Metrology and the consequences of bad measurement decisions

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Metrology and the consequences of bad measurement decisions

***By* SCOTT M. MIMBS**
NASA Program Manager for Metrology (retired)
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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.*"[1] 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[2] 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."*[3] (Emphasis added.)

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

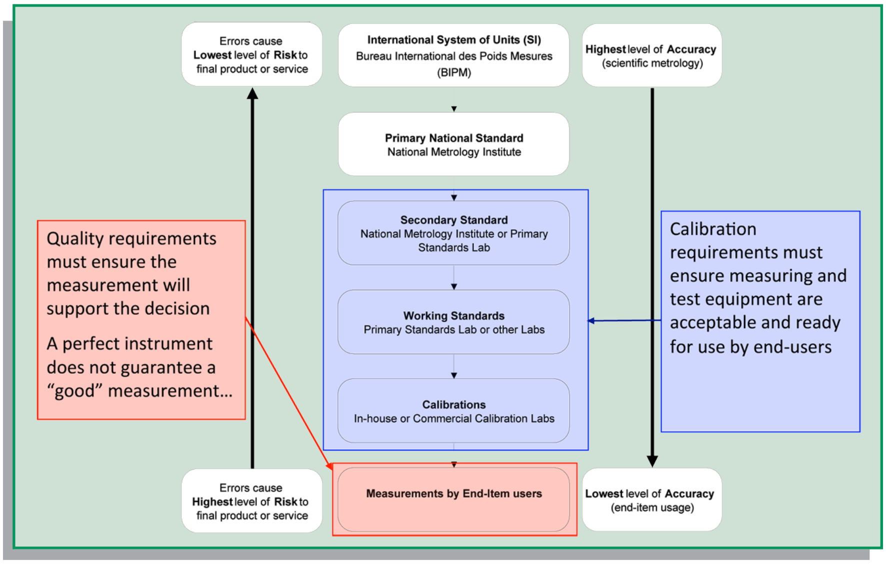


FIG. 1—Measurement accuracy and risk within the hierarchy of the metrological chain.

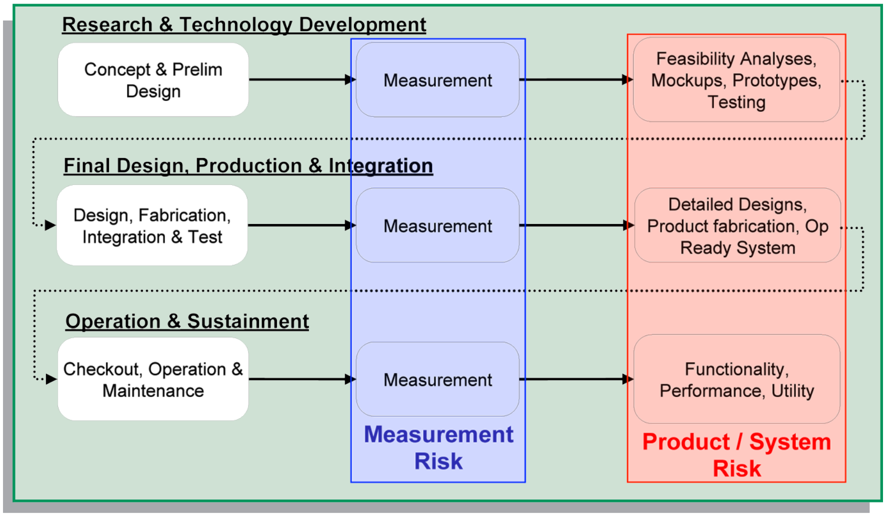
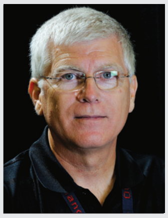


FIG. 2—Measurement risk versus product/system risk through a product lifecycle. Six of the seven phases are represented in groups of two, with the closeout phase not being represented.

Scott M. Mimbs*, currently retired, has more than 35 years of experience in aerospace and engineering. He has held such positions as aircraft mechanic (including pilot), Space Shuttle mechanical technician, Titan rocket technician, Titan Ground Support Engineer, Fluids Design Engineer in the power-generation industry, NASA Space Shuttle Quality Engineer, and Program Manager for NASA metrology. At NASA, Mimbs initiated and led development of a NASA measurement quality assurance handbook. He has authored several metrology papers, and developed training programs on measurements, uncertainty, and the associated risk within the product lifecycle. Mimbs, a U.S. Marine veteran, holds a B.S. in Mechanical Engineering from the University of Central Florida.*



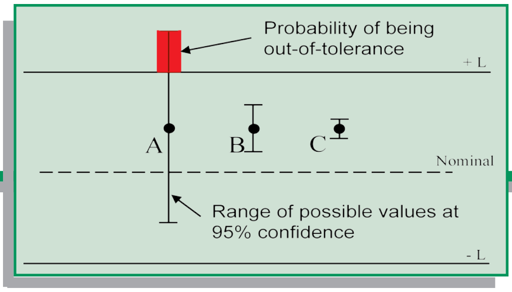


FIG. 3—Measurement uncertainty's influence on incorrect decisions.

