NREL/TP-400-7830 • UC Category: 900 • DE95004087

Using Performance Parameters, Metrified Performance Objectives, and Quality Management Assessment to Improve the Effectiveness of Research Organizations

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Presented at the 22nd Annual National Energy and Environmental Division Education and Training Symposium, Charlotte, North Carolina September 17–20, 1995

National Renewable Energy Laboratory
1617 Cole Boulevard
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A national laboratory of the U.S. Department of Energy
Managed by the Midwest Research Institute
for the U.S. Department of Energy
under Contract No. DE-AC36-83CH10093

April 1995

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Using Performance Parameters, Metrified Performance Objectives, and Quality Management Assessments to Improve the Effectiveness of Research Organizations

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Abstract

This paper begins by raising the issue of whether the theoretical model of customers-suppliers-products-services usefully describes the activities of laboratory life, using a case study from Fermilab. After describing scientific activities as work, not volunteerism, I present a model that has four performance parameters that can be used to evaluate DOE-funded research laboratories: 1) Do they have a well-defined management system? 2) Are they doing good science? 3) Are they managing their resources effectively? 4) Are they responsive to their customers? From these four parameters I describe how to metrify performance objectives, then use them to evaluate research organizations. I describe these performance objectives within the context of views I have published elsewhere,[1] and according to Stephen R. Covey's metaphor of production/production capability (P/PC) balance in his book *The 7 Habits of Highly Effective People*.[2]

Baconian and Cartesian Values for Science

Asking whether or not the researchers at a laboratory are "doing good science" often digresses into discussions about the very purpose of science. In a previous paper, I described the distinction between Baconian and Cartesian values about science, where values are the criteria by which choices are made. For example, those holding to Baconian values tend to view science as the servant of the taxpayers who finance it. The knowledge produced should be utilitarian. In other words, applied science ought to improve the quality of life through technological advances. Funding agencies and congressional committees with a Baconian view of science will tend to support utilitarian applied research, although they might also support basic research projects such as the now defunct Superconducting Super Collider because of the number of jobs and dollars that are brought to congressional constituencies. Those holding to Cartesian values tend to view basic experimental science as the "feedstock" of future utilitarian (applied) science. They might also claim that all cultured societies should support scientific knowledge for its own sake (much as they support art or music), even if there are no immediate known applications of the knowledge. Recently, science has been pushed dramatically toward the Baconian view. As a result, a number of very concrete and subtle, yet profound changes are occurring in DOE funded national laboratories.

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[1] Mark Bodnarczuk, *Science as Knowledge, Practice, and Map Making: The Challenge of Defining Metrics for Evaluating and Improving DOE-Funded Basic Experimental Science*, NREL/TP-320-5401.

[2] Stephen R. Covey, *The 7 Habits of Highly Effective People*, (New York: A Fireside Book, Simon & Schuster, 1990).

Baconian values tend to bring increased financial and mission-related accountability. For example, national laboratories are increasingly being forced to evaluate their research activities against criteria such as: (1) what value and benefit does this research produce for taxpayers? and (2) who will benefit from this research, taxpayers, industry, other stakeholder groups. These questions are at the very heart of Baconian utilitarian values. Such criteria can be modeled in many ways, but one theoretical model that is gaining acceptance is the notion that national laboratories produce products and services for customers - what I will call the customer, supplier/product, service (CS/PS) model. According to this view, a product is a tangible item or thing that is generated by a process; and a service is any activity in which human resources, capital, and equipment are used to meet a customer's need. The person or organization that generates a product or service is called a supplier, and the person or organization who receives and uses that product or service is called the customer. Thus, for the individuals involved, the relationship is symbiotic, and depends on whether they are providing or receiving a product or service. Within an organization, an "internal" customer is a person or organization that receives a service or a semifinished product from a supplier. An "external" customer is a person or organization that receives, pays for, or uses the product or service.

The CS/PS Model Applied to Basic Research: A Case Study at Fermilab

Laboratories that perform applied research and development (R&D), such as the National Renewable Energy Laboratory (NREL), have found the CS/PS model to be a powerful and useful way to describe the myriad interactions that occur in the course of carrying out their mission as a national laboratory. But many scientists who perform basic research claim that the CS/PS model cannot be used to describe their research activities because their *only* goal is to produce knowledge that is so new that it has no known application and will only be of (possible) practical use for future generations. Because future (unborn) generations cannot have expectations, set requirements, or make physicists accountable for their work like other customers do, the only group that many scientists even entertain as being their "customers" are peers who use the published records of their experiments in scientific journals or experimental results presented at professional meetings and scientific colloquia. Historical examples are marshaled to support the claim that the primary users or customers of the knowledge output of basic research are future generations. For example, who could have predicted that quantum mechanics, quantum electrodynamics (QED), and its eventual application to solid-state electronics and VCRs would emerge from obscure theoretical and experimental work such as Einstein's 1905 paper on the photoelectric effect, Heisenberg's work on matrix mechanics and the uncertainty relation, Schrodinger's equation describing wave mechanics, Bohr's and Born's probabilistic formulation of quantum mechanics, Lamb's precise measurements of vacuum polarization, and Feynman, Schwinger, and Tomonaga's theoretical formulation of quantum electrodynamics.[3] Such nostalgic appeals to the history of physics as an explanation for why basic researchers have no living customers (other than themselves) beg the question under discussion. The issue is not defining the relationship between esoteric basic knowledge and its eventual use in applied research and engineering development. The issue is whether or not the CS/PS model can

