Evaluating Public Sector R&D Programs: The Advanced Technology Program's Investment in Wavelength References for Optical Fiber Communications

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Abstract:

Griliches (1958) [*Journal of Political Economy,*66: 419--431] and Mansfield *et al.* (1977) [*Quarterly Journal of Economics* 91: 221--240] pioneered the application of fundamental economic insight to the development of measurements of private and social rates of return to innovative investments. This paper illustrates field-based methods for measuring the social rates of return to innovative investments by the public sector. The case study described herein relates to the development of an improved standard reference material for the measurement of the wavelength of light in an optical fiber network.

Keywords: social rate of return | benefit-cost analysis | internal rate of return | net present value | program evaluation | innovation

Article:

1. Introduction

Fundamental to an evaluation of any federal program, research program or otherwise, is that the program is accountable to the public. For research programs, such accountability refers to being able to document and evaluate research performance using metrics that are meaningful to the institutions' stakeholders—the public, including the taxpayers.[1] Metrics developed for assessing

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[1] The Government Performance and Results Act of 1993 (GPRA) required that public institutions' research programs identify outputs and quantify the economic benefits of the outcomes associated with such outputs. Some public agencies have skirted the issue by arguing that the research they do or that they fund is peer reviewed, and thus it is sound; and if the research is sound, it must be socially valuable. Many embrace the importance of having research peer reviewed both at the pre-funding stage as well as upon completion. However, the peer review process certainly does not address in any precise or reliable way whether or not the research is socially valuable from an economic standpoint. It is not so much that a formal analysis of social economic rates of return is officially out of bounds for the peer review process; rather, such an analysis is simply not a part of the peer review process as it currently exists. Other public agencies are attempting to be more exact in their approach to meeting the GPRA requirement to quantify outcomes' benefits. However, the hurdle that is difficult to clear for most public agencies is how to quantify benefits in a methodologically sound and defensible way.

returns to private investment have been adapted to public investments using case-study techniques that emphasize analysis of public benefits to research users and taxpayers.

With any performance evaluation, it is generally assumed that the government has an economically justifiable role in supporting innovation because of market failures stemming from, among other things, the private sector's inability to appropriate returns to investments, the public-good nature of the research focus, or the riskiness of those investments.[2] Ignoring such an assumption may imply that any evaluation of a public research program is wanting in the sense that the program should initially be scrutinized on first principles as to why it is even undertaking research.

Griliches (1958) and Mansfield et al. (1977) pioneered the application of fundamental economic insight to the development of measurements of private and social rates of return to innovative investments. Streams of investment costs generate streams of economic benefits over time. Once identified and measured, these streams of costs and benefits are used to calculate such performance metrics as social rates of return and benefit-to-cost ratios.

For example, for a process innovation adopted in a competitive market, using the traditional framework, the publicly-funded innovation being evaluated is thought to lower the cost of producing a product to be sold in a competitive market. As the innovation lowers the unit cost of production, consumers will actually pay less for the product than they paid before the innovation and less than they would have been willing to pay—a gain in consumer surplus. The social benefits from the innovation include the total savings that all consumers and producers receive as a result of producers adopting the cost-reducing innovation. Depending on the extent to which reduced costs are reflected in the price charged to consumers, social benefits are shared by producers who adopt the innovation and consumers of their products. Thus, the evaluation question that can be answered from this traditional approach is: Given the investment costs and the social benefits, what is the social rate of return to the innovation?

This paper, written in honor of Ed Mansfield, illustrates—in the context of a public sector investment—the Griliches/Mansfield pioneering field-based methods for measuring the social rates of return to innovative investments. The case study described herein relates to the development of an improved standard reference material (SRM) for the measurement of the wavelength of light in an optical fiber network. That research, which was conducted at the National Institute of Standards and Technology (NIST), was funded by an intramural grant through NIST's Advanced Technology Program (ATP).

The following Section 2 briefly describes ATP's intramural research program. Section 3 overviews the case study, and relevant social rate of return metrics are presented in Section 4. Section 5 concludes the paper with general observations about the evaluation of public sector R&D.

2. ATP's intramural research program

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[2] The origin of this assumption can be traced at least to Bush (1945), although Link and Scott (1998, 2001) have placed this assumption in a specific policy context.

Since its inception in 1990, ATP has stimulated economic growth through the development of innovative technologies that are high in technical risk and enabling in the sense of having the potential to provide significant, broad-based economic benefits.[3] Industry proposes research projects to ATP in competitions in which proposed projects are selected for funding based upon both their technical and economic or business merits.