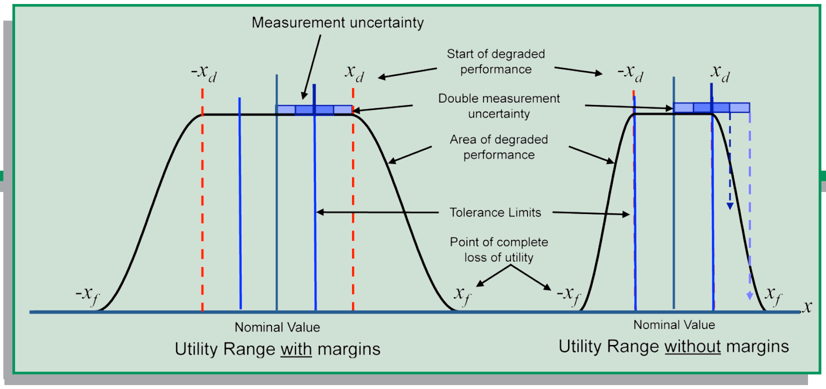


FIG. 4—How the relationship between functional and design requirements impacts measurement risk.

chain is the Bureau International des Poids Mesures (BIPM), which maintains the reference standards for the International System of Units (SI). Measurement accuracy decreases with each successive level of calibration below the BIPM. Measurements at the lowest level that support products and services, such as manufacturing and testing, normally have the lowest level of accuracy, due to the compounding of errors and uncertainty through the measurement chain. Ironically, these same lower-level measurements have the highest level of risk (i.e., potential negative consequences) to products and services.

Figure 1 illustrates the inverse nature of accuracy and risk; however, the proportionality is rarely linear. National and international calibration requirement documents are largely consistent and provide a reasonable level of quality assurance. In contrast, quality requirements, documentation, and guidance for metrology for the end-user application are either insufficient or totally lacking.

Measurement risk through a project lifecycle— The focus of measurement quality assurance is to quantify, and/or manage the "*likelihood*" of, incorrect measurement-based decisions. This requires a balance between the level of effort and the *consequences* resulting from an incorrect decision.

The *NASA Space Flight Program and Project Management Requirements* document and accompanying handbook[4,5] describes a project lifecycle in terms of seven phases that encompass concept to closeout. Although not explicitly discussed in these documents, metrology is crucial to the success of a product throughout its lifecycle.

Metrological errors, either requirements or actual measurement data, can have *negative* consequences to the overall success of a project, wherever they occur in the lifecycle.

1. Measurement-related Risk: Risk of making incorrect measurement-based decisions, based on measurement process limitations or process mistakes.

2. Product or System Risk: The negative consequence of an incorrect measurement-based decision. This type of risk may impact either the quality or performance of end-products, or increase the cost of measurements without adding value.

Figure 2 illustrates how measurement decisions can flow through the lifecycle, carrying the consequences from one phase to the next. Therefore, managing measurement-related risks during each phase of the lifecycle is an essential part of a quality system.

"*The more critical the decision, the more critical the data. The more critical the data, the more critical the measurement.*"[3]

What do I need to look for?

Incorrect decisions and their probability— Measurement uncertainty is 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. Every element within a measurement process contributes to the uncertainty of the measurement result, including characteristics of the item being tested.

Figure 3 illustrates how measurement uncertainty can contribute to incorrect decisions. Three different measurement processes, each with different uncertainty, indicate the same value. A portion of measurement **A**'s uncertainty range extends well beyond the +**L** limit, which means there is some probability that the value estimated by measurement **A** is, in reality, outside of the limit.

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., ± L),
- Knowledge acquired from previous measurements of similar items (i.e., *a priori* distribution).

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: "Good Requirements"— 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[6] and SAE AS9100C[2] provide 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 ISO 9001:2008 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[7]— 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[6] and SAE AS9100C[2] 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 recalling equipment requiring calibration/verification.

CASE STUDY 2: CoxHealth incorrectly calibrated radiation treatment[8]— 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 improperly calibrated 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[6] and SAE AS9100C[2] 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[9]— 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 of a flaw in the optics.

The ensuing Hubble failure report[9] 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 (RvNV), as a crosscheck. 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

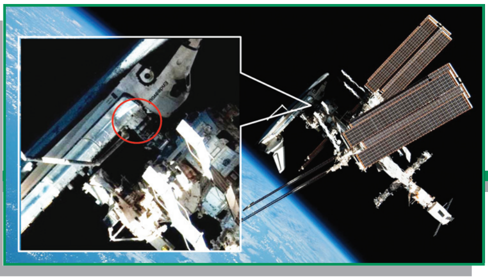


FIG. 5—The Space Shuttle Endeavour docked with the International Space Station, 23 May 2011.

FIG. 6—BrainLAB stereotactic radiation therapy system.

FIG. 7—Hubble Space Telescope floats away from the Space Shuttle Atlantis on STS-125, the final HST servicing mission, May 2009.

