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Introduction

(Courtesy of XKCD, www.xkcd.com)

1.1 Background

Standards, including procedures, rules, codes, regulations, and jurisdictional requirements, play an important role in the engineering world. They furnish a means of ensuring consistent designs, quality, and operating characteristics, with adequate reliability, safe operation of components, and well-defined configurations. This book details their development, applications, limitations, and benefits to give the user, specifier, and standard writer a proper perspective of their importance, usefulness, and limitations, to promote their effective use and to improve the quality of future standards. While focusing on standards

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themselves, it also provides a brief introduction to the field of conformity assessment, by which compliance with standards is assured and verified.

This book does not attempt to address legal, commercial, or other nonengineering aspects of standards.

Rules, procedures, and standards can be developed by a single individual within or with authority over an organization or operation, by a subgroup of an organization, by the organization as a whole, or by other groups with a common interest.

The reader will find that common usage of terminology related to standards is inconsistent in the literature. Accordingly, the following definitions are provided and will be used in this book:

Rule: A single specific requirement that must be met. Many types of such requirements exist, such as requirements to perform actions, for how to perform actions, for results that must be achieved, for specific properties or characteristics that must be attained, and for dimensions that must be met.

Procedure: A set of rules regarding how a task or function is performed. Procedures are used to ensure consistency of results and to promote efficiency.

Standard: A set of rules and/or procedures recognized as authoritative in a particular area of interest.

One definition of standards given by the American Society of Mechanical Engineers (ASME) is as follows:

> *A set of technical definitions, instructions, rules, guidelines, or characteristics set forth to provide consistent and comparable results, including:*
>
> - *Items manufactured uniformly, providing for interchangeability.*
> - *Tests and analyses conducted reliably, minimizing the uncertainty of the results.*
> - *Facilities designed and constructed for safe operation.*

It is of interest to note that by custom, some standards are called codes.

The effectiveness of standards in conducting business is best explained by the American Society for Testing and Materials (ASTM) in a 1991 report:

> *Standards are the vehicle of communication for producers and users. They serve as a common language, defining quality and establishing safety criteria. Costs are lower if procedures are standardized; training is also simplified.*

While the importance of standards is well recognized and while there is what might be called the “legal” definition, as provided in the National

Technology Transfer and Advancement Act (NTTAA) (see below), even the National Institute of Standards and Technology, a part of the US Department of Commerce and that part of the US Government most directly charged with standards development, coordination, and quality, approaches the definition of standards by offering multiple explanations from different sources.

The following text provides the definition from the NTTAA of a standard (clearly covering more than just the engineering standards that are the subject of this book):

> *DEFINITION OF TECHNICAL STANDARDS – As used in this subsection, the term 'technical standards' means performance-based or design-specific technical specifications and related management systems practices.*

The Office of Management and Budget OMB Circular A-119 further amplifies upon this:

(a) The term "standard," or "technical standard," (hereinafter "standard") as cited in the NTTAA, includes all of the following:

i. common and repeated use of rules, conditions, guidelines or characteristics for products or related processes and production methods, and related management systems practices;

ii. the definition of terms; classification of components; delineation of procedures; specification of dimensions, materials, performance, designs, or operations; measurement of quality and quantity in describing materials, processes, products, systems, services, or practices; test methods and sampling procedures; formats for information and communication exchange; or descriptions of fit and measurements of size or strength; and

iii. terminology, symbols, packaging, marking or labeling requirements as they apply to a product, process, or production method.

(b) The term "standard" does not include the following:

i. professional standards of personal conduct; or

ii. institutional codes of ethics.

(c) "Government-unique standard" is a standard developed by and for use by the Federal government in its regulations, procurements, or other program areas specifically for government use (i.e., it is not generally used by the private sector unless required by regulation, procurement, or program participation). The standard was not developed as a voluntary consensus standard as described in Sections d and e.