[3] For historical reflections on these events by those who performed the work, see A.P. French and P.J. Kennedy, eds., *Niels Bohr: A Centenary Volume*, (Cambridge, MA: Harvard University Press, 1985). Also see Richard P. Feynman, *QED: The Strange Theory of Light and Matter*, (Princeton: Princeton University Press, 1985).

usefully describe the activities that occur in basic research environments - does it describe laboratory life?

The fact is that other scientists *are* a very real customer group of basic research. But as I have noted elsewhere, the tendency of basic researchers to characterize science almost exclusively in terms of the product of esoteric "knowledge" ignores many of the *other* products and services they generate and many of the other customers, for example, university administrators, students at universities, industrial partnerships, and those who utilize technological spin-offs.[4] This narrow definition of products (science-as-knowledge only) also ignores another crucial component of their mission - providing services for these other customers. Given the definitions of customer, supplier, product, and service provided above, I believe the CS/PS model describes basic research activities quite well. I will support this claim by using a case study I performed of the fixed-target physics program at Fermilab in the 1980s.[5] As I describe some of thc insights that emerge through the Fermilab case study, take note of how often the CS/PS model usefully describes organizational relationships and interactions.

Let me begin by describing a few organizational relationships that illustrate some basic examples of the CS/PS model. Fermilab is a "user facility" funded by U.S. taxpayers, with the U.S. Department of Energy (DOE) distributing the resources and serving as the steward of the taxpayer's interests. This stewardship provides a service to the taxpayers, who can be viewed as the paying customers and who eventually will benefit from basic research as part of the population previously referred to as future generations. Universities Research Association Inc. (URA - the M&O contractor for Fermilab) is charged with operating Fermilab as a national resource which produces the particle beams and provides other services necessary to perform high-energy physics experiments. These particle beams and services are available to qualified researchers who are called "users." According to the CS/PS model, these users are some of Fermilab's most important external customers. These organizational relationships between Fermilab, DOE, and URA Inc. during the time period of our case study (the 1980s) are much like they are today.

Because Fermilab operated the highest energy particle beam accelerator in the world during the 1980s, the competition for the particle beams produced was intense - there was nowhere else physicists could go to obtain particle beams with such high energies. However, to gain access to one of these particle beams, as the case study reveals, users had to navigate a number of interrelated resource economies, each of which had associated commodities; these commodities are clear examples of either products or services as defined above. Furthermore, the resource economies were embedded within an institutional structure headed by a single scientist, the Fermilab director, who had ultimate authority in all matters scientific and otherwise.[6] The symbiotic nature of the customer-supplier relationship is seen in the relationships between the Fermilab director (who was a steward of yet another external customer group, the overall high-energy physics community) and the users (who were both customers of the products and services Fermilab provided and also

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[4] Mark Bodnarczuk, *Science as Knowledge, Practice, and Map Making: The Challenge of Defining Metrics for Evaluating and Improving DOE-Funded Basic Experimental Science*, NREL/TP-320-5401.

[5] Mark Bodnarczuk, *The Social Structure of Experimental Strings at Fermilab: A Physics and Detector Driven Model*, Fermilab-Pub-91/63, (Batavia, IL: March, 1990) for a detailed case study of Fermilab experiments E-516, E-691, E-769, and E-791, and Mark Bodnarczuk, "Some Sociological Consequences of High-Energy Physicists' Development of the Standard Model, 1964-1979" in Hoddeson et al., eds., *The Third International Symposium on the History of Particle Physics: The Rise of the Standard Model*, (New York: Cambridge University Press, 1995).

