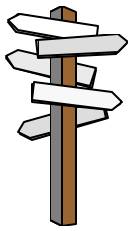
THE RESEARCH VALUE MAPPING PROJECT

Qualitative—Quantitative Case Studies of Research Projects Funded by the Office of Basic Energy Sciences



— FINAL REPORT —

Office of Basic Energy Sciences
Department of Energy

February 19, 1999

DRAFT

RVM project, Technology and Science Policy Program and State Data and Research Center, Georgia Tech, GCATT Building, 250 14th Street, Atlanta, Georgia, 30318-0490. For further information contact: Barry Bozeman, phone: 404.894.0093, email: barry.bozeman@pubpolicy.gatech.edu. Project contributors include Barry Bozeman, Juan Rogers, David Roessner, Hans Klein, Jongwon Park, Gordon Kingsley, Susan Silver, Srikant Sreedhar, Todd Sykes, Melissa Kelman, and James Dietz.

Foreword

Final report of a study funded by Office of Basic Energy Sciences (BES) of the US Department of Energy (Grant # DEFG0296ER45562)

In this report, we draw together a number of broad findings from 28 case studies and a survey of BES-funded projects conducted as part of a four-year project. ***While the findings presented in this single document, the final report, represent the major themes of our research, they by no means capture the depth and complexity of the entire study. We refer readers to the APPENDIX for a complete inventory of the project research products.***

The RVM project has included the contributions of five professors and has provided training for six graduate students. To date, the project has yielded numerous scholarly outputs including:

Research Products

Product	*Quantity*
Published articles and articles submitted for publication	14
Conference and Symposium Presentations	9
Case Study Reports	14
Papers in Process	9
Technical Reports	2
Quantitative Case Maps	16

Most importantly, the project has produced a proven method for evaluating R&D impacts, and has given rise to several unexpected, new scholarly directions in our research: R&D portfolio management, a theory of knowledge value communities, and the beginnings of a new project to assess scientific and technical human capital.

Table of Contents

About The Research Value Mapping Project

Among the core strengths of the U.S. national innovation system, are the great diversity and sheer magnitude of government research programs (Crow and Bozeman, 1998). Scores of government departments, agencies, and offices distribute more than $40 billion in research and development (R&D) funds annually—each agency acting through its own procedures and norms for the planning, selection, and the distribution of project funds. And despite the wellspring of research discoveries and achievements that has accumulated over the years, few advancements beyond existing economic, bibliometric, and historical analyses can be claimed in the area of methods for assessing the impacts of research.

The RESEARCH VALUE MAPPING PROJECT, funded in 1995 by the Office of Basic Energy Sciences (BES) of the Department of Energy, employed a new approach to evaluation of research by using case studies to examine both the qualitative and quantitative aspects of projects. The R&D value mapping (RVM) method yields an inventory of benefits and empirical generalizations, and provides a tool for research evaluation and management. Because RVM uncovers the root reasons why R&D outcomes were achieved, government officials can incorporate it

into policy strategies that seek to promote ongoing success and the effective management of research portfolios.

R&D value mapping has much in common with earlier case study-based attempts to assess research (see for example, Sherwin & Isenson, 1967; IIT, 1968; SPRU, 1972), but is in many respects a significant departure. As in previous case studies of R&D impacts, RVM focuses intensely on particular projects and the events surrounding them. But RVM seeks to avoid some of the pitfalls of traditional qualitative analysis——namely, the lack of a systematic approach to investigation.

By beginning with carefully specified and testable models of causation as well as a scheme for linking the cases, the RVM method yields both particularistic and generalizable data. The particularistic information is much like that derived from a traditional case. The generalizable data comes from the quantification of elements across cases. As a result, each project not only “tells a story” of its own but contributes to systematically measured, cross-case findings.

What Are the Lessons of BES Research Projects?[1]

Lesson One: Stable BES Funding is Invaluable to the Field.

Rather than fund a set of discrete and unrelated projects, BES program managers seem to cultivate balanced R&D portfolios. As a result, BES grant funding is viewed in the field as relatively stable, having limited red tape, focused on long-term quality, and permitting more discretion and change of direction than some other funding sources. Regardless of how dependent they are on BES funding, project leaders often referred to BES as their "core funding" source. We believe this is an effective means of building the *capacity* of a field's scientists to produce important work, to make ongoing contributions to the body of knowledge, and to provide quality training to future researchers.