(d) "Voluntary consensus standard" is a type of standard developed or adopted by voluntary consensus standards bodies, through the use of a voluntary consensus standards development process as described in Chapter 3. These bodies often have intellectual property rights (IPR) policies that include provisions requiring that owners of relevant patented technology incorporated into a standard make that intellectual property available to implementers of the standard on nondiscriminatory and royalty-free or reasonable royalty terms (and to bind subsequent owners of standards essential patents to the same terms). In order to qualify as a "voluntary consensus standard" for the purposes of this Circular, a standard that includes patented technology needs to be governed by such policies, which should be easily accessible, set out clear rules governing the disclosure and licensing of the relevant intellectual property, and take into account the interests of all stakeholders, including the IPR holders and those seeking to implement the standard.

(e) "Voluntary consensus standards body" is a type of association, organization, or technical society that plans, develops, establishes, or coordinates voluntary consensus standards using a voluntary consensus standards development process that includes the following attributes or elements:

i. Openness: *The procedures or processes used are open to interested parties. Such parties are provided meaningful opportunities to participate in standards development on a non-discriminatory basis. The procedures or processes for participating in standards development and for developing the standard are transparent.*

ii. Balance: *The standards development process should be balanced. Specifically, there should be meaningful involvement from a broad range of parties, with no single interest dominating the decision-making.*

iii. Due process: *Due process shall include documented and publically available policies and procedures, adequate notice of meetings and standards development, sufficient time to review drafts and prepare views and objections, access to views and objections of other participants, and a fair and impartial process for resolving conflicting views.*

iv. Appeals process: *An appeals process shall be available for the impartial handling of procedural appeals.*

v. Consensus: *Consensus is defined as general agreement, but not necessarily unanimity. During the development*

> *of consensus, comments and objections are considered using fair, impartial, open, and transparent processes.*

Some definitions of standards include only those standards with which compliance is voluntary, referring to mandatory standards as technical regulations or by other names. Because many voluntary consensus standards have been incorporated into laws and regulations, confusing the meaning of voluntary, this book does not make this distinction.

Other definitions require consensus, or establishment or approval by a recognized body. These distinctions are often significant, but would exclude such important documents as the standards of the American Boiler Manufacturers Association and the Tubular Exchanger Manufacturers Association (TEMA) as well as certain standards developed by private corporations but well recognized as authoritative (An example of the latter is a series of material and other standards developed by the AO Smith Company and used by them and other companies in the construction of many thousands of pressure vessels beginning in the 1940s and continuing into the 1960s.).

Conformity Assessment: Processes used to verify the compliance of a product, service, person, process or system to either a standard or a regulation (e.g., testing, certification, inspection).

1.2 Procedures and Rules

Procedures and rules are usually developed within an organization to establish operating methods that will lead to consistent desired results. They include such items as drawing and calculation formats, dimensional standards, checking sequences, and hierarchical progression of a task within the organization. The applications of procedures and rules form the operating norm of an organization, and they differ from one organization to another. Hence, the procedures and rules used for the design and manufacturing of the same product at two companies may differ substantially even though the end product is the same.

One company manufacturing a light switch, for example, might bring in large quantities of component parts from suppliers and depend on a high level of automation and process control to ensure a consistent product. A competitor may choose to manufacture all parts in-house, use hand assembly, and control product quality through a rigorous inspection process. The final products may be practically indistinguishable in spite of procedures that have little in common.

Procedures and rules, by their general nature, are limited in scope to an individual task or component within an organization such as a how to manufacture and assemble a gear box, or a methodology for project progression within the organization. A separate procedure then details the next step, whether packaging the gearbox for shipping or assembling it into an automobile. Procedures and rules also can be updated or revised frequently to fit the changing requirements of the organization.

1.3 Standards

1.3.1 History and Purpose of Standards

Any discussion of the purpose of standards is nearly impossible without a concurrent look at their history. The nature of society, the natural human resistance to accept constraints, the thought and effort needed to develop standards, and general inertia have dictated that they not be produced and imposed without a reason. As society has become more complex, the need for standards has occurred more frequently, and the increasing sophistication of society has been mirrored by an increasing sophistication in the standards developed.

While there is sometimes resistance to their development and implementation, the term "Voluntary Consensus Standard" refers to the benefits that standards provide to business and to society in general, and it is applicable to a vast number of standards developed for a wide range of reasons and applications. People, companies, and other organizations now generally recognize that standards can have a favorable effect on their lives, the quality of their work, and their business opportunities. Companies and individuals are therefore willing to apply resources, to give up a certain amount of freedom, to admit that they may function better and be more successful operating as a part of a larger whole than with complete independence, and to share a certain amount of what may be proprietary knowledge. These things are given up in the interest of a safer home or society, efficiency in design, improved business opportunities, a certain amount legal protection in case of product failure, and other benefits.