The ATP intramural research program provides funding to NIST laboratories to conduct research to advance the U.S. technology infrastructure in order to assist industry in continually improving products and services. Under the statute governing ATP, up to 10% of ATP's budget could be allocated for this research. Since 1997, ATP required that these intramural projects:

- emphasize generic basic research,
- relate to groups of ATP extramural projects, and
- focus on measurement and standards that would facilitate the deployment and diffusion of technologies developed in ATP extramurally-funded projects.

3. Case study of wavelength references for optical fiber communications

The goal of this research project was to develop an improved SRM for the measurement of the wavelength of light in an optical fiber network.

The Optoelectronics Division of the Electronics and Electrical Engineering Laboratory began research on optical communications in the mid-1970s and expanded its research program substantially in the late 1980s. The Optical Fiber and Components Group of the Division began research on SRMs in 1991. The Group's first SRM became available in 1993; with SRM 2520, an optical fiber diameter standard. Since then the Group has produced a number of optoelectronic standards. SRM 2517 was issued in 1997; it was intended for use in calibrating the wavelength scale of wavelength measuring equipment in the spectral region from 1510 to 1540 nm.

In 1998, Dr. Sarah Gilbert in the Optical Fiber and Components Group began a two-year ATP intramural project to develop a more accurate version of SRM 2517. Dr. Gilbert received \$145,000 over two years—\$70,000 in fiscal year 1998 and \$75,000 in fiscal year 1999. The project produced the new SRM for calibration of wavelengths in the spectral region from 1510 to 1540 nm. The references in the 1500 nm region are important to support wavelength division multiplexed (WDM) optical fiber communications systems. In a WDM system, many channels, each associated with a different wavelength, of communication information are sent down the same fiber. Thus, WDM in effect increases the bandwidth of the communications system, because any given spectral region will support more channels through which communications information can be sent. A WDM system requires stable wavelengths throughout the components of the system, and equipment must be calibrated to measure those wavelengths. The wavelength references provided by NIST are needed to calibrate the instruments—such as optical spectrum analyzers, tunable lasers, and wavelength meters—that are used to characterize the components of WDM optical fiber communications systems. The wavelength references are also used to

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[3] For background information about ATP see, for example, Link and Scott (1998, 2001).

monitor the wavelengths of the channels while the system is in use, because if one channel's wavelength were to shift, crosstalk could occur between it and a neighboring channel, thus disrupting the accurate flow of communications information through the channels of the system.

The output of Dr. Gilbert's ATP-funded NIST research with William Swann was Standard Reference Material 2517a, High Resolution Wavelength Calibration Reference for 1510—1540 nm Acetylene (12C2H2). Quoting NIST's description of the new SRM provides an exact description of the artifact—an "absorption cell" filled with acetylene gas that produces characteristic "absorption lines" in the readouts resulting when lasers project light of various wavelengths through the gas-filled cell. The absorption lines observed can then be used to identify the wavelengths for the laser emitting device being calibrated.[4] NIST's description of the artifact is as follows.[5]

> "Standard Reference Material 2517a is intended for wavelength calibration in the spectral region from 1510 nm to 1540 nm. It is a single-mode optical-fiber- coupled absorption cell containing acetylene (12C2H2) gas at a pressure of 6.7 kPa (50 Torr). The absorption path length is 5 cm and the absorption lines are about 7 pm wide. The cell is packaged in a small instrument box (approximately 24 cm long × 12.5 cm wide × 9 cm high) with two FC/PC fiber connectors for the input and output of a user-supplied light source. Acetylene has more than 50 accurately measured absorption lines in the 1500 nm wavelength region. This SRM can be used for high resolution applications, such as calibrating a narrowband tunable laser, or lower resolution applications, such as calibrating an optical spectrum analyzer."

The primary difference between the new wavelength calibration standard, SRM 2517a, and its predecessor, SRM 2517, is the use of lower pressure in the acetylene cell to produce narrower lines. Because of that difference, SRM 2517a can be used in higher resolution and higher accuracy applications.

This ATP intramural project complemented the SRM-related research of the Optical Fiber and Components Group and was a natural extension of previous research related to SRM 2517. While research on SRM 2517a would have occurred in the absence of ATP's support, it would not have progressed as rapidly. According to Dr. Gilbert: "The ATP funding accelerated this project and enabled us to complete the development of a new wavelength calibration SRM about 1 year faster that we would have without this funding."

Thus, if ATP had not funded the project, in the course of its ongoing operations, the NIST laboratory would have invested a similar amount, but the streams of costs and benefits would have begun roughly a year later. In this paper, we evaluate the social rate of return from the investment in the project. We do not try to identify the incremental gain from having the project

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[4] Because of fundamental molecular absorptions when light is projected through the absorption cell filled with acetylene gas, the power transmitted through the cell is distinct at specified wavelengths, allowing accurate references to those wavelengths. Those references can then be used to calibrate instruments for industry.