Lesson Two: New Organizational Designs Contribute to Project Effectiveness.

One of the more interesting and potentially important aspects of BES projects is their great variety of innovative institutional and organizational designs. In some cases, these designs have resulted from planning and considerable directed effort, but often they seem to have evolved directly from practice. We observed new and powerful organizing principles for research: large, fluid teams based on a set of scientific techniques or methods applicable to a wide range of fields. New R&D management infrastructures support a range of productive work from path-breaking fundamental science, to the production of enabling scientific techniques, and even upstream marketable technologies. What holds this diverse set of enterprises together is the project manager's role which seems more like an industry-based R&D manager than a project-based principal investigator. The resulting project impacts are much more diverse and far-reaching than those from more conventional projects whose work is contained within either a discipline or a set of interdisciplinary projects.

Lesson Three: Basic Research Often Spills Over, Resulting in New Directions.

Most of the projects we studied accomplished their basic research goals and succeeded in other realms as well. In some cases, success in activities such as the production of algorithms or new

[1] For a more comprehensive discussion of these themes, see "RVM Project Highlights and Conclusions: "What We have Learned"

manufacturing techniques occurred by systematic planning. More commonly, these outputs emerged organically over the life of projects with little front-end planning. We found concrete evidence not only of the malleability of basic research but also of its fertility for other aspects of the technical enterprise. Previous studies have not really captured this aspect of basic research because they are often focused too narrowly. The results of this project (and previous work using quite different methods, such as Rogers and Bozeman, 1997), suggest that basic research has "spillovers" that go well beyond previous findings and require a broader methodological approach to document.

Lesson Four: Interdisciplinary Work Requires A Different Management Concept. Federal funding of R&D originally assumed relatively small-scale, individual investigator, disciplinary-oriented projects, which led to management styles based on these assumptions. Almost all the BES projects we examined were multidisciplinary; most oriented to research teams rather than individual investigators. BES has developed an effective means of managing multidisciplinary, multifocus research that combines traditional peer review with a nontraditional emphasis on institution- and capacity-building. To a large extent this occurred because BES has been out of the spotlight. Compared to the National Science Foundation, BES has considerable funding resources, but fewer nontechnical boards, much reduced turnover at both top- and mid-levels, and, in general, less intense scrutiny of particular projects. This has resulted in a longer term, more comprehensive view of research support.

Lesson Five: University–Based Projects Differ Little from those at Federal Labs. While there were some differences between university- and government lab-based BES projects, they were not nearly so numerous or substantial as anticipated. The two project types tend to produce (at least under BES funding) quite similar products in terms of range, technical focus, and impact. The university labs (and national labs near universities) have a vital advantage of access to graduate students. However, those projects located within academic departments are often disadvantaged by the difficulty disciplinary-based colleagues encounter in interpreting their work. Government labs have a significant advantage with respect to stability and clarity of focus. What we did find generally missing, however, was extensive interaction between university and federal lab personnel. It might prove useful to seed more projects with close university–federal lab ties.

What Constitutes Value in R&D?[2]

Traditionally, value has been judged by economic benefit (see Link, 1987, for an overview) or perceptions of scientific and technical progress (e.g. Laudan, 1977). The former valuation has led to a variety of assessment approaches, ranging from cost-benefit analysis (Link, 1996; Tassey, 1997) to production function studies seeking to ascertain the impact of technological growth on national economies (e.g. Solow). The latter has resulted in a focus on a wide variety of quality indicators, ranging from Nobel prize awards to citations. While each of these general approaches to valuation (respectively, *economic valuation* and *valuation of state-of-the-art)* has many uses, the two do not capture all the dimensions of value important to either the scientific and technical enterprise or to policy-makers and their clients.

State-of-the-art valuation often exists as a counterpoint to economic valuation. Scientists and engineers opine "some things cannot be measured by standard economic criteria." By the same

---

[2] For a more comprehensive discussion of these themes, see:

Bozeman and Kingsley (1997) "The Research Value Mapping Approach to R&D Assessment." *Journal of Technology Transfer,* 22, 2: 33-42.