While standards can be categorized in a number of ways, for purposes of this chapter we will consider the following categorization on the basis of benefits: safety and reliability, quality, uniformity, cost reduction, increased flexibility, variety control, promotion of business, and generally helping society to function. Most standards provide more than one of these benefits.

1.3.2 A Few Examples of Standards throughout the Ages

One of the first known, and very rudimentary, standards, known as the Code of Hammurabi, was developed approximately 4000 years ago, apparently to ensure fairness in the kingdom of Babylonia. In this case, the standard was promulgated by the king and enshrined in laws. Many of the laws included in this document related to crimes, torts, marriage, and general legal obligations. The Code of Hammurabi may be most well-known for its "an eye for an eye and a tooth for a tooth" approach to justice, but portions of this document also provide very basic performance standards for construction of buildings and boats. That is, the document specified what must be achieved. Walls must not fall down, and boats must be tight.

It appears that there was a problem with the quality of workmanship in the kingdom of Babylonia, but the solution had no specific criteria for how things were to be constructed. Rather, the standard that was put in place simply required that the construction be good, and if it failed, specified the penalty. This approach, using what are referred to as performance standards, typically provides little or no guidance as to how the requirements are to be met, simply specifying the required result. A performance standard is in some cases the easiest to write, and it allows the maximum level of flexibility to the implementer, since any means of accomplishing the end is sufficient. This particular standard promoted a fair and just – if somewhat brutal – society. It should also be noted that this standard dealt with very limited aspects of the products, and including in a performance standard all the details that are needed to ensure a successful product can be challenging.

Another step on the way to modern standards came about as a result of a massive fire that burned most of the city of London in 1666. The Rebuilding London Acts, promulgated by the Parliament of England over the following several years, are precursors of current building and safety codes. The specific motivation of these acts was first to ensure safety and stability in society, and they did so by widening streets and by specifying brick construction, so as to prevent recurrence of the disastrous fire.

Compared to the Code of Hammurabi, these Acts are quite prescriptive, specifying street widths, brick construction, thickness of walls (in terms of bricks), story heights and maximum heights of houses, and requirements for roof drainage. The effect of these and other associated requirements was to improve access, provide fire breaks in case another fire got started, and reduce the probability of its spread by replacing what was previously almost entirely wooden construction largely with bricks. Safety was enhanced, and it is to be expected that quality of life may also have been improved.

With the advent of the industrial revolution, other benefits of standards became obvious. As society developed the ability to produce products in quantity and, as machine tools were developed, the interchangeability of components became desirable. In the mid-1800s, for example, the British Standard Whitworth thread system was developed to allow for interchangeability of threaded parts.

Throughout the 1800s, there were many boiler explosions [6]. While mourned, these seemed to be somewhat accepted as a cost of having boilers, which were providing benefits to society in the forms of more efficient transportation, working efficiency, and heating. The explosion of the boiler in a shoe factory in Brockton, MA, in 1905, which resulted in close to 60 deaths, and another shoe factory boiler explosion in Lynn, MA, the following year led to a greater concern with industrial safety. In 1907, the Massachusetts legislature passed the Massachusetts Boiler Law. This was followed by the first ASME Boiler Code in 1914.

The years between then and now have seen a proliferation of standards. These include the further development of the ASME Boiler Code (later to become the Boiler and Pressure Vessel Code (BPVC)) with sections on various types of pressure vessels, materials, welding, inspection, etc., and piping codes, lifting devices standards, electrical codes, and more. More recent work includes standards in the fields of energy efficiency, electronic components, software development, assessment of risk, and conformity assessment, and every time a new technology arises, it seems that standards for its application are not far off.

1.3.3 Classification

Engineering standards are sets of rules and procedures developed, documented, approved by general consensus, and configuration managed to assure the adequacy of a given product, methodology, or operation. Standards are normally developed in committees by people who have experience in a particular field of endeavor and who have an interest in the outcome that the standard is intended to ensure.