[6] While the laboratory director appoints members to his advisory groups, he is ultimately responsible for all decisions that affect the laboratory.

suppliers of physics results). Because the Fermilab director had ultimate authority to approve an experiment and provide many of the resources needed to perform that experiment, he was also a very important customer of these physics results. The case study shows that the users who were granted access to the particle beams and services provided by Fermilab had to learn to trade with and for these commodities in order to participate in the process of constructing knowledge about the microworld. These resource economies reveal well-defined, symbiotic relationships between customers and suppliers and well-defined products and services ("commodities") that were the currency of laboratory life. Physicists negotiated with these commodities and often they fought over them when they were in short supply.[7]

The first resource economy was proton economics, based on protons as the commodity or product. The overall magnitude of the economy was limited by such factors as the number of protons that could be produced by Fermilab's accelerators, efficiencies in transporting those protons to experimental targets, and the rates at which particle reactions could be produced in experimental targets.[8] Approval of an experiment was based on the proposed number of protons required to perform the experiment; this number became an important component of all negotiations between the users and Fermilab management. High-energy protons - the product of the accelerator - and the services involved in transporting this product to experimental targets and detectors show how the CS/PS model usefully describes the very heart of operations in a basic research environment. The second resource economy was experimental real estate. Here, the commodity was possession of an experimental hall (at the end of a beam spigot) used to house the experimental collaboration's apparatus, as well as general purpose experimental and beam transport equipment provided by the laboratory to service the experiment. After approving an experiment, the laboratory would assign physicists and engineers to supply products and services such as designing and constructing the beam transport system, beamline electronics, computing, and myriad other support systems to service their experimental customer's needs. A clear example of a service organization serving these user/customers was the operations personnel, whose sole purpose was to operate the beamlines and other systems for their user/customers and provide any other service needed to make the experiment successful - an unambiguous example of the nature of the customer-supplier relationship in performing basic research.

The third resource economy, what I call "physicist economics," is based on the commodity of physics expertise. Although the scale and complexity of the fixed-target experiments performed during the 1980s continued to increase at an unprecedented rate, the number of high-energy physicists able to perform experiments was constrained by the total number of physicists then available and the rate at which new Ph.D. students were being produced. Consequently, the enormous increases in the scale and complexity of experiments made physics expertise an increasingly valuable commodity. Larger, more complex, increasingly modularized detectors

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[7] Using numerous case studies, David Hull claims that not only are infighting, mutual exploitation, and even personal vendettas typical behavior for many scientists, but that this sort of behavior actually facilitates scientific development. David Hull, *Science as a Process: An Evolutionary Account of the Social and Conceptual Development of Science*, (Chicago: The University of Chicago Press, 1988), p. 26.

[8] More detailed information and references describing these resource economies can be found in Mark Bodnarczuk, *The Social Structure of Experimental Strings at Fermilab: A Physics and Detector Driven Model*, Fermilab-Pub-91/63, (Batavia, IL: March 1990) for a detailed case study of Fermilab experiments E-516, E-691, E-769, and E-791, and Mark Bodnarczuk, "Some Sociological Consequences of High-Energy Physicists' Development of the Standard Model, 1964-1979" in Hoddeson et. al. eds, *The Third International Symposium on the History of Particle Physics: The Rise of the Standard Model*, (New York: Cambridge University Press, 1995).

required larger, more complex, increasingly modularized social structures with the appropriate *number* of physicists and the *distribution* of expertise needed to design, fabricate, install, and operate the apparatus, and to develop the computing systems and software programs used to reconstruct and analyze the particle events that were recorded. Within the economy of physicist economics, proposals were increasingly judged on the "physicist design" of the experiment and how well it mapped to the experimental design, with laboratory directors and their advisory committees focusing more and more on whether the collaboration had enough "physicist power" to make good on its experimental claims. Although the notion of physics expertise may seem intangible, it was a crucial component of obtaining resources, it was sought after and traded like any other commodity, and it was sometimes the crucial ingredient to the success or failure of the experiment.

The fourth resource economy, computing economics, was based on the commodity or product of on-line and off-line computing power needed to perform increasingly more complex experiments which attempted to isolate low cross-section signals against tremendous backgrounds - for example charm particle experiments like those in our case study. One way of handling the problem of backgrounds was to use sophisticated on-line "trigger processors" that would select (trigger) and then record events only when they met preestablished criteria such as mass and transverse momenta. But there were trade-offs involved. On the one hand, the advantages of *on-line* data reduction using trigger processors did reduce the need for the commodity of *off-line* computing power, but this had to be balanced against the risk of coming up empty handed because of wrong trigger assumptions. On the other hand, the more secure approach to on-line data acquisition (the write-it-all-to-tape approach) had to be balanced against the problem of obtaining the commodity of immense off-line computing resources. In this resource economy, the CS/PS model describes these complex interactions very nicely, with the experimental users being the customers of the Fermilab computing division, which is the supplier of products (the amount of computing power) and services (reliable computing services 24 hours a day).

The final resource economy was physics economics, with the commodity or product being the publication of physics results in a professional journal or the presentation of such results at professional meetings. Science-as-knowledge is the product that many scientists tend to define as the *only* real product of basic research. In this economy, the users performing the experiment were suppliers who traded the product of published physics results back to the laboratory director as a return on his investment, e.g. as a key customer, the Fermilab director provided the resources that the user/suppliers needed to perform the experiment. Delivering the product of physics results to this key customer was the most important factor that enabled users to obtain additional resources to perform follow-up experiments. The product of carefully obtained physics results also increased the collaboration's and Fermilab's credibility in the larger physics community. Because other physicists would often use the physics results in designing their own experiments, they were customers who had much to lose or gain depending on the quality of the research. This is yet another example of how the CS/PS model usefully describes some of the most important symbiotic relationships involved in basic research at laboratories such as Fermilab.