Bozeman and Rogers (1998) "Research Value Mapping Analysis: Quantitative Case Studies of Basic Energy Sciences-Funded Research Projects."

Barry Bozeman and Juan Rogers (1998) "Information Use as a Criterion for Knowledge Value."

token, many analysts are dissatisfied with the purely intrinsic (Weinberg) evaluation criteria favored by scientists, arguing that it makes little sense to examine scientific results with no thought to their economic implications, especially when so much of the scientific and technical enterprise is supported by public tax dollars.

An alternative approach to valuation is *use-and-transformation*. This concept of value assumes that the creation and valuation of knowledge are one in the same, that information without use is information without value. Once put into use, it becomes knowledge and, perforce, has value. The value is not, of course, transitive. The appropriate “metric” for value is as diverse as the aspirations of users, including not only pricing and profits, but status, curiosity, and mastery of the physical world. Any appropriate metric must nonetheless be amenable to description.

Arguably, public R&D evaluation should center not on economic value or even improvements in state-of-the-art, but on the growth of capacity. And, typically, the object of public R&D policy is *not* to support knowledge that will lead linearly to economic wealth, but rather to develop capabilities and capacity. Incidentally, these capabilities and capacities are exercised through what we call "knowledge value collectives" (discussed later) and measured through research value mapping (discussed next).

Scientific and technical knowledge does not contain its consequences and potential within itself. Rather, quality of research output is a result of its success among the relevant clients (e.g. published papers, hired students, adopted innovations). Therefore, the array of uses that reflect attribution of value of research output must be established empirically rather than imposed a priori. So, for example, in the case of basic research, citations of journal publications are just one of a number of other possible indicators of research outputs that become valuable as they are used.

The R&D Value Mapping Approach[3]

In capsule, RVM begins with one or more analytical models that track the flow of knowledge and specify possible outcomes of R&D projects. The outcomes are modeled in terms of sequences of events, depicted as a branching model. Each step in the model

---

[3] See for example: Bozeman and Kingsley (1997) "The Research Value Mapping Approach to R&D Assessment." *Journal of Technology Transfer,* 22, 2: 33-42.

Bozeman and Rogers (1998) "Research Value Mapping Analysis: Quantitative Case Studies of Basic Energy Sciences-Funded Research Projects."

Bozeman and Roessner. "Prototype Case Studies for R&D Value Mapping: Assessment of Basic Research Impacts." October 23, 1995.

Bozeman and Klein. "The Case Study as Research Heuristic: Lessons from the R&D Value Mapping Project." June 24, 1998.

might be either the final outcome for the project or a preliminary stage to the next step. By conceiving the progress of project results along certain branched alternatives (i.e., the steps given below), it is possible to develop predictive models of the factors related to project outcomes. Thus, as a simple example, the sequences might include:

(step 1) project completed (yes, no), [if yes...]

(step 2) results disseminated outside the laboratory (yes, no), [if yes...]

(step 3) results used by an individual or organization not a affiliated with the lab (yes, no), [if yes...]

(step 4) product developed from results (yes, no), [if yes...]

(step 5) develop map of project attributes to project outcome.

A key to the successful application of RVM is to begin with theory-based models depicting the flow of impacts from projects. The underlying question such mapping hopes to answer is, what factors (e.g., resources devoted to a project, the number of industrial participants, disposition of intellectual property rights) relate to the ultimate path position, the final step, of the project? Since RVM is iterative, these models are revised and refined continuously during the project in order to add explanatory precision and further knowledge about the nature of the research outcomes.

After the analytical models and associated hypotheses have been developed, data gathering in RVM is much the same as for traditional case studies. Case selection is driven by criteria relevant to the model. And, although selection can include multiple units of analysis (R&D projects) within a single institutional setting, there is no requirement in the RVM method that cases share a common institutional frame.

While the resulting data——such as personal interviews, documentary evidence, records, and files——can be fashioned into traditional “thick description” cases, oftentimes the measurement approach is similar to most quantitative studies. That is, RVM cross-case analyses can resemble empirical explanation in quantitative social science.

For each case, indicators are developed for such variables as amount of funding for the project, numbers of personnel devoted to the project, and——on the benefit side——such variables as estimated monetary rewards and numbers of personnel receiving advanced training. The potential benefits of projects will, of course, vary according to the objectives of projects. However, there is nothing inherent to the RVM approach that limits outcome measures to benefits alone. For example, Kingsley, Bozeman, and Coker (1996) examined the impacts of failures to transfer technology from R&D projects.

