November 1990.

"What is clear from the error that occurred, and the evidence found, is that QA has a significant role to play in the avoidance of similar problems on future programs. For this to happen, however, the role of QA must be understood and seen as a positive factor by top management. *QA organizations must be adequately staffed by fully qualified individuals, and these people must be given free access to all aspects of the project, from conceptualization through final delivery. They should have clear authority to stop work on projects where there are unresolved quality issues. They should also have an independent reporting path to top management to avoid the undue influences and schedule pressures being imposed by the program or the engineering organizations.*

Further, thorough and well-cataloged documentation of all these aspects of the project must be maintained by the contractor and/or NASA for the duration of the mission. To do otherwise will make recovery of salvageable missions improbable or impossible."

Metrology for Project Development

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Considerations and Cautions

Measurements support decisions – accept, reject, rework, scrap, or even launch a space vehicle. In conformance testing, if a measurement does not support a decision, it is unnecessary.

Essential Components:

1. Design specifications must be linked to functional requirements
   a) Over specification is expensive,
   b) Under specification can be hazardous
2. Calibration ensures the accuracy of measuring equipment
   a) Links units of measurement to International standards (i.e., provides a pedigree)
3. Measurement processes must control errors that may lead to incorrect measurement-based decisions
   a) Proper selection and utilization of measuring equipment
   b) Control/mitigate other relevant sources of error in the measurement process
      – After all, a perfect instrument does not guarantee good measurement data

The more critical the decision, the more critical the data. The more critical the data, the more critical the measurement.

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Although no measurement system can provide 100% assurance of conformity, the probability of an undetected non-conformance can be greatly reduced by using appropriately designed measurement decision rules. The underlying foundation for the best decision rules is the fundamental tenets of metrology (traceability and uncertainty). Without metrological traceability and measurement uncertainty, assurance of conformity to specified requirements is greatly reduced and acceptance or rejection becomes a gamble.

Traceability and uncertainty are the fundamentals of metrology and are essential to assuring quality measurement data. This is especially true in research and testing where independent validation and minimizing wrong conclusions are important considerations. Although the fundamentals are important in design, the most crucial step is linking the functional requirements to the design tolerances. Without this link, the cost of verifying the design tolerances increases without adding value.

The key to achieving an integrated metrology program is to standardize across the entire organization, including researchers, engineers, and technicians. All elements must be working from the same "playbook" to achieve the maximum benefits, which are fewer rejected items, less costly inspection processes, higher quality products, etc. The goal of metrology is good decisions based on reliable measurement data.

Component 1:

- **Specified tolerances are not created equal.** The specification limits can affect measurement quality. Design specifications must be linked to functional requirements. Without this link, the cost of verifying the measurement requirements can increase without adding value; or worse, verification of the design performance may not be adequate.

Component 2:

Know how good the measurement can be made. The selection, care, and utilization of measuring equipment is essential to the quality of measurement data. Calibration ensures instrument accuracy, as well as establishes the link for a given measurement to the national or international standard for that unit of measure.

Component 3:

- **Know how good the measurement needs to be.** The criticality of the measurement is the same as the criticality of the decision. All measurements have some degree of doubt (uncertainty). Adequate measurement processes/procedures are necessary to control errors which could lead to incorrect decisions based on measurement data.