As stated previously, laboratories such as NREL have been quicker to accept the usefulness of the CS/PS model to describe its mission in terms of products (development of new technological products and processes), and services (the management of DOE-funded subcontracted R&D). However, I believe the case study shows that the theoretical CS/PS model is useful for describing the activities of laboratory life at basic research facilities such as Fermilab, as well as other national laboratories. Notions of customers and suppliers are a useful framework within which to describe the symbiotic organizational interactions between users, DOE, laboratory management, operations personnel, and other participants in basic research. Also, products such as the protons, computing power, and published physics results are nicely described by the CS/PS model. Additionally, when we define a "service" as the use of human resources, capital, and equipment to satisfy a customer's need or expectation, it is clear that one of the main purposes of laboratories such Fermilab, the Stanford Linear Accelerator Center, and the Continuous Electron Beam Acceleration Facility is to provide the services necessary for qualified physicists to do fundamental research.

Science as Employment, Not Volunteerism

Once we establish that *both* basic and applied research can be usefully described by the CS/PS model, Baconian values forces us to think about science as being a source of employment and work, not volunteerism. In the 20th century, science as volunteerism is a myth. The fact is that science requires scientists, engineers, and technicians to have a set of refined skills and knowledge for which they are hired and paid a salary. The myth of science as volunteerism emerges largely from an anachronistic appeal to the way "experiments" were performed in the 17th century when science was still referred to as natural philosophy. Careful historical studies of the emergence of the organization of science in Western society, particularly in the Royal Society of England, show that in the 17th century natural philosophy was mostly volunteerism. Almost without exception, those who performed natural philosophy were either independently wealthy to the point that they could financially support their scientific work from their own resources, or they were supported by royalty or had endowed chairs at universities where a part of their work involved teaching. As Steven Yearly describes these early years of natural philosophy: "In its early stages scientific activity was indeed extraordinarily voluntary; scientists' work was largely self-directed, and the topics they researched were commonly freely chosen. [Today], the scientists who fit the stereotype...constitute only a small fraction of the people employed in scientific work...the only place where these conditions are even approximately met is in universities and related higher education and research institutions."[9] The fact is that science and technology provide work and employment for hundreds of thousands of people, with the ratio of most scientific workers to the archetype of the "university" researcher being about 17 to 1.[10]

This view is in stark contrast to the Mertonian image of science as an open intellectual community where the "goods" of science are held in common ownership by the scientific community and scientists are disinterested seekers after "truth."[11] Bauer goes so far as to claim that, while scientists may have been disinterested seekers after truth when science was an avocation or hobby, the organization of science from the 17th century Royal Society on led scientists to also be the organizers and managers of science. This meant that scientists earned their living as scientists; in effect, they were forced into an inevitable conflict of interest between seeking the truth and making a living and establishing a professional career.[12] N.D. Ellis explored the stereotypic images of the "university" versus "industrial" scientist, studying the variance between the perceptions and

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[9] Steven Yearly, *Science, Technology, and Social Change*, (London: Unwin Hyman, 1988), pp. 67-68.
[10] Yearly, p. 68.
[11] See Robert R. Merton, "The Normative Structure of Science," in Norman W. Storer, ed., *The Sociology of Science: Theoretical and Empirical Investigations*, (Chicago: University of Chicago Press, 1973).
[12] Henry H. Bauer, *Scientific Literacy and the Myth of the Scientific Method*, (Chicago: University of Illinois Press, 1992), p. 92.

expectations of the "image" of science held by scientists in industry and those scientists working in universities. The study showed that scientists in industry were not particularly dissatisfied with the fact that they did not have the freedom to choose the direction of their research like their university-based colleagues, nor were they dissatisfied by the fact that they had few options in deciding whether they would focus their research expertise on basic rather than applied science projects.[13] Many actually found the assignment of a research problem by management to be more satisfying in terms of developing their technical abilities. Thinking about science as work and a source of employment rather than as avocational volunteerism and hobbies for the scientists, engineers, and technicians that constitute the scientific workforce, makes the CS/PS model even more useful for describing the activities of laboratory life.