[5] Gilbert, Sarah L., and Swann, William C., Acetylene $^{12}C_2H_2$ Absorption Reference for 1510 nm to 1540 nm Wavelength Calibration—SRM 2517a, NIST Special Publication 260–133, 2001 Edition, Standard Reference Materials, Issued February 2001 (Washington, D.C., U.S. Government Printing Office, 2001), p. 2.

funded by ATP rather than the NIST laboratory that performed the research. NIST has been selling SRM 2517a at a rate of two to three per month since it was introduced in late 2000.[6]

4. Estimating the social rate of return

The traditional evaluation method pioneered by Griliches and Mansfield is used in this case study to estimate the social rate of return to ATP's (i.e. the public sector's) investments in SRM 2517a.[7] To implement that method, two general data series are needed. One data series is related to investment costs, and in the case of this study the relevant investment costs are those associated with the ATP intramural project.[8] The other data series is related to the benefits realized by society, net of society's costs to use the innovation (i.e. pull costs). Society includes both private sector companies and consumers. ATP's investment costs are known.

Benefit data have to be collected, and these data can be of two types. Benefit data can be retrospective in nature, meaning that the company or consumer who has benefited from the ATP

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[6] The rough breakdown of all of the SRM 2517a sales by industry category is 45% to manufacturers of test equipment, 30% to manufacturers of components, 10% to companies providing network systems, and 15% to other users—mostly research laboratories—of the SRM. According to Dr. Gilbert, a company will typically purchase one SRM 2517a.

[7] Link and Scott have developed, through ongoing evaluations of federal research programs, an alternative approach to the *economic* evaluation of publicly-funded research. This approach differs from traditional evaluation methods that have been used in addition to peer review. The alternative approach is needed to provide additional insights because the traditional evaluation methods are limited in an evaluation world that is performance accountable. The genesis of this approach is in Link (1996a), and recent applications are in Link (1996b) and Link and Scott (1998, 2001). Link and Scott, and others, have used this approach in a number of the evaluation studies sponsored by the Program Office at NIST, as well as in several ATP-sponsored projects. More specifically, and in general terms, Link and Scott argue that asking what is the social rate of return to an innovation and asking how that compares to the innovator's private rate of return may not always be the most appropriate question to ask. The fact that the social rate of return is greater than the private rate of return does indeed provide evidence that there are benefits spilling over to society. However, the fact that the social rate of return is greater than the private rate of return ignores consideration of the cost effectiveness of the public sector undertaking the research as opposed to the private sector. In other words, the Griliches/Mansfield traditional evaluation method does not address the efficiency with which social benefits are being achieved. Two alternative evaluation methods could be more appropriate for publicly-funded research. When publicly-funded publicly-performed investments are being evaluated we argue that our Counterfactual Evaluation Method could be appropriate. Holding constant the economic benefits that the Griliches/Mansfield model measures, and making no attempt to measure that stream, the counterfactual evaluation question is: What would the private sector have had to invest to achieve those same benefits in the absence of the public sector's investments? See as an example of the Counterfactual Evaluation Method Link and Scott (1998). Alternatively, when publicly-funded privately-performed investments are being evaluated, we argue that our Spillover Evaluation Method could be appropriate. The question asked is one that facilitates an economic understanding of whether the public sector should be underwriting a portion of private-sector firms' research, namely: What proportion of the total profit stream generated by the private firm's R&D and innovation does the private firm expect to capture; and hence, what proportion is not appropriated but is instead captured by other firms that imitate the innovation or use knowledge generated by the R&D to produce competing products for the social good? The part of the stream of expected profits captured by the innovator is its private return, while the entire stream is the lower bound on the social rate of return. The extent of the spillover of such knowledge with public good characteristics could determine whether or not the public sector should have funded the research. See as an illustration of the Spillover Evaluation Method, Link and Scott (2001).

[8] As relevant, other investment costs will be discussed below. Such investment costs are costs that the private sector will incur to utilize the ATP project's output. These are, stated differently, the costs incurred by the private sector to pull in ATP's output and utilize it efficiently. Hence, these costs are referred to as pull costs.

project has already realized benefits; or benefit data can be prospective in nature, meaning that the company or consumer who will benefit in the future from the ATP project can estimate when and to what degree benefits will be realized.[9] Both types of benefit data were collected in this study.