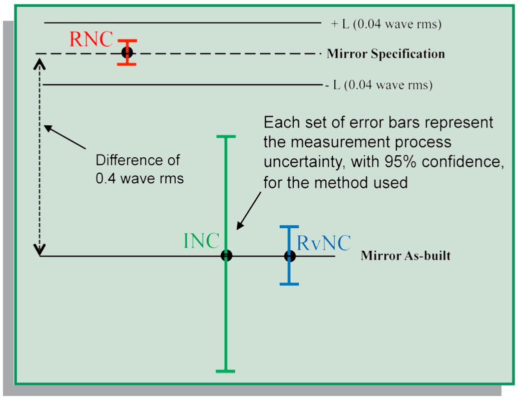


FIG. 8—A visual representation of the three optical measurements made in the fabrication of the HST mirror.

FIG. 9—The remains of the U.S. Air Force B-2A, *Spirit of Kansas*, lie next to the runway at Anderson AFB in Guam.

FIG. 10—The aftermath of the BP Refinery explosion.

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*[10]—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*[11]—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 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.*"

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2. BUSINESS OF COMPANY/ORGANIZATION:

What end products/services are produced at your company location? ***Check ONE OR MORE boxes:***

☐ **ALSO indicate the ONE letter that shows your company's PRIMARY end product.**

- ☐ **A.** Aerospace
- ☐ **B.** Military/government equipment/systems
- ☐ **C.** Research & development
- ☐ **D.** Measurement & control equipment/systems
- ☐ **E.** Consulting & engineering services
- ☐ **F.** Testing services
- ☐ **G.** Automotive
- ☐ **H.** Consumer products
- ☐ **I.** Environmental test equipment/facility mfg.
- ☐ **J.** Education & training
- ☐ **K.** Rotating machinery/power generation
- ☐ **L.** Other (please specify) ____________

About what percentage of your business is related to aerospace engineering/testing?
☐ 0% ☐ 1-33% ☐ 34-66% ☐ 67-100%

About what percentage of your business is related to automotive engineering/testing?
☐ 0% ☐ 1-33% ☐ 34-66% ☐ 67-100%

3. TYPE OF JOB:

What category covers your **PRIMARY** organizational title? ***Check ONLY ONE box:***

- ☐ **T. Mid-level technical/engineering management** (directors or assistant directors of test engineering, project managers, group leaders, section heads, department heads, supervisors, engineers, scientists, researchers, etc.
- ☐ **U. Top-level technical/engineering management** (corporate officers, owners, presidents, vice presidents, government agency heads, etc.)
- ☐ **V. Technical/professional** (engineers, scientists, researchers, etc., with **NO** managerial/supervisory authority)
- ☐ **W. Professional & supporting services** (consultants, educators, technical librarians, technical sales & marketing people, service engineers, etc.)
- ☐ **X. Top-level non-technical/non-engineering management** (corporate officers, owners, presidents, vice presidents, government agency heads, etc.)
- ☐ **Y. Technical/non-professional** (facility operators & maintainers, instrumentation specialists, etc.)
- ☐ **Z. Other** (please specify) ____________

4. JOB FUNCTIONS & RESPONSIBILITIES:

What are your job responsibilities and/or functions? ***Check ONE OR MORE boxes:***

☐ **ALSO indicate the ONE number that shows your PRIMARY job function/responsibility.**

☐ **1.**	Data acquisition & measurement	☐ Mfr.	☐ User
☐ **2.**	Dynamics test & evaluation (vibration, shock, acoustics, etc.)	☐ Mfr.	☐ User
☐ **3.**	Climatics test & evaluation (temp., humidity, etc.)	☐ Mfr.	☐ User
☐ **4.**	Research & development		
☐ **5.**	Product & package testing (prod. fragility testing, distribution dynamics, etc.)		
☐ **6.**	Reliability assurance		
☐ **7.**	Materials evaluation	☐ Mfr.	☐ User
☐ **8.**	Nondestructive testing	☐ Mfr.	☐ User
☐ **9.**	Environmental stress screening	☐ Mfr.	☐ User
☐ **10.**	Modal/structural analysis	☐ Mfr.	☐ User
☐ **11.**	Process/quality control		
☐ **12.**	Safety testing		
☐ **13.**	Regulatory compliance/verification		
☐ **14.**	Space simulation	☐ Mfr.	☐ User
☐ **15.**	Other (please specify) ____________		

5. PURCHASING INFLUENCE:

Over the next 12 months, do you plan to specify, recommend, or authorize the purchase of:

50.	Dynamic test	☐ Equipment	☐ Service
51.	Climatic test	☐ Equipment	☐ Service
52.	Product & package testing	☐ Equipment	☐ Service
53.	Biomedical test	☐ Equipment	☐ Service
54.	Automotive test	☐ Equipment	☐ Service
55.	Other (please specify) ____________		

How much spending can you specify, recommend, or authorize?
☐ None ☐ $5,000 or less ☐ $5,000 to $10,000
☐ $10,000 to $25,000 ☐ $25,000 or more