Metrology and the consequences of bad measurement decisions

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While serving at NASA as the Program Manager for Metrology, I was asked to create a presentation to help educate/remind NASA’s higher-level decision makers about the importance of metrology. With the help of some very smart colleagues, a presentation was created that, we hoped, captured the essence of what a decision maker needs to know. We focused the presentation on answering the three basic management questions, tailoring them to metrology: (1) How does metrology affect me? (2) What do I need to look for? (3) What are the consequences of “bad” measurement-based decisions?

Since retiring from NASA, I have had the privilege of giving this presentation at different events around the country. The Editor’s invitation to turn the presentation into an article for TEST was very timely. I hope that it is helpful to you and your organization.

**How does metrology affect me?**

Metrology, measurement data, and risk—The international definition of metrology is the "science of measurement and its application." Although this definition includes all theoretical and practical aspects of measurements, the overall objective should be to focus on what is being done with the measurement data. In the simplest terms, measurements are made to support 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).

If the data from measurements are not being used in decision-making or in establishing facts (including scientific research), the measurement is unnecessary. There is always some form of risk associated with decisions. AS9100C defines risk as, “An undesirable situation or circumstance that has both a likelihood of occurring and a potentially negative consequence." Decisions have consequences and measurement data directly affects the decision-making process. Decisions based on bad measurements are never good and sometimes they literally can be catastrophic to individuals and corporations.

For example, a poor automotive design specification could lead to failures resulting in accidents, deaths, and recalls costing billions of dollars; an improperly calibrated medical device could lead to the death of a patient; and a deficient measurement process in a forensic test could lead to the incarceration of an innocent person.

“The objective of the design and control of measurement processes is to manage the risks taken in making decisions based on measurement data.” (Emphasis added.)

**Accuracy, risk, and the metrology chain**—The highest level of the metrology...
Risk

Three 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.

Each component will be reviewed in detail. 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.

Component 1: "GoodRequirements"—A "good requirement" must be a realistic and documented link between the functional and design requirements. Functional requirements, or performance specifications, are how the product is intended to perform (e.g., "spacecraft will operate in an orbit between 400 and 650 kilometers"). Design requirements provide the realization for the functional requirements. Design requirements are the physical (e.g., size, weight, etc.) and operational (e.g., pressure, RPM, etc.) requirements of the product.

Without this link, the cost of verifying the measurement tolerances can increase without adding value, or worse, verification of the performance specification may not be adequate. The link between measurement requirements and system performance is especially important for complex systems where seemingly innocuous measurements can be critical to the overall system.

Component 1 can have the largest impact on the subsequent cost of metrology. In addition, it can have the largest negative consequences on the achievable quality, and the functionality of the end-product.

Component 1: standardizing "Good Requirements"—Although not explicit to metrology, ISO 9001 and SAE AS9100 provides a standardized approach to "Good Requirements." In section 7.3, Design and Development, ISO 9001:2008 provides requirements (7.3.2 a) and 7.3.3 c)) linking the functional and performance requirements to their specific acceptance criteria. SAE AS9100, adds to ISO9001:2008 with a requirement (7.3.1) that explicitly states inspection and test—both traditionally measurement-intensive—be an early consideration in the lifecycle planning.

Component 1: "Good Requirements," measurement risk, and end-item performance—For any given design parameter, there is a range, or set of ranges, where optimal performance is achieved. Call this the functional or "utility range." There is also a point for this parameter, where performance will begin to degrade. As you get further away from the "utility range," performance will continue to degrade until the parameter is no longer functional. An easy visualization is a hole for the installation of a bolt. If the hole is drilled too large or too small, it will lose its functionality.

Using this concept, Figure 4 illustrates the relationship between functional and design requirements and where measurement risk can easily become product risk.

CASE STUDY 1: Space Shuttle passive latch torque—The overly stringent flight torque requirements for Shuttle payload latches led to three flight waivers and an expensive redesign of a failed torque system. Certain types of payloads were attached to the Shuttle payload bay with latches that were bolted closed, including the external airlock, used for Shuttle flights to the International Space Station (Figure 5). The flight torque design requirement for this latch was 8,000–8,500 inch-pounds for a maximum flight load of 121,000 pounds.
Metrology and bad decisions (continued)

The 8,000 inch-pounds specification was based on an analysis to prevent latch gapping during maximum flight loads. There was no analysis linked to the upper limit of 8,500 inch-pounds.

The Shuttle Design Center determined a standard Class 3 torque of 10,200 inch-pounds was acceptable for the upper limit. By linking the design specifications to the complete functional requirements for the latch torque, there would not have been a need for the custom-built torque system.

Application of existing NASA or Industry standards would most likely have allowed the use of off-the-shelf torque systems.

**Component 2: “Good Equipment”—** Managing and controlling the accuracy of measuring equipment is an essential component. 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.

**Component 2: Standardizing “Good Equipment”—** In the same manner as Component 1, ISO 9001 and SAE AS9100C provide a standardized approach to “Good Equipment.” Section 7.6 of ISO 9001:2008 provides requirements for the measurements and the measuring equipment used to, “provide evidence of conformity of product to determined requirements.” Calibration is the largest part of this section.