Benefit and cost information[10]

Detailed descriptions of the uses of SRM 2517a are provided below, but in overview NIST's experience suggests that most of the test equipment manufacturers in industry use the SRM units to conduct periodic calibration checks on their equipment. The calibration checks with the SRM are not typically in the production line where various intermediate standards are used for routine calibration checks. Rather, the SRM is used to check those intermediate standards. Some of these test equipment manufacturers make absorption cells—commercial versions of the SRM 2517a artifact described above—to incorporate into their products. In those situations where the absorption cells are purchased, discussions with industry experts reveal that SRM 2517a is used both to check the commercial versions of the absorption cells and for study as a manufacturing guide in the production of the commercial high-volume versions of the cell. Discussions with industry show that the component manufacturers often integrate the SRM 2517a into their production lines to continuously calibrate their equipment. Network systems providers use the SRMs to calibrate their test equipment.

The industry costs and benefits for SRM 2517a are based on estimates—obtained through detailed telephone interviews—from industry respondents that collectively have purchased about 30% of the SRM 2517a cells.[11]

Discussions with industry identified several types of benefits and costs associated with SRM 2517a. Benefits fall within five general categories: production related engineering experimentation cost savings, calibration cost savings, yield, negotiation, and marketing. Costs are the ATP development costs plus the pull costs associated with using the SRM purchased from NIST.

Separating the benefits from SRM 2517a from the benefits from other SRMs in the 25xx family was often difficult for industry respondents.[12] Some use the entire set of SRM 25xx artifacts; those respondents sometimes think of the set of artifacts as an integrated whole, covering different parts of the spectrum of wavelengths to which equipment must be calibrated. Thus, to some extent the benefit estimates below reflect a joint benefit from the set of NIST SRM 25xx artifacts. However, there are also major sources of unmeasured industrial benefits from SRM 2517a. As a result, the benefit estimates used are, on balance, conservative for at least three

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[9] Of course, it is assumed that the benefit information provided by interviewed individuals is accurate and reproducible should subsequent interviews by others take place.

[10] The data developed for discussion of the outcomes in this case study are based on discussions with Dr. Gilbert and several industry experts from Wavelength References, Burleigh Instruments, Corning, Agilent, and Chorum Technologies.

[11] The information about the industry-wide coverage of our sample of respondents in industry was provided by NIST.

[12] For a discussion of other optoelectronics SRMs, see: http://patapsco.nist.gov/srmcatalog/tables/view_table.-cfm?table=207–4.htm.

reasons. First, the estimates are truncated after 10 future years, even though some respondents believed that the commercial usefulness of SRM 2517a would extend well beyond that period. Second, and more importantly, many respondents could not quantify the loss in sales, and therefore profits, that would occur without traceability to NIST of their wavelength calibrations. And third, the benefit estimates reflect only the benefits to the purchasers of the NIST SRM 2517a artifacts; they do not capture the additional benefits to users further down the supply chain.[13] Given these sources of downward bias, we believe that, on balance, the benefit estimates used to compute the evaluation metrics to characterize the outcomes of SRM 2517a are conservative. Use of SRM 2517a results in:

- *Production related engineering and experimentation cost savings*: Users of SRM 2517a regularly conduct what we call production related engineering experimentation.[14] These activities are an important aspect of production. The new more accurate measurement technology associated with SRM 2517a lowered the cost of these activities and hence represents a cost-savings benefit. Also experimentation costs for industry have been lowered because of industry's interaction with the NIST scientists that developed the artifact.[15]
- *Calibration cost savings*: SRM 2517a reduces the costs of calibrating production equipment and products. It is not uncommon to recalibrate production devices for an optical fiber network on a daily basis, or even more frequently. SRM 2517a reduces the cost of each calibration; it permits equipment to be calibrated on the production floor. The alternative would be to purchase tunable lasers, which not only are more costly but also must be set for one frequency at a time, whereas the SRMs provide a fingerprint covering a whole range of the spectrum of wavelengths. In addition, tunable lasers entail additional operating time using well-trained technicians involved in production.[16]
- *Increased production yields*: Production yields have increased because SRM 2517a improved process control and thereby reduced the costs of product failure. Manufacturers of optical fiber network components manufacture to the customer's specifications and needs. SRM 2517a, as well as other SRMs in the 25xx series, provide useful reference points across a stable wavelength range for the tuning of the components for optical communications systems. As a costly and less accurate alternative, the points of reference could be simulated with expensive cascades of optical filters strung together.[17]

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[13] As one respondent whose company manufactures commercial gas cells (based on SRM 2517a) for use in instruments stated: "If there were no SRM 2517a, all along the way through the supply chain the additional calibration expenses (suites of equipment and extra labor costs) would be incurred. Roughly half of the optical spectrum analyzers sold to industry incorporate the SRM 2517a technology to calibrate better. There would be extra expense and time at each research site."