There are many ways of looking at and classifying standards. These include

1. performance versus design (descriptive, or prescriptive)
2. mandatory versus voluntary
3. purpose
4. intended user group
5. the way they were developed.

The International Organization for Standardization (ISO) and the International Electrotechnical Commission (IEC) Guide 2, Standardization and related activities – General vocabulary, offers a number of ways of looking at standards in addition to providing vocabulary such as the following:

> 1. *Level of standardization, which is a generally geopolitical classification based on the coverage of the standard.*
> 2. *Aims of standardization, addressing issues from fitness for purpose and safety, through protection of the environment.*
> 3. *Category of the standard, such as technical specifications (e.g., ASME B16.5), codes of practice (e.g., ASME Boiler and Pressure Vessel Code), and regulations (e.g., OSHA and DOT regulations).*
> 4. *Type of standard, from terminology to testing, product, process, service, interface, and data to be provided.*

With many possible approaches, we will first look at standards as they fit into the following three categories:

1. Limited consensus
2. General consensus (also referred to as Voluntary Consensus Standards)
3. Governmental action.

1.3.4 Limited Consensus Standards

Limited consensus standards, by their nature, are developed by experts in a given organization and then made available to the organization for its guidance. Prime examples are some internal company standards for work hardened, heavy wall, stainless steel tubing for ultrahigh pressure applications, and a number of company standards for compression fittings. Trade groups such as the Heat Exchange Institute (HEI) and the TEMA have developed standards specific to their lines of work. While keeping a greater level of control than would be allowed them if their standards were subject to the American National Standards Institute (ANSI) process and requirements, these organizations reap for the company or trade group as well as for society many of the same benefits that they would achieve by following that more public process.

1.3.5 Voluntary Consensus Standards (VCS)

There is a great difference between the procedures involved in writing limited consensus and voluntary consensus standards. Voluntary consensus standards are developed by experts to serve the need of a given industry with substantial input from other interested parties, and potentially from the public. An example of such standard is the ASME's BPVC. The BPVC contains numerous standards (referred to in the BPVC as sections, divisions, and parts) as will be explained later. The development of each of these standards follows a unique process by which experts from differing interest groups (designers, fabricators, users, and insurers of pressure vessels, and perhaps others) collaborate in writing the rules in order to arrive through a balanced consensus process at a product that is not dominated by any one particular interest group. The resulting standard becomes acceptable to a wide range of interested parties within the industry since all entities were involved in developing it. These standards have been so successful and have garnered such a high level of respect that they are often cited in laws and regulations (a process referred to as "Incorporation by Reference" or "IBR") making them a part of governmental standards, discussed below, and addressed in more detail in Chapter 2.

Typically, in the United States, the organizations developing such standards follow a process certified by the ANSI and note that fact by including "ANSI" in the document name, identifying number, or on their cover or title page. International standards typically follow a similar process. Because of the integrity of the process and the quality of the resulting product, the standards from many

US standards developers are commonly accepted, or even demanded, overseas, and many of the international standards are likewise accepted or required in the United States, both by industry and by jurisdictions.

1.3.6 Governmental Standards

Both jurisdictional and nonjurisdictional standards are produced by a wide range of governmental organizations. Jurisdictional standards are those promulgated by governmental agencies to implement laws, ordinances, and other legal documents, and carrying with them legal enforceability by fines, injunctions, imprisonment, or other sanctions. Nonjurisdictional governmental standards are developed by governmental entities for their own use, whether for internal purposes or for contracted or other outside work.

1.3.6.1 Jurisdictional Standards

Jurisdictional standards are normally produced by the enforcing jurisdiction, which has legal authority for their enforcement. Jurisdictions include the US (federal) Government, states, cities, and municipalities, and their defined sub-authorities such as federal agencies, building departments, and districts, with the authority to enforce the law, regulation, or other standard. Standards such as those published by the US Occupational Safety and Hazard Administration (OSHA) are intended to assure safety in the workplace by providing generally prescriptive requirements for the design and operation of various pieces of equipment and products, or for processes performed, within a wide range of occupations. Many standards published by local jurisdictions are intended to do the same.

