Appendix I – Engineering Design, Technology, and the Applications of Science in the Next Generation Science Standards

One of the most important messages of the *Next Generation Science Standards* for teachers, parents, and students is that science is profoundly important in addressing the problems we face at the beginning of the 21st century. The purpose of science education is to equip our students with the knowledge and skills essential for addressing society's needs, such as the growing demand for pollution-free energy, to prevent and cure disease, to feed Earth's growing population, and maintain supplies of clean water. Just as these grand challenges inspire today's scientists and engineers, the intent of these new standards is to motivate all students to fully engage in the very active practices of science and engineering.

The idea of integrating technology and engineering into science standards is not new. Chapters on the nature of technology and the human-built world were included in *Science for All Americans* (AAAS 1989) and *Benchmarks for Science Literacy* (AAAS 1993, 2008), and standards for "Science and Technology" were included for all grade spans in the *National Science Education Standards* (NRC 1996). Despite these early efforts, however, engineering and technology have not received the same level of attention in science curricula, assessments, or the education of new science teachers as have the traditional science disciplines. What is different in *Next Generation Science Standards* (NGSS) is a commitment to fully integrate engineering design, technology, and mathematics into the structure of science education by raising engineering design to the same level as scientific inquiry when teaching science disciplines at all levels, from kindergarten to grade 12. This new integrated approach to science education is sometimes referred to by the acronym STEM.

It is important to add at the outset, however, that including core concepts related to engineering design and technology does not imply that schools are expected to develop separate courses in these subjects. It is essential that these concepts are closely integrated with study in science disciplines at all grade levels. To that end, these standards include numerous examples of linkages with other disciplines. Nor is the intention to discourage schools from offering courses at the middle and high school level that focus on engineering design and technology. Such courses can include and go beyond these standards, and provide additional information on the wide variety of career opportunities afforded to people who have a solid STEM background.

The limited purpose of these standards is only to emphasize what all students are expected to know and be able to do as a result of Pre-K-12 education. This latest set of standards includes an increased emphasis on engineering and technology for the reasons discussed below.

Rationale

The rationale for this increased emphasis on engineering and technology rests on two arguments from *A Framework for K-12 Science Education: Practices, Core Ideas, and Crosscutting Concepts* (NRC 2012). One argument is inspirational; the other is practical. From an inspirational standpoint the *Framework* emphasizes the importance of technology and engineering in solving meaningful problems. From a practical standpoint the *Framework* notes that engineering and technology provide opportunities for students to deepen their understanding of science by applying their developing scientific knowledge in real-world contexts. Both arguments converge on the powerful idea that by integrating technology and engineering design into science curriculum, teachers can enable their students to use what they learn in their everyday lives.

Although the primary rationale for including engineering practices is not to recruit more engineers, the explicit inclusion of engineering and technology opens the door to curriculum materials that communicate to students the broad spectrum of career opportunities that includes not only scientists but also technicians, engineers, and other careers that require knowledge and abilities in the STEM fields.

One of the problems of prior standards documents has been the lack of clear and consistent definition of the terms science, engineering, and technology. A major contribution of the *Framework* has been to define these terms as follows:

> *In the K–12 context, "science" is generally taken to mean the traditional natural sciences: physics, chemistry, biology, and (more recently) earth, space, and environmental sciences. . . . We use the term "engineering" in a very broad sense to mean any engagement in a systematic practice of design to achieve solutions to particular human problems. Likewise, we broadly use the term "technology" to include all types of human-made systems and processes—not in the limited sense often used in schools that equates technology with modern computational and communications devices. Technologies result when engineers apply their understanding of the natural world and of human behavior to design ways to satisfy human needs and wants.* (NRC 2012, p. 11-12)

The *Framework*'s definitions address two common misconceptions. The first is that engineering is not just applied science. Although the practices of engineering have much in common with the practices of science, and engineers do apply their understanding of natural science in their work, engineering is a series of distinct fields (e.g. electrical, mechanical, and environmental engineering), each with its own goals, practices, and core concepts. The second is that technology does not just refer to computers or other electronic devices; but rather applies to all of the ways that people have modified the natural world to meet their basic needs and to realize their dreams.