[14] Our understanding is that these activities fall under the rubric of research and development (R&D), but absent information about how companies classify these activities we refrain from using the policy-sensitive term "R&D."

[15] To paraphrase one industry expert: SRM 2517a reduced our investigation costs; we would have invested additional engineering person-years with equipment to maintain production. See also the note to Table I.

[16] One respondent, whose company manufactures locked lasers and gas cells, observed that the alternative to SRM 2517a for calibration is to invest in a suite of equipment and then take the extra time to get the calibration results. A telecommunications company responded that prior to SRM 2517a it relied on its own internal standards based on one frequency and then extrapolated to other frequencies. The company's expert stated that the SRM 2517a standard, with multiple indicators of various frequencies, is a critically important advance for telecommunications.

[17] A manufacturer of narrow band optical filters told us: SRM 2517a provides narrow line widths for reference to absolute vacuum wavelengths and this is critical to meeting the performance specification needs of our customers.

- *Negotiations cost savings*: Negotiation with customers over disputes about the performance attributes of products are reduced because of SRM 2517a and the traceability to the NIST standard that it provides. In the absence of wavelength stability, manufacturers and customers would both have grounds to disagree about performance characteristics. Without SRM 2517a and the traceability that it provides, costly negotiations and testing would occur.[18]
- Reduced marketing costs: Marketing costs are reduced because of the traceability of an important new standard to NIST that SRM 2517a allows, and sales are greater than for SRM 2517 because of the confidence inspired by the new standard traceable to NIST.[19]

Quantitative estimates of each of the above categories of benefits were obtained from the five manufacturers with whom we spoke. According to Dr. Gilbert, these five companies collectively have purchased about 30% of the SRM 2517a cells sold to date. The benefit data in Table I captures industry-wide benefits. Each datum in Table I is the product of the sum of the dollar values for each respondent multiplied by 3.33 (3.33 = 1/0.30), and all dollar values are converted to year 2000 dollars.

To be conservative, the estimated benefits from SRM 2517a are truncated after ten years. Respondents indicated that the SRM 2517a provided knowledge that would be commercially useful for the foreseeable future. Some respondents emphasized that, as a standard, the knowledge embodied in SRM 2517a would last and be useful virtually forever. However, industry may require even more development of the standards for measuring the wavelength of light as time passes, and the respondents as a group believed that a commercial lifetime of ten years would be a conservative estimate for the period of industrial use of SRM 2517a.

The observed variance through time in the benefits (in year 2000 dollars) reflects three key things. First, there are different periods of primary incidence for the various cost savings. For example, production-related engineering cost savings occur primarily in the early years of the time series and in some cases even before the introduction of SRM 2517a.[20] In contrast, the costs of reduced yields (benefit of increased yields) are avoided throughout the time series after SRM

This artifact gives us an unquestionable reference to absolute wavelengths so that secondary standards can be recalibrated as they drift. Our alternative, over say 30 nm of wavelength range for a particular product, maybe 10 optical filters would be strung together. While the cost of this alternative is not that great, performance tolerances and wavelength stability would be lost. Using the alternative would have resulted in a yield loss of about 30%.

[18] One respondent noted that without NIST traceability through SRM 2517a, interactions with the customers over performance characteristics would be like dealing with “a wound that would not heal.”

[19] Paraphrasing a component manufacturer: There are two parts to the sales/marketing impact of SRM 2517a for our company. First, there is a savings in personnel costs because there is less effort needed to convince customers about the quality and reliability of our products. More importantly, there is a positive effect on our reputation and the customers’ confidence in our product line because of having NIST standards integrated in the production process. That positive effect translates into extra sales and extra profits. Paraphrasing a manufacturer of wavelength meters: We use SRM 2517a as we manufacture wavelength meters. SRM 2517a is used to check periodically the calibration of test lasers and equipment used for the qualification of our wavemeters. We can claim traceability to NIST. There are cost savings to us in the sales/ marketing category.

[20] Industry interacts with NIST and stays abreast of the latest developments through direct communication with NIST scientists, and through scientists’ presentations and publications. In this case, some respondents reported that they began benefiting from the new knowledge—gained from interaction with NIST researchers—about wavelength calibration even before SRMs were sold, as industry coped with the need for the actual SRMs but substituted experimental work in their absence.