Performance Parameters and Metrified Performance Objectives

The push toward a Baconian view of science has also resulted in an increase in the accountability of laboratories in terms of defining performance measures for evaluating the management of contractors at national laboratories.[14] In this section, I will describe four types of performance parameters from which performance objectives can be derived then metrified and subsequently used to evaluate DOE-funded national laboratories. I have formulated the performance parameters as a series of questions: (1) Do they have a well-defined management system? (2) Are they doing good science? (3) Are they managing their resources effectively? (4) Are they responsive to their customers? I will describe the essential components of these performance parameters within the context of views I have published elsewhere,[15] and according to Stephen R. Covey's metaphor of production/production capability (P/PC) balance in *The 7 Habits of Highly Effective People*.[16]

Before discussing the four performance parameters, I would like to address the common confusion between performance objectives and metrics, and how I will try to avoid this confusion by using the notion of ***metrified performance objectives***. Although performance objectives and metrics are closely interrelated, they are not synonymous because metrics must be quantifiable. Performance objectives should be expressed as outcomes that can be metrified (quantified) by expressing some component of the performance objective as a unit of measure. Research examples demonstrate this nicely. For example, a high-energy physics experiment's performance objective might be to obtain a factor of three increase in the precision of measuring photoproduced charmed

[13] N.D. Ellis, "The Occupation of Science," in Barry Barnes, ed., *Sociology of Science* (London and Baltimore: Penguin Books, 1972), pp. 188-205; and B.S. Barnes, "Making Out in Industrial Research," in *Science Studies*, Vol. 1, pp. 157-175.

[14] At the recent 23rd Annual ASQC Energy and Environmental Quality Division Conference in February 1995, a number of talks were given on this topic e.g., Buck Koonce, *Contract Reform: Performance Metrics for National Laboratories*, Jerry Bellows, *Department of Energy Contract Reform Initiative*, and Jeffrey Baker, *CQI in Award Fee Contracting: Beyond Compliance*.

[15] Mark Bodnarczuk, "Defining Metrics for Evaluating and Improving Basic and Applied Experimental Science" in Part II of the *Proceeding of the Tenth International Conference of the Israel Society for Quality*, November 14-17, 1994, pp. 883-888.

[16] Covey uses Aesop's fable of the goose and the golden egg to illustrate how effectiveness is achieved through a balance of production (the golden egg = the output of individuals or organizations) and production capability (the goose = the material, financial, and human assets of individuals or organizations), abbreviating this as P/PC balance. See Stephen R. Covey, *The 7 Habits of Highly Effective People*, (New York: A Fireside Book, Simon & Schuster, 1990), p. 52 ff.

particle lifetimes, with the metric being the three-fold increase. The operations group at Fermilab mentioned earlier might have the performance objective of optimizing the tune of a particle beam with the goal of increasing the efficiency of particle transport by 20%, with the metric being 20%. Or in wind energy research, the performance objective might be doing a complete analysis of U.S. and European aerodynamic data with the goal of defining methods of gaining a 5% improvement in energy capture, where the metric is the 5% improvement. Performance objectives are *not* synonymous with metrics. Metrics must be quantifiable. Metrics must also be contextual in that a 5% improvement in energy capture has meaning only within the context of the current state of the field as determined by a complete analysis of U.S. and European aerodynamic data, and a factor of three increase in the measurement precision only has meaning within the context of all other relevant high-energy physics experimental data samples. Because it is common to develop performance objectives that do not contain metrics, I believe that part of the confusion between performance objectives and metrics is alleviated by using the term metrified performance objectives.

The first performance parameter is, Do they have a well defined management system? Although it is possible to define measures of organizational performance simply by surveying internal and external customers, such efforts can be made more effective by defining such performance measures within the context of an institution-wide approach to managing. While there are a variety of approaches to defining such a management system, one way is to adopt Covey's *7 Habits of Highly Effective People* as the foundation for organizational and individual values, and the Malcolm Baldrige National Quality Award criteria (MBNQA) as the overall institutional framework for doing business, even in research environments. Having discussed the notion of Covey-based total quality management (TQM) elsewhere,[17] I will only discuss the MBNQA criteria aspect of this performance parameter here. The MBNQA criteria are an assessment tool, not a management system. Although the seven criteria are designed to probe and evaluate the essential constituents of effective management systems, they need to be reformulated and contextualized for each organization.[18] One way of doing this is to rearrange the dynamic relationships between the MBNQA criteria into a Deming-Shewhart cycle - plan, do, check, act (PDCA). The result is a Baldrige-based planning, operating, assessment, and improvement system, all driven by *leadership* and informed by *customer feedback*.

Another approach that more tightly *links* and *aligns* the foundation of the 7 Habits with a well-defined management system on the personal, interpersonal, managerial, and organizational levels is described in *Principle Centered Leadership*.[19] These principles can be applied to organizations using an alignment tool called the Performance-Cycle which shows how to obtain 360 degree alignment of an organization's customer and stakeholder needs, mission, strategy, structures and systems, cultural behaviors, and business results. The Performance-Cycle is a powerful (yet easy to use) tool that helps organizations know where to *begin* the process of implementing QM and how to *align* the components they already have in place. Regardless of the approach adopted,

[17] Mark Bodnarczuk, "DOE 5700.6C, 10CFR830.120, DOE-ER-STD-6001-92, and Covey-Based TQM: A Historical Perspective on Current Issues in Research Environments," in *The Proceedings of the 21st Annual ASQC National Energy and Environmental Quality Division Conference*, September 18-21, 1994.