The writers of the NGSS acknowledge that some of the terms in this document have different meanings in different disciplines. For example, in the pharmaceutical industry the term "engineering" is reserved for the process of scaling up production of a new medicine to industrial levels. The purpose of defining "engineering" more broadly in the *Framework* and NGSS is to emphasize practices that all citizens should learn—such as defining problems in terms of criteria and constraints, generating and evaluating multiple solutions, building and testing prototypes, and optimizing—which have not been explicitly included in science standards until now.

It is also important to point out that the NGSS does not put forward standards for engineering education; but rather includes those ideas that are closely connected to science and that are essential for everyone to learn.

Approach to Integration

The first drafts of the NGSS integrated engineering and technology as recommended by the *Framework*. That is, standards were developed to represent the two core ideas in this discipline: 1. Engineering Design; and 2) Links Among Technology, Engineering, Science, and Society. These standards were represented in the NGSS as a fourth discipline, parallel to standards in the life sciences, physical sciences, and Earth and space sciences.

The majority of lead state partners objected to including separate standards on Engineering Design for two reasons. First, the core ideas of engineering design described in Chapter 8 of the *Framework* were largely represented in the practices of science and engineering described in Chapter 3. Consequently, performance expectations that combined engineering practices with the core ideas of engineering design seemed redundant. Second, since a major purpose of integrating engineering into the science standards was for students to learn how their growing knowledge of science can be applied to solve practical problems, that goal could better be achieved by integrating the core ideas of engineering design directly into the science disciplines.

Similar reasoning applied to the second core idea from Chapter 8: Links Among Technology, Engineering, Science, and Society, leading to the recommendation that these ideas be integrated into the major science disciplines as crosscutting concepts. The reasoning behind this recommendation became evident when considering the two sub-ideas: 1) Science, technology, and engineering are interdependent; and 2) Science, engineering and technology influence society and the environment. The majority of lead state partners thought that these ideas could best be represented in the context of specific disciplinary ideas rather than as stand-alone standards.

Core Idea 1. Engineering Design

The term "engineering design" has replaced the older term "technological design," consistent with the definition of engineering as a systematic practice for solving problems, and technology as the result of that practice. According to the *Framework*: " From a teaching and learning point of view, it is the iterative cycle of design that offers the greatest potential for applying science knowledge in the classroom and engaging in engineering practices," (NRC 2011, p. 8-1). This idea contrasts with a common practice challenging children to build a tower out of newspaper with no guidance for how to go about solving the problem. Instead, the *Framework* recommends that students learn about three phases of solving problems:

A. Defining and delimiting engineering problems involves stating the problem to be solved as clearly as possible in terms of criteria for success and constraints, or limits.

B. Designing solutions to engineering problems begins with generating a number of different possible solutions, evaluating potential solutions to see which ones best meet the criteria and constraints of the problem, then testing and revising the best designs.

C. Optimizing the design solution involves a process in which the final design is improved by trading off less important features for those that are more important. This may require a number of tests and improvements before arriving at the best possible design.

The *Framework* is explicit about what students at different grade levels are expected to do in engineering design. This progression of capabilities is summarized in the *Framework* as follows:

> *In some ways, children are natural engineers. They spontaneously build sand castles, dollhouses, and hamster enclosures, and they use a variety of tools and materials for their own playful purposes. Thus a common elementary school activity is to challenge children to use tools and materials provided in class to solve a specific challenge, such as constructing a bridge from paper and tape and testing it until failure occurs. Children's capabilities to design structures can then be enhanced by having them pay attention to points of failure and asking them to create and test redesigns of the bridge so that it is stronger. Furthermore, design activities should not be limited just to structural engineering but should also include projects that reflect other areas of engineering, such as the need to design a traffic pattern for the school parking lot or a layout for planting a school garden box.*
>
> *Middle school students should have opportunities to plan and carry out full engineering design projects in which they define problems in terms of criteria and constraints, research the problem to deepen their relevant knowledge, generate and test possible solutions, and refine their solutions through redesign.*
>
> *High school students can undertake more complex engineering design projects related to major local, national or global issues. Increased emphasis should be placed on researching the nature of the given problems, on reviewing others' proposed solutions, on weighing the strengths and weaknesses of various alternatives, and on discerning possibly unanticipated effects.* (NRC 2012, p. 70-71)

