Achieving Innovation and Affordability
Through
Standardization of Materials Development and Testing

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Abstract

The successful expansion of development, innovation, and production within the aeronautics industry during the 20th century was facilitated by collaboration of government agencies with the commercial aviation companies. One of the initial products conceived from the collaboration was the ANC-5 Bulletin, first published in 1937. The ANC-5 Bulletin had intended to “standardize the requirements of various government agencies in the design of aircraft structure.”[i] Its subsequent revisions and conversion to MIL-HDBK-5 and then MMPDS-01 established and then expanded to contain “standardized mechanical property design values and other related design information for metallic materials…used in aircraft, missiles, and space vehicles.” It also includes guidance on standardization of composition, processing, and analytical methods for presentation and inclusion into the handbook. This standardization enabled an expansion of the technologies to provide efficiency and reliability to the consumers.

The national space policy shift in priority for NASA with an emphasis on transferring the travel to low earth orbit to commercial space providers highlights an opportunity and a need for the national and global space industries. The same collaboration and standardization that is documented and maintained by the industry within MIL-HDBK-5 (MMPDS-01) and MIL-HBDK-17 (nonmetallic mechanical properties) can also be exploited to standardize the thermal performance properties, processing methods, test methods, and analytical methods for use in aircraft and spacecraft design and associated propulsion systems. In addition to the definition of thermal performance description and standardization, the standardization for test methods and analysis for extreme environments (high temperature, cryogenics, deep space radiation, etc) would also be highly valuable to the industry.

It can be established that many individual programs within the government agencies have been overcome with development costs generated from these nonstandard requirements. Without industry standardization and acceptance, the programs are driven to shoulder the costs of determining design requirements, performance criteria, and then material qualification and certification. A significant investment that the industry could make to both reduce individual program development costs and schedules while expanding commercial space flight capabilities would be to invest in standardizing material performance properties for high temperature, cryogenic, and deep space environments for both metallic and nonmetallic materials.

Introduction

Development of complex integrated systems is inherently difficult. The balancing act of the systems engineer is to leverage existing technologies and capabilities while also enabling innovation into the development process to achieve a timely and affordable solution to low volume production designs. The challenge of the aerospace systems engineer is made even more difficult due to the wider range of operational environments in which aerospace systems and their materials must perform.

The Apollo paradigm of NASA provided virtually unlimited funding to develop any new capabilities that were not available to achieve the goal. Given the political climate, there was significant political will to ensure the success of the program. That paradigm did not exist during the Shuttle Program development. As a result of development cost constraints and predicted volumes of production, the philosophy of development for many of the shuttle systems and elements required development and qualification of materials to be integrated into the full scale systems tests. The result was a certification of the design through an integrated qualification, verification, and validation of the materials, components, and systems.

While understood and refined through its long operational life, the performance assessments of the Space Shuttle's technologies are still limited. Much of the materials and technologies performance data, obtained from Shuttle Operations, is limited to its specific design and performance limits. Development of new materials and capabilities have been a primary focus of funding only when necessary due to obsolescence of raw materials, vendors or out of date manufacturing techniques. This leads to investment in development simply to maintain the current operational requirements and leaves little opportunity for the development of increasing capability.

There are four underlying premises to be remembered during this presentation. First, the funding for NASA is lower than during the Apollo program era. This is not likely to change within this generation. This will serve to further constrain development costs for numerous programs. Second, the flight rate of the Space Launch System (SLS) is planned to be much smaller than the predicted flight rates of the shuttle program. Therefore, full scale system qualification, testing, and validation cannot be leveraged over many production sets – driving the cost of each production set further up. To eliminate this testing without consideration of alternate methods for qualification and system testing, will simply drive increased risk. Third, materials specifically developed for the space shuttle systems for a flight rate of 8 to 20 per year were already stretched in keeping production viable and semi-affordable for the unique applications to space launch systems. A reduced production rate will further challenge existing vendors to remain in operation causing an increase in obsolescence costs for the SLS program. Finally, the use of high temperature and cryogenic materials development is not unique to the SLS program nor is it even unique to NASA systems.