1.3.6.2 Nonjurisdictional Governmental Standards

These standards are typically produced by governmental entities to promote safe, predictable, and efficient performance of their work. Some of these will be implementing standards for jurisdictional standards. An example of this type of standard would be an internal standard of a large governmental agency providing requirements enforced internally and used to ensure compliance with a jurisdictional standard enforced by another agency such as the Department of Transportation (DOT). For example, it might detail the design process or other specific requirements related to procurement of pressure vessels to be used by the National Science Foundation on research aircraft. Their application could be either internal or through its application on an external procurement.

Another category of nonjurisdictional governmental standards might be used within a National Aeronautics and Space Administration (NASA) Center to ensure reliable and consistent designs for instrumentation on spacecraft. Such a standard could define the design flow, component ranges, and reliability requirements needed for a successful mission. It helps with the implementation of the mission, but is not an implementation of any other governmental mandate such as a regulation from OSHA, DOT, Department of Energy (DOE), or the Environmental Protection Agency (EPA).

1.4 Applicability of Standards

Standards form the backbone for many engineering processes by providing the following requirements and guidelines:

1. Practical limits for operating conditions to improve safety and reliability
2. Permissible materials of construction, performance criteria, and material properties
3. Safe design rules
4. Construction details
5. Available methodologies for inspection and testing
6. Safe operating parameters
7. Process control
8. Practical limits for operating conditions to improve safety and reliability.

Standards often take theoretical material and make modifications to permit its application in a practical way. Theoretical equations for a variety of engineering applications are found in textbooks. An example is the equation for circumferential stress in a thin cylindrical shell ($R/T < 10$), given by

$$S = \frac{PR}{T} \tag{1.1}$$

where S is stress, P is internal pressure, R is inside radius, and T is shell thickness. Another example is the elastic buckling of a column given by the equation

$$S_c = \frac{\pi^2 E}{(L/r)^2} \tag{1.2}$$

where S_c is the critical compressive buckling stress, E is the modulus of elasticity, L is the effective length, and r is the radius of gyration of the column.

While representing a classical analysis and being theoretically correct, both of these equations have limitations that could lead to unsafe designs if not used properly. Accordingly, standards have been written to promote the effective application of engineering principles to everyday life, establishing limits and modifying theoretical equations in order to aid engineers in developing safe designs.

Thus for easy, practical, everyday usage, the ASME Boiler and Pressure Vessel Code [3] modifies Eq. (1.1) to the following:

$$t = \frac{PR}{SE - 0.6P} \tag{1.3}$$

In this equation, t is the required minimum wall thickness, and P is pressure. R is the inside radius and the denominator is an approximation of the Lame's equation for thick shells. S includes a design factor (currently 3.5 in Section VIII, Division 1 of the BPVC) used to account for material properties, including a reasonable design life, to account for unknowns such as a certain amount of out-of-roundness (limited by the Code to 1%), residual stresses, possible local material variability below the specified material properties (from another part of the Code), and other aspects of final construction. Finally, the joint efficiency E provides an additional factor based on the level of nondestructive evaluation performed on welds, and allowing for a certain amount of weld defects.

Similarly, the Steel Construction Manual from the American Institute of Steel Construction (AISC) [1] reformats Eq. (1.2) in order to prevent S_c from getting higher than the yield stress of the material. The reformatting also allows for a certain amount of material variation, lack of straightness of the column and other variation in form, and actual installation characteristics, with, again, a design factor to ensure that the column does not fail just as it reaches its design load. Equation (1.2) is thus modified to the following format

$$F_a = F_n/1.67 \tag{1.4}$$

where

$$F_n = (0.658^{\lambda_c^2})(F_y) \quad \text{when } \lambda_c \leq 1.5 \text{ or } \tfrac{L}{r} \leq 4.71\sqrt{E/F_y}$$

$$F_n = 0.877\, F_y/\lambda_c^2 \quad \text{when } \lambda_c > 1.5 \text{ or } \tfrac{L}{r} \leq 4.71\sqrt{E/F_y}$$

$$\lambda_c^2 = F_y/F_e$$

$$F_c = \pi^2 E/(L/r)^2$$

and

F_y = yield stress

E = elastic modulus

F_a = allowable compressive stress

L = effective length

r = radius of gyration

Often, one of the most important aspects of an engineering standard is the application of a design factor, variously referred to as "design factor," "safety factor," and "ignorance factor."