What distinguishes engineering design in the NGSS from earlier attempts to engage students with fun, hands-on activities like packaging eggs so they can be dropped without breaking, or building bridges or catapults, is that students learn to solve problems systematically. For example, it is common for both children and adults to jump at the first solution that comes to mind when solving a motivating problem. Students who approach problems using the practices of engineering design take the time to clearly define the problem that they are expected to solve, and specify the criteria for success so they will be able to judge the quality of their solutions. They also generate a number of different solutions before deciding what to test, and compare each of their initial ideas with the requirements of the problem. And once they find a workable solution they are not done. They also recognize that further tests and modifications are necessary to develop optimal solution.

As students become more sophisticated in their reasoning abilities, it is important for them to keep sight of the purposes of engineering, and to recognize that although technological decisions can have tremendously beneficial effects for people and the environment, they may also have unintended negative consequences for society and/or the environment. Therefore, it is important for every citizen to understand how technologies are developed and improved, to apply these capabilities to problems that are important in their own lives, and to have the knowledge and skills to participate as members of society in shaping the world of the future.

Core Idea 2. Links Among Engineering, Technology, Science and Society

The second core idea involves the connections among engineering, technology, science and society that are important for all people to understand in order to function and thrive in the modern world. This core idea includes two sub-ideas: (a) The interdependence of science, engineering, and technology; and (b) The Influence of engineering, technology, and science, on society and the natural world.

A. The interdependence of science, engineering and technology includes the complementary ideas that scientists depend on engineers to produce technologies for them to use as tools for learning about the natural world; while engineers depend on scientists to provide inspirational new discoveries and accurate knowledge of how the world works. Engineering and technology drive each other forward in the research and development (R&D) cycle. This idea is described in the *Framework* as follows:

> *The fields of science and engineering are mutually supportive, and scientists and engineers often work together in teams, especially in fields at the borders of science and engineering. Advances in science offer new capabilities, new materials, or new understanding of processes that can be applied through engineering to produce advances in technology. Advances in technology, in turn, provide scientists with new capabilities to probe the natural world at larger or smaller scales; to record, manage, and analyze data; and to model ever more complex systems with greater precision. In addition, engineers' efforts to develop or improve technologies often raise new questions for scientists' investigations.* (NRC 2012, p. 203)

In the NGSS the idea that science, engineering and technology are interdependent is treated as a crosscutting concept, since it is best illustrated through performance expectations in the major science disciplines. For example, the following represents a performance expectation in physical science at the high school level from the NGSS:

> *Students can obtain and communicate information about how scientists and engineers use the principles of electrical and magnetic forces in the design of new devices through a process of research and development*. (NGSS, HS-PS-FI)

B. The Influence of engineering, technology, and science, on society and the natural world is important for students to learn at increasing levels of sophistication as they mature. This idea also has two complementary parts. The first is that scientific discoveries and technological decisions affect human society and the natural environment. The second is that people make decisions that ultimately guide the work of scientists and engineers. As expressed in the *Framework*:

> *From the earliest forms of agriculture to the latest technologies, all human activity has drawn on natural resources and has had both short- and long-term consequences, positive as well negative, for the health of both people and the natural environment. These consequences have grown stronger in recent human history. Society has changed dramatically, and human populations and longevity have increased, as advances in science and engineering have influenced the ways in which people interact with one another and with their surrounding natural environment.*
>
> *Not only do science and engineering affect society; society's decisions (whether made through market forces or political processes) influence the work of scientists and engineers. These decisions sometimes establish goals and priorities for improving or replacing technologies; at other times they set limits, such as in regulating the extraction of raw materials or in setting allowable levels of pollution from mining, farming, and industry.* (NRC 2012, p. 212)

This second core idea emphasizes the human dimension of science and engineering. It is essential that our students recognize that their decisions as individuals, their choices as consumers and workers, and their participation within society drive the work of scientists and engineers. If no one was interested in purchasing a cell phone, or accessing the Internet, then scientists and engineers would not have combined forces to develop them; and our world would be very different today.