[18] The seven criteria of the 1995 MBNQA are: 1.0 Leadership, 2.0 Information and Analysis, 3.0 Strategic Planning, 4.0 Human Resource Development and Management, 5.0 Process Management, 6.0 Business Results, and 7.0 Customer Focus and Satisfaction.

[19] Stephen R. Covey, *Principle Centered Leadership*, (New York: Summit Books, 1991). The Performance-Cycle is a training module developed and offered by the Covey Leadership Center and is described in detail in David P. Hanna, *Designing Organizations for High Performance*, (New York: Addison Wesley, 1988).

the leadership of senior managers and a commitment to obtaining and using customer feedback are the components needed to begin using the principles and practice of QM to define a management system. Once defined, this type of management system makes Covey's relationship between an organization's production and production capability more concrete and it is within the context of this management system that organizations can determine whether production and production capability are in balance.

Performance objectives for the planning system might be to develop strategic quality plans with mission and vision statements, business plans, experimental proposals or field work proposals (FWPs), site development plans, or human resource development and management plans. Performance objectives for the operating system might include identifying key processes in an organization, identifying process owners, and developing, charting, and publicly displaying real-time metrified key indicators and results for processes that are rolled-up to the business unit and corporate levels. Performance objectives for the assessment system might include identifying organizational strengths and areas for improvement using the MBNQA criteria, with corrective actions and improvements being a major part of the improvement system. As described above, each of these performance objectives needs to be metrified based on external and internal customer requirements and baseline performance plotted against improvements.

The second performance parameter - Are they doing good science? - emerges from the management system and explores the quality of the scientific knowledge being produced by an organization; consequently, it is usefully described by the term "production" in Covey's P/PC balance formula. Performance objectives that provide indirect indications about the quality of basic scientific knowledge would include counting the number of citations that a particular publication receives,[20] using the awarding of Nobel Prizes received by Americans as an indication of the effectiveness of U.S. science policy, or using a laboratory's growth in funding and staff as an indicator of the quality of its research. Of course, each of these performance objectives would have to be metrified (for example, how many citations, which journals are the most prestigious, the number of Nobel Prizes awarded; however these are only indirect indications of the quality of the scientific knowledge).

Performance objectives that are more direct indicators of the quality of basic experimental science might include obtaining more direct, stable experimental measurements (as Galison suggests), or performing crucial experiments.[21] *Direct* measurements bring experimental reasoning another rung up the ladder of causal explanation (for example, measuring a background that had previously only been calculated).[22] *Stable* measurements mean varying a feature of the experimental setup (including changes in the test substance, apparatus, arrangement, or data analysis) and obtaining the same basic result.[23] Stable measurements are desirable because each variation introduced into the experimental design makes it more difficult to postulate an alternative causal story that will satisfy all the observations; this is because the effect is nested within ever more complex loops of experimental demonstration. Finally, there are *crucial* experiments - experiments

[20] See J. Irvine and B. R. Martin, "Basic Research in the East and West: A Comparison of the Scientific Performance of High-Energy Physics Accelerators," in *Social Studies of Science*, 1985, vol. 15, p. 300, and also Steven Yearly, *Science, Technology, & Social Change*, (London: Unwin Hyman, 1988), p. 88 ff.

[21] See Peter Galison, *How Experiments End*, (Chicago: The University of Chicago Press, 1987), pp. 259-260.

[22] Galison, pp. 259-260.

[23] Galison, p. 234 ff. Latour describes roughly the same notion in terms of the "trials of strength" that various effects and substances endure at the hands of experimenters in Bruno Latour, *Science in Action*, (Cambridge, MA: Harvard University Press, 1987), p. 74 ff.

at the "crossroads" - that yield new effects, new experimental or theoretical directions, more direct and stable measurements, or data that enable scientists to choose between competing theories.[24] Each of the above types of performance objectives needs to be metrified (for example, to what level of accuracy will the background be measured, and what level of variances will occur when test substances are changed). For applied experimental science, performance objectives might include developing new or improved technological processes or products, reducing the cost and cycle time of technologies, improving performance of technologies as evidenced by increased reliability, availability, maintainability, safety, or demonstrating the knowledge's usefulness through commercialization. Each of these performance objectives would also have to be metrified.

The third performance parameter - Are they managing their resources effectively? - emerges from the management system and is essentially an evaluation of how effectively the organization is using its resources to achieve its mission. This performance parameter derives from the production capability side of Covey's formula and is essentially an analysis of the metrified performance objectives and key indicators that emerge from the management system. Covey taxonomizes organizational resources into three kinds: human, material, and financial. He points out that many of the resources that are crucial to an organization's mission are not tracked by standard accounting systems. For example, although the human resource is the most important resource in achieving an organization's mission (because it is the only one that can act on the other two), it is either not tracked by standard accounting systems or is viewed as a cost (training, professional development) rather than an asset. Consequently, it is crucial to obtain and analyze this type of information as a way of determining how effectively the human, material, and financial resources are being used to achieve the mission of the organization.