Somewhat of a departure, however, is the attempt to use dummy variables (i.e., 0,1) to measure qualitative aspects of the cases. Thus, it is possible to quantify such variables as whether the lab's technology transfer office was involved in the project (0=not involved, 1=involved), whether a diffusion plan was developed at the outset of a project (0=developed later or not at all, 1=developed at outset), or whether the results of the project required the user to develop new manufacturing processes (0=not required, 1=required). A series of causally relevant independent variables are developed by combining the traditional interval-level variables with the dummy variables which indicate the presence or absence of a project attribute.

These independent variables are then analyzed in terms of the sequential models developed at the outset. This assessment is made both in terms of the step reached in the branching model and the benefits (or "disbenefits") that occur. RVM is similar to other case survey techniques whereby multiple coders score individual cases and resulting scores are subjected to inter-coder reliability analysis (Bullock & Tubbs, 1987, Larsson, 1993, Wolf, 1993). Case scores are then categorized for pattern-matching both within groups of cases and between case groupings.

The research procedures of RVM can be summarized as follows:

1. Develop sequential, but nonlinear, branching model(s) of the flow of knowledge from research to exhaustive outcomes.

2. Develop propositions about causal factors related to those outcomes.

3. Develop indicators of costs and benefits from projects and project-related outcomes.

4. Select cases on the basis of factors specified in the model(s) and hypotheses.

5. Gather data on cases.

6. Organize data by writing traditional case studies.

7. Develop a quantitative database by coding the case studies according to the model variables.

8. Validate data coding conventions (e.g., inter-rater reliability indices).

9. Use resulting quantitative data in connection with models, determining (through contingency analysis or dynamic programming) the relation of independent variables to project outcomes.

R&D Value Mapping: Outcomes of BES-Funded Projects[4]

One of the initial motivations for this project was the observation that many of the most important impacts of publicly funded R&D are generally not counted at all. The tendency in much of the extant research is to focus on the obvious or the easily measured. In order to remedy this narrow view, RVM used case studies to develop ideas from the researchers themselves as to the nature and importance of the impacts of their work.

The result is a relatively long list of impacts (summarized below) that goes well beyond the more traditional focus on publications (as sole measures of scientific accomplishment) and patents and licenses (as sole measures of technological impact). A broader view of impacts adds support of students, technology assistance to industry, development of products, development of manufacturing techniques and processes, equipment sharing, development of algorithms and, as an indicator of interorganizational cooperation, establishment of CRADAs.

---

[4] See "Research Value Mapping Analysis: Quantitative Case Study of Basic Energy Sciences-Funded Research Projects" *Interim Report.* June 23, 1998

Bozeman and Rogers. "RVM Project Highlights and Conclusions: "What We have Learned" *Mid-Term Report.* June 19, 1998

Bozeman and Rogers. "Strategic Management of Government-Sponsored R&D Portfolios: Lessons from Office of Basic Energy Sciences Projects." November 20, 1998

Scientific Publications. Unlike all the other outcomes examined here, publication productivity is an outcome of all projects (at least all those in our case database) making it impossible to compare those projects with and without this attribute. One alternative is to compare projects that produced 100 or more published papers with those that produced less than 100 publications. Naturally, the publication of 100 papers is an imprecise measure of value since it may be possible to publish many fewer and have them be quite important. But it is a measure of activity and, from the standpoint of RVM, a useful one. Six of the 24 project cases produced more than 100 publications to date.

- Almost all of the high producing projects were motivated by a self-conscious desire to shape a discipline, sub-discipline, or field of science. Half reported that equipment development or sharing was an important project motivation (compared with about 15 percent of other projects). Only one was motivated by the development of new technology (compared with nearly 60 percent of the other projects). This seems to imply that projects that sought to shape a scientific field were quite distinct from technology development projects——each type resulted in different publication productivity outcomes.

- Five of the six high producing projects (compared to only half of other projects) reported having worked with the lab's technology transfer office. Despite the differences in *motive*, the high producing projects were, at the least, positioned to generate intellectual property with possible market value.