How these ideas play out in the NGSS is illustrated with the following performance expectations:

> From high school life science: *Students can use evidence to construct explanations and design solutions for the impact of human activities on the environment and ways to sustain biodiversity and maintain the planet's natural capital.*
>
> From high school physical science: *Students can construct arguments using data provided about the relative merits of nuclear processes compared to other types of energy production.*
>
> From middle school Earth and space science: *b. Students can use system models and representations to define solvable problems brought about by increases in the human population and consumption of natural resources that significantly impact: (1) the geosphere, (2) the hydrosphere, (3) the atmosphere, and (4) the biosphere.*

Perhaps more than any other part of the *Framework*, the core idea "Links among science, engineering, technology, and society," border on social studies. Reading about current events in which a new scientific discovery spawns a new or improved technology illustrates sub-concept A. about the interdependence of science and engineering. Articles about the growth of new technologies, such as electric or hybrid cars, and about environmental issues illustrates sub-concept B. about the influence of engineering, technology, science and society and the environment.

The vision of the *Framework* and the NGSS encompasses those ideas, but go beyond them, to recognize that that key discoveries of science are happening today and will be happening in the future, and that advances in science are intimately tied to advances in engineering, as each one drives the other, within the greater context of society and the natural environment.

Conclusion

Although the standards presented in this section are not new to science education, they nonetheless will require a new way of thinking in planning curriculum, instruction, and assessment. The *NGSS* introduces a number of new practices not commonly taught within school curriculum, such as trade-offs and optimization that are foreign to science, but essential to developing the instruments used in science class. Technology is not just the tool that students when doing science—improvements in a technology may constitute the purpose of a scientific investigation. And discussions of science, engineering, technology, society and the environment are not simply ways to enliven discussion, but become essential learning experiences with specific learning outcomes. The tables that follow identify the performance expectations that integrate engineering.

Engineering Performance Expectations

The following chart shows all performance expectations that require engineering design practices, disciplinary core ideas, or the crosscutting concepts of engineering, technology, and society. Engineering performance expectations are designated with an asterisk (*). This chart allows readers to quickly identify the performance expectations in each grade/grade-band. Following the chart are the actual performance expectations in the NGSS architecture.

Engineering in Kindergarten through Fifth Grade

Grade / Grade-Level	Science and Engineering Practices	Disciplinary Core Idea	Cross-Cutting Concept
K	K-PS1-c.		K-PS1-c.
	K-PS3-b.	K-PS3-b.	K-PS3-b.
	K-ESS3-c.		K-ESS3-c.
	K-ESS3-d.		
1	1-PS4-d.		
	1-PS4-e.	1-PS4-e.	1-PS4-e.
	1-LS1-b.	1-LS1-b.	1-LS1-b.
	1-ESS1-b.		1-ESS1-b.
2	2-PS1-a.		2-PS1-a.
	2-PS1-b.		2-PS1-b.
	2-PS1-c.		2-PS1-c.
	2-PS2-c.		
	2-PS3-b.	2-PS3-b.	2-PS3-b.
		2-LS2-b.	
	2-LS2-c.	2-LS2-c.	
	2-ESS2-c.		
	2-ESS2-d.	2-ESS2-d.	2-ESS2-d.
3	3-PS2-d.		3-PS2-d.
	3-LS4-c.		3-LS4-c.
			3-LS4-e.
	3-ESS3-a.		3-ESS3-a.
	3-ESS3-b.		3-ESS3-b.
4	4-PS3-d.	4-PS3-d.	4-PS3-d.
	4-PS3-e.	4-PS3-e.	4-PS3-e.
	4-PS4-d.	4-PS4-d.	4-PS4-d.
	4-PS4-e.	4-PS4-e.	4-PS4-e.
	4-LS1-b.	4-LS1-b.	4-LS1-b.
	4-ESS2-b.	4-ESS2-b.	4-ESS2-b.
	4-ESS3-a.		
	4-ESS3-b.	4-ESS3-b.	4-ESS3-b.
5	5-PS1-e.		5-PS1-e.
	5-PS4-a.	5-PS4-a.	5-PS4-a.
		5-PS4-b.	5-PS4-b.
	5-LS2-c.	5-LS2-c.	
	5-ESS3-a.		5-ESS3-a.