Proposed in this presentation is a new algorithm for development of materials within NASA to be partnered with other government agencies and industries. Its implementation could not only reduce the overall costs of the SLS program, but could enhance the development capabilities available to NASA, other agencies, the commercial space suppliers and customers, and international civilian space partners.

A necessary aspect of this new algorithm for aerospace material development is the segregation of the development activities into three distinct, yet interrelated and overlapping phases:

1) Development and Qualification of materials and material production processes,
2) Development, Certification, and Verification of the design,
3) Validation of the system production processes.

Through segregation of the activities, the industry can be freer to collaborate in phase 1 and more effectively spread the cost of the common aspects of the development across all members and partners in the industry. This enables/creates a better classification system for defining material technical readiness levels as they apply to various environments and supplies an improved tool to program managers and systems engineers for assessment of cost and schedule forecasts during program development.

This presentation discusses in greater detail only the development aspects included within phase 1 above. Thus, this presentation will:

- Briefly describe the history of the international materials standards
- Describe the opportunity for similar nonmetallic materials standardization for spacecraft development
- Present two case studies of materials development under the current philosophy as examples of the benefit of an alternate approach
- Recommend implementation strategies for the industry standardization

Brief History of Material Standards

Since the advent of the industrial revolution, there have been oscillating tensions between invention and production. As the construction, railroad and material refining industries developed in the 19th century, the need for standards was identified. However, "*suppliers in many industries such as construction and metallurgy objected to standard material specifications and testing procedures because they feared that strict quality controls would make customers more inclined to reject items and default on contracts*.[ii]" Quality control was costly since it was highly customized based on application. The idea that standard material testing, while perhaps excessive for some material applications, was nevertheless more cost effective if uniformly applied to all industries was difficult to sell. Therefore, this lack of standards placed the industries in routine tension with their and suppliers and customers. "*Without standard specifications, and with each mill following its own material testing procedures, buyers of industrial products were unable to ensure uniformity and frequently found reason to complain about the uneven quality of steel rails for railroads*." [iii]

Throughout the late 1800's the call for standardization of materials development and testing continued. The International Association for Testing Materials was formed and national chapters were formed. The action which resulted from the meeting in June of 1898 was to answer two critical questions:

1. *How could standards for materials contribute to industrial progress? and*
2. *How could producers and users of industrial materials reach a consensus on standards?*

From that meeting, ASTM was born. By 1901, ASTM had their first technical meeting to develop its first standard specification for "Structural Steel for Bridges".

In 1918, the Report of Secretary of Commerce included an entire section on materials testing and characterization. "The measurement and investigation of the properties of materials have in recent industrial practice become a vital necessity." In fact, the report goes on to conclude that the work done during World War I to win the war could not have been done had the "properties of materials not already been studied from a military point of view[iv]."

The development of standards for interchangeable parts and materials testing enabled Henry Ford to develop the assembly line which enabled mass production of automobiles. The success of American productivity, rapid expansion of large integrated products, and the continued reduction in costs and prices through economies of scale through the 1920's are directly related to, if not a direct function of, firstly establishing standards. This enabled multiple suppliers to compete for the work to produce component hardware and allowed the producer/integrator to choose the best value for their application. Figure 1[v] illustrates this by plotting the decreasing costs and increasing production numbers during the onset of the automobile industry.

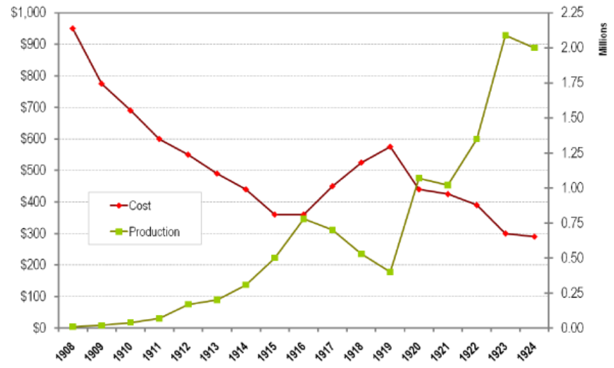

Figure 1: Ford Automobile Production and Cost from 1908-1924

While the development of standards for materials and testing continued through the 1920's and 1930's, the emerging aircraft industry recognized a more specific need. Due to the tight margins for aircraft performance previous standards for materials development and testing were insufficient for design and production of aircraft and their materials. The costs for this development were relatively high compared to the costs of other industries. Furthermore, there were complex engineering tradeoffs for the performance parameters.