2517a was introduced and the technology transferred to industry. Second, the introduction of SRM 2517a occurred in late 2000 and partial-year benefits are reported; benefits increase in subsequent years since the SRM is used throughout each year. Third, the variance over time reflects the collapse of optical fiber communications industry sales from record highs in 2000–2001 to low levels in 2002. Projections by industry then reflect an expected recovery of industry sales to the levels experienced in 1999—levels that in 1999 were between one-third and one-half of their subsequent peaks in 2000–2001 before the bubble burst—by 2004–2005. Thereafter, the projections reflect what knowledgeable industry observers expect to be a 15% rate of growth.

Table I. Industry benefits truncated at 10 years (year 2000 dollars)

Year	Production cost savings ($1000s)	Calibration cost savings ($1000s)	Increased production yield ($1000s)	Decreased negotiation costs ($1000s)	Decreased marketing costs ($1000s)
1999	$3,193.9				
2000	$3,266.5	$401.0	$2,613.3	$245.0	$473.7
2001	$1,388.3	$1,832.6	$10,531.7	$1,094.3	$1,894.7
2002	$1,682.3	$353.5	$2,106.3	$218.9	$383.0
2003	$1,388.3	$441.8	$2,632.9	$273.6	$478.8
2004	$1,388.3	$589.7	$3,514.2	$365.2	$639.0
2005	$1,388.3	$735.8	$4,384.6	$455.6	$797.3
2006		$846.8	$5,046.5	$524.4	$917.7
2007		$973.8	$5,803.2	$603.0	$1,055.2
2008		$1,119.9	$6,673.7	$693.4	$1,213.5
2009		$1,287.8	$7,674.7	$797.5	$1,395.6

Note: Production related engineering and experimentation cost savings decrease in 2001 because, although some experimental production uses of the measurement technology were reported after the introduction of the SRM, the most intense realization of such experimental benefits came from the application of the new measurement technology—gained in industry's interaction with NIST through publications, presentations, and ongoing interaction with the researchers—to production problems encountered by industry as it coped with the need for the actual improved SRM and substituted experimentation for it. Publications about the SRM 2517a technology started appearing in 1999. The other categories of industry benefits increase after the introduction of the SRM 2517a because those benefits reflect the actual use of the SRMs once they were available for use.

The costs associated with the SRM 2517a project are in Table II. The actual costs of the ATP intramural project are shown along with estimates of the pull costs for industry. Respondents were asked to estimate any initial costs, over and above any fees paid to NIST for SRM 2517a to be able to use (i.e., pull in) the artifact in production. These pull costs are one-time costs.

Table II. Estimated costs associated with SRM 2517a (year 2000 dollars)

Year	ATP Funds ($1000s)	Industry pull cost ($1000s)
1998	$72.6	
1999	$76.7	
2000		$16.3
2001		$73.5

Table III aggregates the cost and benefit estimates from Tables I and II.

Table III. Estimated total costs and estimated total industry benefits associated with SRM 2517a (year 2000 dollars)

Year	Total costs ($1000s)	Total industry benefits ($1000s)
1998	$72.6	
1999	$76.7	$3,193.9
2000	$16.3	$6,999.5
2001	$73.5	$16,741.6
2002		$4,744.0
2003		$5,215.4
2004		$6,496.4
2005		$7,761.6
2006		$7,335.4
2007		$8,435.2
2008		$9,700.5
2009		$11,155.6

Results of the economic analysis

Table IV summarizes the four evaluation metrics calculated for this case study.[21] Clearly, based on one or all of the metrics in Table IV, the ATP intramural funded SRM 2517a project was successful from society's economic perspective. The internal rate of return is 4,400%, the benefit-to-cost ratio is 267 to 1, and the net present value in 2002 in year 2000 dollars is 76 million.

Table IV. Evaluation metrics for the SRM 2517a case study

Metric	Estimate
Real internal rate of return	4,400%
Benefit-to-Cost ratio	267 to 1
Net present value using 1998 as base year in year 2000 dollars	$58.1 million
Net present value using 2002 as base year in year 2000 dollars	$76.2 million

The metrics in Table IV reflect the social return on investments, and these are the returns that economists call producer surplus. Producer surplus is the profit resulting because of the use of the infratechnology embodied in SRM 2517a. Although the estimate will be a rough one, we are also able to provide a first-order approximation of the consumer surplus gains as well. Figure 1 represents the situation for the typical company selling a differentiated product that uses SRM 2517a in the production process.[22] The availability of the new standard reference material lowers the unit costs as shown in the figure from "unit cost 2517" to "unit cost 2517a." Consequently,

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[21] Regarding evaluation metrics, see the appendix to this paper.