1.4.1 Permissible Materials of Construction, Performance Criteria, and Material Data

Engineers have access to thousands of materials of construction varying from metallics such as steel, aluminum, copper, and titanium to nonmetallics such as concrete, wood, plastic, and composites. Numerous subcategories of these materials are available with their own properties, limitations, and advantages. Steel, for example, has many product forms such as structural steel shapes, rods, plates, forgings, tubes, and castings, and a myriad of alloys designed to perform under different types of loads and over different temperature ranges.

Engineers rely on national and international material standards to provide them data such as the chemistry, tensile and yield strength, and other physical properties for use in design of components and systems.

ASTM standards provide a wealth of material characteristics at room temperature for thousands of metallic and nonmetallic materials. In addition, ASME provides material data for several thousand metallic materials at elevated temperatures and testing requirements for low-temperature operations.

1.4.2 Safe Design Rules

Engineers must often rely on national and international standards for obtaining appropriate material properties and safety factors for their designs. Such standards establish factors of safety based on experience, practical limits, and understanding of material characteristics such as endurance limits, creep, and fatigue crack growth rates. Most engineers do not have the means of establishing such factors on their own. A case in point is the ASME BPVC, Section VIII, Division 1 allowable stress, referred to in the discussion above. It uses four criteria for establishing the allowable tensile stress. This allowable stress is taken as the smaller of the values obtained from 2/3 times the yield stress, 0.286 times the tensile strength, stress that causes rupture at 100,000 h, or stress at a creep rate of 0.01% in 1000 h. Division 1 also uses a factor of safety of 3 for lateral buckling of cylindrical shells and a factor of safety of 10 for the axial compression of cylindrical shells. Determination of these values is based on a significant amount of underlying work experience, including assumptions used in the derivation of the basic theoretical equations, practical limits, and life calculations. While not obvious in the simple tables providing allowable stress values, significant effort goes into determination of the criteria just noted, including the obvious stress failure criteria, and also fatigue life, comparison to success of other codes, and actual success in service.

1.4.3 Construction Details

Details of construction of intricate components such as column-to-beam connections, heat exchangers, and concrete slab reinforcement are provided in established standards. The details in these standards are based on years of practical experience that are in this way made accessible to the engineer. However, even these standards change sometimes based on new information. A case in point is the considerable changes made in steel construction joint details and other design requirements in construction standards in the years following the Sylmar (1971) and the Northridge (1994) earthquakes in the Los Angeles area.

1.4.4 Available Methodologies for Inspection and Testing

Although some industries depend almost entirely on process control, many components need to be inspected during manufacturing to assure good quality. This is especially true if the manufacturing does not involve mass production. For metallic structures, inspection methods such as radiography, ultrasonic testing, and magnetic particle examination are among those available. These methods are covered by standards produced by ASTM and ASME that provide detailed requirements for the engineer or technician performing the inspection, ensuring consistency in the performance and the results of inspections, and thereby in the final product.

1.4.5 Safe Operating Parameters

Certain precautions must be followed in order to operate equipment and machinery in a safe manner. Standards are available to assist the engineer and operator in their jobs. Some of these are industry standards put in place to protect employees and to reduce employer liability, while others are jurisdictional standards such as the OSHA regulations.

1.4.6 Conformity Assessment

With standards applicable to all fields, and compliance with them critical to guarantee society the benefits that they provide, a whole field has arisen to verify compliance. This field, referred to as *conformity assessment*, is defined as those processes used to verify the compliance of a product, service, person, process or system to either a standard or a regulation (e.g., testing, certification, inspection).

Conformity assessment has its own set of standards, and while manufacturing, service, and other organizations devote significant resources to maintaining compliance, there is also a cadre of organizations (ANSI, ASME, ISO, UL, etc.) that make a business of certifying company processes and compliance. A more detailed discussion of this field is provided in Chapter 8.

1.5 Summary

Standards have existed throughout much of recorded history. While the first ones were fairly rudimentary, with time they have become more sophisticated, more complete, and more pervasive. As society has become more complex and as technology has advanced, they have also become more necessary for the smooth functioning of society. It can only be expected that more standards will continue to be developed, and that they will become more interlinked. A basic understanding of standards will be useful in any technical field.