- Despite the commonly interacting with technology transfer offices, basic research was the focus of five of the six high producing projects and half also listed pre-commercial applied research as a focus. None of the commercially-related research foci (e.g. product development or technical assistance) apply to the high producing projects. Nevertheless, the half that did not list technology

development or technology transfer as a motive, have patents and licenses from these projects.

- There was, perhaps, a bit of a mismatch between, on the one hand, R&D focus and intent and, on the other, outcome. Put simply, high scientific producers often produce patents and licenses even if it is not a focus of the project or a major motivation.

- Half the high producing projects originated in national labs and half in universities. Interestingly, there was no relationship between the age of these projects and production of scientific articles (however, 21 of the 24 projects began before 1990, implying that most have had sufficient time to mature).

- Five of the six high producing projects had more than ten persons. High producers were also more likely to involve persons from outside their own laboratory (five of six). Overall, only 11 of the 24 projects had more than 10 persons.

- Generally, the high producing projects were the ones with relatively high levels of BES funding and were of longer duration. All but one had more than one million dollars in funding. In the overall population, 11 had more than one million dollars in funding, while 13 projects had less than that.

- In sum, large-scale scientific production takes large-scale resources in terms of funding, equipment focus, personnel and time. The smaller-scale projects may produce high quality but they do not seem to have as much potential to either produce in great quantity or to produce sweeping changes in scientific disciplines and fields. These types of changes require large, stable infusions of resources.

Patents and Licenses. Eleven of the 24 projects produced patents; there was little difference according to setting——five were university projects and six were government laboratory projects. Of the eight projects with licenses, half were universities and half were government laboratories.

- The motives for projects with patents did not vary much from other projects. The most significant departure was that five

of the 11 projects with patents were motivated to contribute to new manufacturing processes, whereas only two of the remaining 13 projects were so motivated.

- With respect to licenses, all reported a motivation to reshape the field or discipline and five of the eight had graduate student education and support as motives.

- Interestingly, nine of 11 projects with patents reported that basic research was a very or most important focus, and *all* the projects with licenses reported such a focus. By contrast, only two patents projects reported a focus on applied research and only one on product development. The profile is similar for license projects.

- Projects with patents or licenses were likely to have more than 10 project personnel (seven of 11 patent projects, six of eight license projects).

- In sum, it seems that those projects with patents and licenses are even more likely than others to be oriented toward basic research and less likely than others to be oriented toward commercially-oriented applied research or technology development.

Technical Assistance. The work of laboratories on technical assistance to industry often goes unreported and, thus, uncredited. But industrial technical assistance is becoming an ever-more common activity. Indeed, half the 24 cases examined reported significant activities pertaining to technical assistance to industry. Among these, five are government laboratories and seven are universities.

- As expected, projects engaged in technical assistance to industry were somewhat more likely than other projects to be motivated by problems related to industry and to focus on developing new processes.

- The research focus was somewhat more oriented toward precommercial and commercial applied research, but no more strongly oriented than other projects to technology transfer. As is the case for all the projects, there was a strong orientation to basic research.

- Projects involving technical assistance were somewhat more likely to involve personnel from a variety of internal divisions and much more likely to involve persons from outside the focal laboratory (11 of 12 involved outsiders, whereas only two of the remaining 12 projects involved outsiders).

- In sum, technology assistance activities are particularly important, even more than technology transfer activities, in forging links with outsiders and working directly with people outside the institution.

Algorithms. Unlike many other activities supported by BES, the institutional setting makes a considerable difference in the production of algorithms: of the 11 producers of algorithms, eight were national laboratories.

- Projects producing algorithms tended to include a larger number of personnel (drawn from more than one division of the lab) than other projects. They were also larger with respect to funding, with more than half having had at least one million dollars in funding.

- The production of algorithms was associated with *less* encouragement of collaboration with similar labs but somewhat *more* encouragement of collaboration with industry.

- The research focus of projects producing algorithms was distinctly different than in other projects——they tended to place more emphasis on product development, technology transfer, and technical assistance.

- Projects developing software or algorithms were much more likely to entail CRADAs and to have licenses and patents than other project.

- In sum, from every standpoint, algorithm software production seems to be the major category of product development and application produced by BES funding. To the extent that BES projects end up (near term) in the market, they tend to

produce this sort of technology rather than durable physical goods.