[22] As is seen in Figure 1, in addition to gaining new profits that we have identified as industrial benefits, industry loses some of its previous profits on the previous amount sold before unit costs fell because the use of SRM 2517a lowers costs and consequently price falls. However, those lost profits (lost producer surplus) are completely offset by a gain of exactly that amount in consumer surplus, leaving just the new profits measured in Table III and represented by A + B + C in Figure 1 as the increase in total surplus because of increased producer surplus. The net gain in consumer surplus (represented by D in Figure 1) is then added to get the change in total economic surplus that is the social return to the use of SRM 2517a—consumers gain more than D, but that additional gain is exactly offset by an equal amount of lost previously existing surplus for producers, leaving D as the net gain in consumer surplus.

the company chooses a lower price and sells more of its product or service.[23] The company's profit maximizing price falls from P_1 to P_2, and the optimal output increases from Q_1 to Q_2. The new surplus—resulting because of the new lower unit costs of production enabled by SRM 2517a—is the sum of the areas A, B, C, and D. Area A represents the new producer surplus on sales of the original amount of output. Area B plus area C represents the new producer surplus from the sale of additional output. Finally, area D represents the net gain in consumer surplus (new consumer surplus that does not simply offset a loss in previously existing producer surplus).

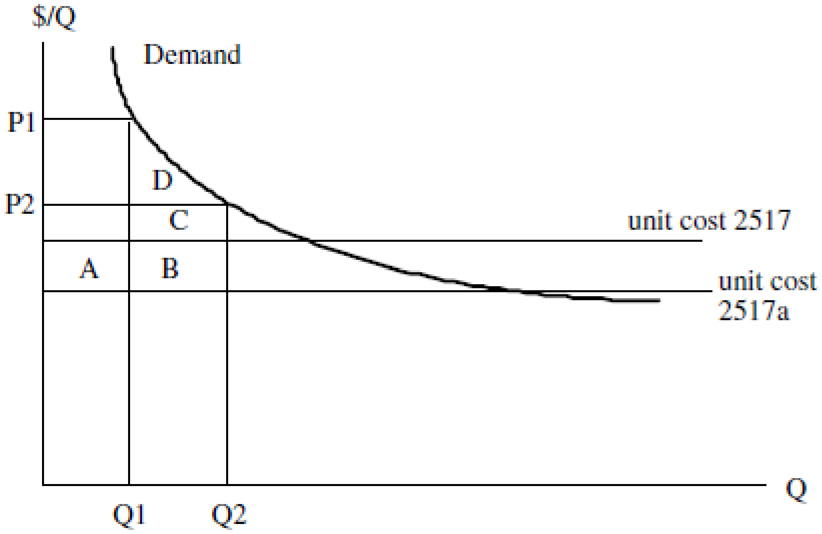

Figure 1. Demand, unit cost and net gain in producer and consumer surplus from the use of SRM 2517a.

Table V. Revised evaluation metrics for the SRM 2517a case study using total benefits (net gains in the total of producer surplus and consumer surplus) (year 2000 dollars)

Metric	**Estimate**
Real internal rate of return	5,500%
Benefit-to-Cost ratio	331 to 1
Net present value using 1998 as base year in year 2000 dollars	$72.0 million
Net present value using 2002 as base year in year 2000 dollars	$94.4 million

Details about price, output and unit cost are considered highly confidential and the industry respondents were typically unwilling to provide such information. However, one of the respondents was willing to provide detailed information, for its own production, about P1, P2, Q1, Q2, and unit cost both before SRM 2517a was introduced and then after it replaced SRM 2517. For that company, the ratio of net new consumer surplus to new producer surplus, D/(A + B + C), equals 0.238. That company conjectures that its experience with the cost lowering effect of replacing SRM 2517 with SRM 2517a would be similar to the experiences of others in the industry. Therefore, as a first-order approximation of consumer surplus gains because of the process innovations from applying SRM 2517a, we multiply the new producer profits—the industry benefits column of Table III—by 0.238. Table V recalculates the metrics for the SRM

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[23] Note that Figure 1 depicts optimal output in the long run when all costs are variable.

2517a project by using the total of the net gains in producer and consumer surplus (the industrial benefits from Table III multiplied by 1.238) as the social return on the investment.

5. Concluding observations

Public agencies have taken their own idiosyncratic approaches to respond to the Government Performance and Results Act of 1993 (GPRA), and researchers have offered a variety of evaluation methods in the pages of this journal and others. Whatever the merits of the numerous alternatives to the approach based on the Griliches/Mansfield estimation of the social rate of return for the public investments, the Griliches/Mansfield method is the preeminent way to evaluate public investments' social value from an economic perspective.[24] The Griliches/Mansfield methodology is so important that it could usefully have a category of its own among the subset of categories in the *Journal of Economic Literatur*e category for technological change (O300—Technological Change; Research and Development: General). We hope that our case study has illustrated the usefulness of their methodology for evaluating public investments.