SAE AS9100 adds to ISO 9001:2008 with requirements to maintain a register for measuring equipment, ensure suitable environmental conditions for calibration, inspection, and testing, and establish a process for recalibrating equipment requiring calibration/verification.

**CASE STUDY 2: CoxHealth incorrectly calibrated radiation treatment**—In February 2010, CoxHealth of Springfield, Missouri, announced that 76 cancer patients had received radiation doses up to 70 percent higher than the prescribed therapeutic levels. The overdosing was caused by an improper setup of the BrainLAB stereotactic radiation therapy system (Figure 6), used to treat brain tumors. The chief physicist for CoxHealth incorrectly calibrated the BrainLAB during its initial setup in 2004. The error went undetected for five years, until September 2009 when another CoxHealth physicist received training on the BrainLAB system. Despite being periodically rechecked, the problem was not discovered because the wrong measurement device was used each time, leading to the same incorrect calibration.

CoxHealth, with the help of independent experts, determined that only 76 patients were overdosed, although 152 cancer patients had received treatment with the BrainLAB. The calibration error only affected the radiation field size used to treat very small tumors.

It should be noted that there is little or no government oversight, or regulation, for medical radiation therapy. Therefore this type of problem could easily exist elsewhere.

**Component 3: “Good Measurements”—** Adequate measurement processes/procedures are necessary to control errors, which could lead to incorrect decisions concerning the acceptability of end-products. A properly calibrated instrument is only the first step in the measurement process/procedure. Other factors such as environmental, instrument resolution, operator bias, and repeatability can introduce much larger errors into the measurement result. To ensure accuracies sufficient to support quality decisions, measurement procedures must be developed which adequately account for all relevant errors in the measurement process.

**Component 3: Standardizing “Good Measurements”—** As with Component 1 and 2, ISO 9001 and SAE AS9100C provide a standardized approach to “Good Measurements.” Section 8.2.4 of ISO 9001:2008 explicitly requires verification of product requirements, at the appropriate stages of product realization, and records of conformity to acceptance criteria be maintained. Adding to these requirements, SAE AS9100C requires documentation of measurement requirements for product acceptance, including acceptance/rejection criteria, where in the sequence, records for measurements, and any specific measurement instruments.

**CASE STUDY 3: Hubble Space Telescope optics failure**—NASA launched the Hubble Space Telescope (HST) aboard the Space Shuttle Discovery on April 24, 1990 (Figure 7). However, during checkout in orbit, it became evident that the telescope could not properly focus due to a flaw in the optics.

The ensuing Hubble failure report identified the proximate cause of the flaw as an incorrect setup of the primary measuring system used for the final polishing the mirror. A contributing factor was that project decision makers, both NASA and contractor, did not understand the risks the metrology might have on the mission.

The Perkin-Elmer Corporation built the primary mirror and used three optic units to measure the mirror specification: the reflective null corrector (RNC), to final-polish the mirror; the inverse null corrector (INC), to align the RNC; and the refractive null corrector (RvNC), as a croscheck. The RNC was the most accurate of the instruments, although the other two units were adequate to detect gross errors.

The RNC was set up incorrectly for the final polishing of the mirror. The test procedures did not provide adequate testing criteria or guidance. Both the INC and the RvNC clearly showed the setup error, yet the Perkin-Elmer team discounted the data as flawed. Figure 8 provides a visual representation of the three optical measurements made in the fabrication of the HST mirror.

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representation of the three measurements. A servicing mission to correct the error was flown in December 1993 at a cost of over $1 billion.

**When more than one Component is missing**

When examining measurement-based failures, in many, if not most cases, multiple components are inadequate.

**CASE STUDY 4: Air force B-2A, Spirit of Kansas crash**—The loss of the U.S. Air Force B-2 bomber (Figure 9) in February 2008 is a dramatic example of measurement-based decisions leading to catastrophe. The proximate cause of the crash was moisture in the air data system, which introduced large errors during a field calibration of several port transducer units onboard the aircraft. The measurement procedure did not account for all sources of measurement error (Component 3), and there was also a lack of understanding regarding how the air data system affects the aircraft flight safety (Component 1).

Although the field-calibration procedure was followed, an incorrect measurement-based decision led to the loss of a $1.4 billion asset, fortunately without loss of life.

**CASE STUDY 5: BP’s Texas City Refinery explosion**—On March 23, 2005, at 1:20 p.m., the British Petroleum (BP) Texas City Refinery exploded (Figure 10), killing 15 people and injuring another 180, with resulting financial losses exceeding $2 billion. The accident occurred due to a high-level liquid alarm failure in conjunction with miscalibrated liquid-level indicator (Component 2) that allowed 7600 gallons of highly flammable liquid to be released causing the explosion. The root cause was a progressive deterioration of safety at the refinery, caused by cost-cutting, leading to a culture where workers developed procedural workarounds to compensate for deteriorating equipment (Component 3).

**Summary**

It is imperative that we “lead our leaders” to understand that ignoring good metrology can result in bad decisions, with potentially negative consequences.

Good measurements are crucial to quality products, whether they are baked goods, racecars, or spacecraft. It is even important to footballs used in the Super Bowl. As the old saying goes, “An ounce of prevention is worth a pound of cure.”

**References**


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