As I have argued elsewhere, researchers and funding agencies need to adopt a new philosophy that does not *automatically accept* missed milestones, increased requests for computing, and the inability to estimate other experimental and human resources as an *inevitable* aspect of doing basic experimental science.[25] Was the problem attributable to a limitation that nature imposed on the experiment? Was it impossible to push the technologies involved any further? Was the problem an inevitable part of the pedagogic process of obtaining knowledge by actually *doing* an experiment and could not be avoided? Or was it a systemic problem where a spokesperson had no authority to make collaborators come through on their commitments? Was it a lack of planning or management on the part of the principal investigator or the inability to stop introducing new parameters and changes into an experimental design that should have been fixed? Was the problem due to a lack of supervision of a graduate student by his or her senior professor or laboratory manager? Problems imposed by nature may be unavoidable, but the practice of science would certainly be improved if most of the other problems were solved. Only when a scientist's ability (or inability) to manage their resources effectively are factored into the scientific community's evaluation of a scientist's *competence as a scientist*, and only when funding agencies develop methods for teasing apart the difference between problems that are intrinsic to basic research and those that result from poor planning and management techniques, will we be able to metrify the performance objectives that scientists have defined for themselves in experimental proposals, FWPs, and similar documents, and then use these as measures of success or failure.

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[24] See Ian Hacking, *Representing and Intervening*, (New York: Cambridge University Press, 1983), p. 249.

[25] Mark Bodnarczuk, *Science as Knowledge, Practice, and Map Making: The Challenge of Defining Metrics for Evaluating and Improving DOE-Funded basic Experimental Science*, NREL/TP-320-5401, p. 12 ff.

The fourth performance parameter - Are they responsive to their customers? - also emerges from the management system, but is predicated on the organization's willingness to apply the theoretical model of customer, supplier, product, service to the activities of laboratory life. As I mentioned earlier, other scientists *are* a very real customer group of basic research, but the tendency to characterize science almost exclusively in terms of the product of esoteric "knowledge" for future generations ignores many of the *other* products and services generated and many of the other customers (university administrators, university students, industrial partners, and those who use technological spin-offs). One key to this performance parameter is focusing on the organization's commitment to its customers and its ability to develop the information systems needed to obtain customer feedback on products and services; consequently, it can be characterized in terms of both the production and production capability sides of Covey's formula. There are two important factors to consider. First, the organization should be unambiguously committed to identifying who its customers are and then prioritizing them in terms of importance. Prioritizing customers is crucial to becoming a highly effective organization according to Pareto's Law which states that 20% of activities are high-leverage and produce 80% of the results (for example, 20% of an organization's customers normally produce 80% of their funding and revenues). Organizations must identify and focus on high-leverage activities. Second, it is crucial to develop systems for obtaining honest, uninhibited, anonymous customer input and feedback at all points in the process. Obtaining this type of feedback is especially important when customers such as students, junior professors, and users are members of small, well-defined professional scientific communities where perceived (or real) professional retribution could be taken by the established professional "system" or "community."

As Covey points out, the key to being a highly effective organization is to keep production and production capability in a dynamic balance. Within many DOE funded research environments, however they are often out of balance. On the one hand, when some laboratories are asked to report on their performance, they wax eloquent on "what great science" they do, but back away from discussions about whether they have a well-defined management system, how well they are managing their resources, or how responsive they are to their customers - they want to talk about production, not production capability. On the other hand, because many DOE personnel do not have the technical competence to assess whether laboratories are doing good science, they tend to focus on whether they have a well-defined management system, how responsive laboratories are to their customers (meaning themselves), and how well they are managing their resources - they talk about production capability without production. Highly effective organizations have an ecological balance between production and production capability. I believe that the performance of the DOE complex can be made more effective by implementing the four performance parameters I have defined above, and then deriving metrifed performance objectives that can subsequently be used to evaluate laboratory and DOE performance toward mission.

Quality Management Assessments

If the performance of research laboratories can be parameterized and metrified along the lines I have suggested above, and if focusing on P/PC balance can increase the production capability of research laboratories, how do we begin the process of developing and implementing Covey-based TQM, and how do we assess the progress made? Key to beginning the quality journey is to commit the organization to a unified set of management principles such as the MBNQA criteria or Principle

Centered Leadership and a unified set of individual values and principles such as Covey's 7 Habits. Then a well-defined management system tailored to the organization can be generated and personnel at all levels in the organization can be trained extensively in those principles. Although training can be viewed as a cure-all (gotta problem, throw some training at it), it is crucial to implementing institution-wide quality. A common criticism will be "This is just the flavor of the month." One way to overcome the "flavor of the month" criticism is to commit to a set of management principles and stick with them *for more than a month or a year*. In organizations where the above components are founded upon the personal commitment of senior managers, an organization has the necessary components to begin the quality journey

At NREL, we have found that one way to both jump-start implementation and baseline the level of understanding, implementation, and support for QM is through baseline assessments using a modified version of the MBNQA criteria. The assessments are designed to provide feedback to division managers, to help them gain new insights into how their organization is actually functioning, to help them more effectively implement quality management, to identify performance issues that could lead to improved performance, and finally to educate personnel in their organization. To date, we have assessed four of NREL's seven technical divisions and one of the laboratory's five administrative offices and divisions.