Engineering in Grades 6 through 8

Grade / Grade-Level	Science and Engineering Practices	Disciplinary Core Idea	Cross-Cutting Concept
MS	MS-PS1-b.	MS-PS1-b.	MS-PS1-b.
			MS-PS1-f.
	MS-PS1-g.	MS-PS1-g.	
	MS-PS2-a.	MS-PS2-a.	MS-PS2-a.
	MS-PS2-c.	MS-PS2-c.	
	MS-PS2-f.	MS-PS2-f.	MS-PS2-f.
		MS-PS3-a.	
	MS-PS3-c.	MS-PS3-c.	
	MS-PS3-g.	MS-PS3-g.	
	MS-PS4-e.	MS-PS4-e.	MS-PS4-e.
	MS-LS1-a.		MS-LS1-a.
	MS-LS1-d.		MS-LS1-d.
	MS-LS2-c.		
		MS-LS2-g.	
		MS-LS2-i.	MS-LS2-i.
	MS-LS4-c.		
			MS-LS4-g.
			MS-LS4-i.
			MS-LS4-j.
		MS-ESS1-d.	MS-ESS1-d.
		MS-ESS1-e.	MS-ESS1-e.
	MS-ESS3-c.	MS-ESS3-c.	MS-ESS3-c.
		MS-ESS3-d.	MS-ESS3-d.
	MS-ESS3-e.	MS-ESS3-e.	MS-ESS3-e.
		MS-ESS3-h.	MS-ESS3-h.
	MS-ESS3-i.	MS-ESS3-i.	MS-ESS3-i.

Engineering in Grades 9 through 12

Grade / Grade-Level	Science and Engineering Practices	Disciplinary Core Idea	Cross-Cutting Concept
HS	HS-PS1-g		
	HS-PS2-a.	HS-PS2-a.	HS-PS2-a.
	HS-PS2-c.	HS-PS2-c.	HS-PS2-c.
	HS-PS3-b.	HS-PS3-b.	HS-PS3-b.
	HS-PS3-f.	HS-PS3-f.	HS-PS3-f.
	HS-PS4-c.	HS-PS4-c.	
	HS-PS4-d.	HS-PS4-d.	
	HS-PS4-f.	HS-PS4-f.	HS-PS4-f.
	HS-PS4-h.	HS-PS4-h.	HS-PS4-h.
	HS-LS1-f.	HS-LS1-f.	
			HS-LS1-k.
	HS-LS2-c.		
	HS-LS2-f.		
	HS-LS2-j.	HS-LS2-j.	
	HS-LS2-l.	HS-LS2-l.	
	HS-LS3-c.	HS-LS3-c.	HS-LS3-c.
			HS-ESS1-b.
			HS-ESS1-d.
	HS-ESS1-e.	HS-ESS1-e.	HS-ESS1-e.
	HS-ESS1-f.	HS-ESS1-f.	HS-ESS1-f.
	HS-ESS1-g.		HS-ESS1-g.
	HS-ESS2-b.	HS-ESS2-b.	HS-ESS2-b.
	HS-ESS2-c.	HS-ESS2-c.	HS-ESS2-c.
			HS-ESS2-e.
	HS-ESS2-i.	HS-ESS2-i.	HS-ESS2-i.
			HS-ESS3-a.
	HS-ESS3-b.	HS-ESS3-b.	HS-ESS3-b.
	HS-ESS3-e.	HS-ESS3-e.	HS-ESS3-e.
	HS-ESS3-f.	HS-ESS3-f.	HS-ESS3-f.
	HS-ESS3-h.	HS-ESS3-h.	HS-ESS3-h.
	HS-ESS3-i.	HS-ESS3-i.	

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