Appendix: Quantifying Social Rate of Return Metrics

Using the time series for costs and benefits, measured in constant dollars, the internal rate of return, the benefit-to-cost ratio, and the net present value for the project were calculated in this case study using the year when each project began as the base year. In addition to those three customary metrics, net present value referenced to year 2002 was also computed since it is the year in which the calculations were originally performed.

The metrics are calculated from the time series of costs and benefits in year 2000 dollars. Costs and benefits were converted to constant dollars to allow all dollar figures to be directly comparable. All dollar figures have been converted to year 2000 dollars using the chain-type price index for gross domestic product provided in the *Economic Report of the President*.[25] Year 2000 was chosen because, at the time that the case study was conducted, that was the most recent year for which complete annual data were available.

Internal rate of return[26]

The internal rate of return (IRR) is the value of the discount rate, i, that equates the net present value (NPV) of the stream of net benefits associated with a research project to zero.[27] The time series runs from the beginning of the research project, $t = 0$, to a terminal point, $t = n$.

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[24] As we have noted above, for GPRA purposes, it will sometimes be appropriate to use the development of the Griliches/Mansfield methodology that we have incorporated in our Counterfactual Evaluation Method and our Spillover Evaluation Method.

[25] See CEA (2002), Table B-7, "Chain-type price indexes for gross domestic product, 1959–2001." The index number for 2001 was estimated as the average of the three quarterly observations available.

[26] The characterization of the three metrics follows Link and Scott (1998).

[27] Using the constant dollar figures for costs and benefits, the internal rate of return is a "real" rate of return. In contrast, some economic impact assessments (including many conducted for NIST's Program Office) have presented "nominal" rates of return that were based on time series of current dollars (the dollars of the year in which the benefits were realized or the costs were incurred).

Mathematically,

$$\text{NPV} = [(B_0 - C_0)/(1+i)^0] + \cdots + [(B_n - C_n)/(1+i)^n] = 0 \quad (1)$$

where $(B_t - C_t)$ represents the net benefits associated with the project in year t, and n represents the number of time periods—years in the case study evaluated in this paper—being considered in the evaluation.

For unique solutions for i, from equation (1), the IRR can be compared to a value, r, that represents the opportunity cost of funds invested by the technology-based public institution. Thus, if the opportunity cost of funds is less than the internal rate of return, the project was worthwhile from an *ex post* social perspective.

Benefit-to-cost ratio

The ratio of benefits-to-costs (B/C) is the ratio of the present value of all measured benefits to the present value of all measured costs. Both benefits and costs are referenced to the initial time period, $t = 0$, when the project began as:

$$B/C = \left[\sum_{t=0}^{t=n} B_t \Big/ (1+r)^t\right] \Bigg/ \left[\sum_{t=0}^{t=n} C_t \Big/ (1+r)^t\right] \quad (2)$$

A benefit-to-cost ratio of 1 is said to indicate a project that breaks-even. Any project with $B/C > 1$ is a relatively successful project as defined in terms of benefits exceeding costs.

Fundamental to implementing the ratio of benefits-to-costs is a value for the discount rate, r. While the discount rate representing the opportunity cost for public funds could differ across a portfolio of public investments, the calculated metrics in this paper follow the guidelines set forth by the Office of Management and Budget (1992), which states that: “Constant-dollar benefit-cost analyses of proposed investments and regulations should report net present value and other outcomes determined using a real discount rate of 7%.”

Net present value

The information developed to determine the benefit- to-cost ratio can be used to determine net present value (NPV) as:

$$NPV_{initial\ year} = B - C \quad (3)$$

where, as in the calculation of B/C, B refers to the present value of all measured benefits and C refers to the present value of all measured costs and where present value refers to the initial year or time period in which the project began, $t = 0$ in terms of the B/C formula in equation (2). Note that NPV allows, in principle, one means of ranking several projects *ex post*, providing investment sizes are similar.

To compare the net present values across different case studies with different starting dates, the net present value for each can be brought forward to the same year—here year 2002. The $\mathrm{NPV}_{\text{initial year}}$ is brought forward under the assumption that the NPV for the project was invested at the 7% real rate of return that is recommended by the Office of Management and Budget as the opportunity cost of government funds. NPV_{2002} is then a project's NPV multiplied by 1.07 raised to the power of 2002 minus the year that the project was initiated as:

$$NPV_{2002} = \mathrm{NPV}(1.07)^{2002-initial\ year} \tag{4}$$

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