The aviation industry’s first attempts at standardization originated from a combined effort from the Army, Navy, and Commerce Departments to meet the goals of the Civilian Aviation Authority, the predecessor of the Federal Aviation Administration. The resultant manual was numbered ANC-5 which was first published in 1937. After several iterations during World War II, the value of the materials development methods for metals and their prescribed testing standards began to be realized. Establishment of the standards manual enabled the industry to meet the needs of World War II and quickly increase production of war aircraft.

By the 1950’s, the manual was converted to a military handbook and renamed MIL-HDBK-5 with a specific purpose: to provide the guidelines for metallic material development and to catalogue the mechanical material properties for the existing metallic materials in production. It also served as a place to house future metal alloys developed using the handbook guidelines. Commercial Aviation genuinely benefited from these standards and competition in the marketplace allowed quick movement to the marketplace for numerous commercial aircraft producers. By the 1970’s, the number of commercial aircraft in production exceeded the military aircraft by a factor of ten. Deregulation of the aircraft industry in the early 1980’s enabled further expansion of the production capability lowering the cost and increasing the reliability. The early adoption of standards for design and production enabled a successful commercial enterprise to flourish. Government oversight for citizen safety remains in place while innovation in the aircraft industry continues.

Today, there remains interest in developing a commercial space supply chain and developing commercial markets. Early adoption of material and design standards for interfaces, expansion of existing standards for nonmetallic materials development for thermal (high temperature, reentry, and cryogenic applications) and space environment applications would provide similar benefit to the commercial spacecraft systems manufacturers as well as lower the cost of development for government funded space systems.

Discussion of the Industry Need for Nonmetallic Material Development and Testing Standards

The process for selection and use of a material for a new product or purpose follows a progression from obtaining general knowledge about the types of materials appropriate to the function to having a detailed understanding of the salient characteristics that enable the selected material to reliably perform in the delivered product. In many situations, this process occurs quickly and a solution is obtained while incurring minimal expenses. Familiar examples include alloy selection for a metal component, fasteners for bolted joints, welding filler metal, etc. These types of selections are usually low risk/high success due to the existence of useful sets of data that are readily available and we, as materials practitioners, are not required to redevelop this data each time we need to select a material for an application. In situations where a novel or nonconventional use of a material is required, the organization is driven to perform all steps of the material qualification program. This can drive program costs and delays as materials development progress may not always meet the schedule needs of program managers, requiring difficult decisions regarding risk and costs. This is a common situation for those involved in aerospace propulsion, especially with regard to understanding materials performance at extremely high and low temperature environments. In order to improve affordability, the industry would benefit as a whole if appropriate test data were available for commercial materials, much like the MMPDS is available for alloy structural properties. To enable the development of a similar document, cooperation and collaboration will be required amongst government agencies, aerospace companies, specification development organizations, academia and materials producers. This new handbook will establish standards for nonmetallic performance properties enabling all manufacturers to evaluate their products for general application qualification. It will also allow the suppliers to market them as already meeting the aerospace community’s basic requirements. Finally, it will enable manufacturers to offer their products to alternate markets and reduce obsolescence risk for materials that would otherwise be identified for narrow functionality, tested under

Figure 2: Priorities for Materials Data Handbook

- Material Performance Environments
- Standard Test Methods
- Test Data Distribution

the umbrella of a government program and the resultant data distribution being restricted due to ITAR concerns. In order to advance this proposal, development efforts should be prioritized as shown in figure 2. While the efforts are not purposefully listed sequentially, there is a logical sequence that builds upon the prior effort. It is believed that establishing the performance environments will lead to identification of base material data required to understand the material performance within that environment. Once the data requirements are identified and understood, then a specification can be developed. Once a test method, or standard is developed the data can then be obtained and reported or included in a published format or data base. Additional discussion will be provided for each effort from figure 2.