The conduct of the assessments departs from some of the practices normally associated with more compliance-oriented audits or assessments in two ways. First, the assessment criteria (which are a modified version of the MBNQA criteria and some of Covey's principles) are transmitted to the assessed organization along with the notification of the assessment. In addition, hybrid assessment teams were formed that include personnel from the quality function in the Deputy Director for Operation's Office, the DOE Golden Field Office, several of NREL's technical divisions, DOE EE-64, and a subset of people from the assessed organization. The hybrid nature of the assessment team is an attempt to use the strength that comes from having both insider and outsider perspectives, and also to move beyond any rigid distinction between manager (self) and independent assessments. The lead assessor and subteam leaders are always organizationally independent from the work performed by the assessed organization.

In keeping with the approach used for MBNQA assessments, the assessment team provides feedback on strengths and areas for improvement. Because the assessment teams are chartered by the deputy director for operations and because DOE field and DOE headquarters personnel are members of the team, the assessment team is free to not only identify areas for improvement in the assessed organization, but also in NREL's directorate, and in DOE organizations. The assessment team also performs a confidential pre-assessment survey of all personnel in the assessed organization. Respondents are instructed to return completed surveys to the lead assessor, who asks subteams to prepare draft reports prior to seeing the survey results. This is an added control on data gathering and interpretation. Once draft reports are complete, subteams have access to the pre-assessment survey results.

The final key is corrective action, which can only happen when senior managers hold their line managers and staff accountable for internalizing and acting on assessment results. At NREL, the deputy director for operations holds division directors and office managers accountable for corrective action plans by making them part of that manager's performance evaluation. One NREL success story is our Alternative Fuels Division where the division director formed a corrective action plan team composed of Alternative Fuels Division managers, assessment team members, and DOE customers, then introspectively evaluated the findings, performed root-cause analysis, and rolled the root causes up into three major themes. Subsequently, almost all Alternative Fuels Division managers and staff have received substantial training in *The 7 Habits of Highly Effective People*, the MBNQA criteria, and other principles of QM. Also, because of organizational problems revealed in the assessment, the Alternative Fuels Division eliminated their hierarchical organization, reorganizing into a series of overlapping circles (called bubbles), that are in effect cross-functional, self-directed work teams. They have begun the process of understanding and evaluating the processes by which these teams operate, and of reengineering their management system. Finally, they have established a technical and QM partnership with Eastman Chemical's Research Division, winners of the 1993 Malcolm Baldrige National Quality Award, and are striving to become world class. One of the most important lessons that Eastman learned along their journey to winning the National Quality Award was that QM training, teams, and other legitimate quality functions are *means* to an end, *not ends in themselves*.[26] The key for Eastman was to define quantitative measures of performance for the main output of their organization (what I have called metrified performance objectives), and focus on those results. We are learning from our relationship with Eastman and are developing a similar approach here at NREL.

Conclusions

I believe that the Fermilab case study shows that scientists performing even the most basic experimental science can use the CS/PS model to describe the activities of laboratory life. Given the fact that science is work, not volunteerism, I believe that the four performance parameters can be used to guide the kinds of questions needed to evaluate DOE-funded research laboratories, whether they do basic or applied research. More specifically, I believe that they can be used as a basis for what has come to be known as "contract reform."[27] Understanding the P/PC balance between questions such as 1) Do they have a well defined management system? 2) Are they doing good science? 3) Are they managing their resources effectively? 4) Are they responsive to their customers?, and understanding those questions based on metrified performance objectives, actually gets at what laboratory managers and DOE stewards really want to know about how laboratories are functioning. Making sure that production and production capability are in balance, viewing QM training, teams, and other activities as a means to improved performance rather than an end in itself, focusing on metrified performance outputs are all great challenges, but the greater challenge is just *doing* it, rather than talking about it.

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[26] Jerry D. Holmes and David J. McClaskey, "Improving Research Using Total Quality Management," in Vol. 1 of *The Proceedings of the Juran Institute's 10th Annual IMPRO 92 Conference*, 1992, pp. 3B-13-22.

[27] The concepts of contract reform were recently articulated at the 23rd Annual ASQC Energy and Environmental Quality Division Conference in February 1995 by Jerry Bellows, Director of the Contract Reform Project Office, in a presentation entitled, "Department of Energy Contract Reform Initiative."