Material Performance Environments

Classification of the environments for which the materials are expected to perform is a foundational task. In the aerospace/military propulsion industry, it is anticipated that materials will be subjected to environments that include thermal, chemical, pressure and radiation exposures. Experts and practitioners in each of these areas need to classify the regimes of interest for focused discussion and planning. As an example, thermal environments could be segmented based on temperature exposure zones using current technical convention. After establishing the zones of performance, material data requirements can be identified along with evaluating the sufficiency of current testing practices. Fesmire[vi] discusses this approach for cryogenic environments along with the action that was taken to establish 2 task groups to revise an existing standard as well as create a new standard to address insufficiencies with testing cryo-insulative materials. Similar segmenting would occur for other environments and exposures along with identify and prioritizing data requirements that would benefit all concerned.

Standard Test Methods

The need for establishing standard test methods for providing basic data in support of materials development is great. Constrained budgets and development schedules have created a situation that places a greater reliance on being able to evaluate comparable data on similar materials to intelligently select candidates for in depth, program specific, evaluations. Historically, industry and agencies have developed screening tests and programs using this approach. However, the full cost has been borne by the particular organization. In many circumstances, similar testing has been performed by other agencies but that data is not available or if it is shared, it is often deemed unacceptable due to relatively minor issues with how the test was performed or data measured. It is believed that the development of consensus standards will establish and improve test methods, bringing a larger audience and expertise to development of methods, advancing the state of art as well as expose short and long term materials needs for cutting edge materials researchers, engineers and scientist. ASTM International, in their publication “A Century of Progress”, documents multiple industries that were transformed through the development of standards.

Test Data Distribution

Once these standards are developed and released for use, there will exist a need to collect, catalog, and make the data available for the industry. As previously mentioned the ANC-5 Bulletin started out as such a data distribution and has evolved and expanded into the very familiar MMPDS. The effort required to maintain and update the MMPDS as a “paper” document is substantial. An alternate approach would be to utilize an online database structure to house the data and generate reports specific to the class of material, environment, test method, etc. An example of such a database is the MAPTIS II system developed and maintained by NASA MSFC Materials & Processes. Each approach has benefits as well as short comings, however, the purpose of presenting these possible options is to illustrate the range of options and not debate the merits of any given approach. Once an agreed upon platform or report mechanism has been established, participants can submit data from current as well as historical test programs and this data would be made available to the community at large.

Case Studies of Missing Industry Standards for Spacecraft Materials

The adoption of the approach, outlined in the previous section, would have proven beneficial in numerous cases within the major programs developed by NASA and the Department of Defense. In this section, two examples of material development are discussed demonstrating the weakness of including material development within a specified program with strict cost and schedule constraints.

Ablative Insulation

Ablative insulation has been adopted for several areas of space vehicles including exterior insulation for assent, external heat shields for reentry, and internal insulation for solid rocket motors. These insulations have the advantage of having design options more damage tolerant than permanent insulation and being able to absorb and discharge heat load from the surface rather than being required to simply resist the heat transfer during operation. One disadvantage is that the raw materials used for manufacture are continually having their processes revised or become obsolete and disappear from the market requiring requalification of the insulation.

Raw materials for critical insulations are generally accepted based on measurement of physical properties. The assumption has been that a significant change is physical properties must occur before any significant change in thermal properties can occur. Variations in thermal properties were handled by limited statistical analysis and robust safety factors were used in design, trading performance for safety. Needs for advances in performance require that we abandon this practice reducing the weight of inert components to a minimum. The use of test statistics based on limited lots of material and extremely limited testing increases risks and does not allow for optimum design.

Standard methodology for assessing the capability of materials with thermal, chemical and structural design functions needs to be established. Complete statistical confidence limits for all critical properties, not just the structural requirements, need to be agreed upon and the performance data for the materials must be available. Ideally, the cost for developing this data could be shared between interested projects but we have to put a halt to the practice of redundant testing between projects. This will be critical with the cost control measures we will all be facing for the foreseeable future.

Corrosion Preventative Coatings

Corrosion is a perennial problem for space launch systems. With the minimization of structural components and pressure vessels, the wide variety of materials coupled together, FOD issues with corrosion products and the often aggressive environments of launch locations, space hardware and ground support equipment must be protected to assure mission success.

The Kennedy Space Center materials laboratory established a corrosion test site on their beach to qualify steel coatings for launch pad structures. By participating in comparative testing with other sites they determined that the rate of attack on metals at this location is one of the highest in the world. Over the past forty years they have tested almost every commercial coating system for steel protection and have a complete database on performance. If anyone begins a project with steel at the Center they have a large list of coatings to choose for corrosion prevention and then can down select from this proven list for further testing in hardware specific environments.

The data set collected for this project illustrates several of the problems that come from the lack of a common industry repository:

1. Data is not “certified” for general use. Each individual project continues to spend money and time to replicate the data, or is forced to use data obtained by inferior methods.

2. Not all materials of interest are covered. Testing of aluminum corrosion prevention systems and seal coats for organic substrates has been limited and is not systematic like the testing of steel coatings.

3. Transmission of the data to interested users is inhibited. There is no central location for material information and so great information remains unused.

4. Appropriate use of the data is not developed and explained. Failure to document acceptable interpretation guidelines for the industry can allow mistakes and abuses.

Summary and Recommendations

It has been shown that the cooperation, collaboration and generation of consensus for materials development and testing standards provided significant benefit in the development and expansion of industrial robustness, including automotive, locomotive, aviation, and electronics. The space industry benefited from this standardization during the formative and maturation years of NASA. It has also been shown that there exists a similar need for standardization and collaboration to facilitate innovation and growth of the space industry suppliers.

Not surprisingly, there is a similar resistance to standards today regarding military, civilian, and commercial spacecraft standardization. However, history has shown that the early adoption by industry of standards for interchangeable parts, materials testing, and component validation methods has enabled faster and more efficient development of the technology and the market. The acknowledgment by the electronics industry for the need to develop its own standards enabled it to provide more competitors and reduce costs to the customers while improving reliability of performance.

There are three primary recommendations of this presentation to the aerospace industry at large.

1) Establish priority of standards for needed environmentally driven performance properties for nonmetallic materials.
2) Establish priority to standardize the development and testing for spacecraft materials for environments which are not already characterized and standardized by industry.
    a. Establish a charter with ASTM and AIAA to facilitate industry collaboration to identify and prioritize standards development for materials testing and performance requirements.
3) Develop a material handbook similar to MIL-HDBK-5 (MMPDS) and -17 to utilize the standards and publish volumes of material property data books for true A-basis performance properties. Examples include:
    a. Material performance properties at temperature.
    b. Nonmetallic bond adhesion testing methods and properties.
    c. Thermal insulation and ablative performance test methods and properties.
4) Establish priority for developing subscale test methods for qualification and validation of these materials to be continually compared to actual hardware performance.

These recommendations will foster the innovation needed to continue development of the aerospace industry while increasing affordability of space access to the commercial, civilian, and military sectors.

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[i] AFWAL-TR-84-4123 “An Overview of the MIL-HDBK-5 Program”

[ii] A S T M 1898-1998 A Century of Progress http://www.astm.org/IMAGES03/Century_of_Progress.pdf

[iii] A S T M 1898-1998 A Century of Progress http://www.astm.org/IMAGES03/Century_of_Progress.pdf

[iv] Department of Commerce, Report of the Secretary of Commerce, 1918, page 13

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[v] Rodrigue, J., Comtois, C. Slack, B. The Geography of Transport Systems, May 2009, http://people.hofstra.edu/geotrans/eng/ch2en/conc2en/fordcostproduction19081924.html

[vi] Fesmire, J., Standards for Cryogenic Thermal Insulation Systems; Cold Facts, Summer 2011, Vol. 27, No. 3, page 9