Training Students. The training component of some projects was remarkable: One has had about 25 post-docs who have gone on to scientific careers in universities or industry. Many employed 10 or so graduate students at a time. In one long-standing project, there have been 32 Ph.D. students and postdocs trained since 1984, including six BES-funded Ph.D. dissertations.

The most obvious determinant of the training of students is the institutional setting——19 projects, eight of which were based at government laboratories, reported student training as a significant output. Thus, the interesting question is what are the characteristics of projects that did *not* have student training as a component? A first characteristic is that they were all government laboratories.

- While the motivations of projects that did *not* focus on student training were not substantially different from those that did, the research foci were somewhat different. They were more likely to be oriented toward pre-commericial applied work, and less likely to be involved in technology transfer (none of the five projects without students reported technology transfer as an activity).
- The projects without students were more likely to be in the 100 or more scientific article category, but were less likely to have patents, licenses, or to have developed new technology processes.
- In general, projects that do not train students tend to be oriented almost exclusively to the production of fundamental scientific knowledge and tend to be smaller-scale: All of the projects without students began before 1990, were generally

less likely to be funded at the one million dollar level, and often included less than 10 scientific and technical team members.

Technology Processes and Manufacturing Techniques. Four of the 24 projects resulted in new technology processes or manufacturing techniques, three were located at government laboratories, only one at a university.

- The chief difference in these four projects was their stronger orientation toward commercially-relevant motives, including working on problems of industry.
- All the projects pursued basic research, there was only a modest tendency to be oriented to commercial applied research, and none reported a significant focus on product development. However, three of the four projects held patents and licenses.
- The technology process projects tended to be somewhat larger than others, with three having more than 10 personnel. Each of the projects reported a strong orientation toward collaboration with industry. Two received more than one million dollars in BES funding.
- Interestingly, all four included shaping the field or a discipline as a very important motive, perhaps explained by their tendency to develop processes that enhance the ability of field scientists to perform new studies and tests. These processes were not “near market” incidentally.

Equipment Sharing. Equipment use and sharing was often an important aspect of BES-funding projects and, indeed, can be thought of as an output of the projects. While the projects involving equipment sharing were equally likely to be located in universities or government labs (four in each setting), they otherwise tended to be quite dissimilar from other projects.

- Projects that reported equipment use and sharing as an activity were more likely to be oriented toward problems relevant to industry, to the development of new technological and manufacturing processes, and to the development of interorganizational ties.

- None of these equipment-oriented projects reported being motivated by internal pressures for grants or for funding diversification——implying that equipment-based, equipment-sharing attributes may promote stability.

- The equipment-oriented projects were more likely than others to focus on pre-commercial and commercial applied research, technology transfer, and technical assistance.

- These projects tended to involve a larger number of personnel and were much more likely to include persons from other organizations and from other divisions of the laboratory.

- Research outputs were more likely to include technical assistance to industry and to be framed as CRADAs. The equipment sharing projects all began with BES funding, but were more likely than other projects to have additional funding from non-DOE sources.

Managing Portfolios of R&D Value[5]

The commercial and social value produced by R&D depends upon the conjoining of material, organizational, and institutional resources with the unique scientific and technical human capital embodied in individuals. As evidenced in the preceding section, BES projects produce a wealth of interesting outputs that manifest themselves in various (still more) interesting amalgamations. Arguably, then, government agencies might well

[5] See Bozeman and Rogers. "Strategic Management of Government-Sponsored R&D Portfolios: Lessons from Office of Basic Energy Sciences Projects." November 20, 1998

consider how best to manage this R&D portfolio in order to emphasize or de-emphasize various combinations of infrastructural outputs that may be of policy interest or agency mission congruence.

One area to look for guidance, is R&D portfolio management as practiced in industry. These more traditional approaches (e.g. Gear, 1974; Oehmke, 1990), however, do not appear to be especially useful or appropriate for government management (Vonortas and Hertzfeld, 1998). And, given the more direct and limited approach to evaluating private R&D, pay-off in terms of the company's profit and growth, private sector portfolio management approaches are not directly adaptable to government-funded research.

Cooper and colleagues (1997) surveyed 35 leading firms about their R&D portfolio approach and identified the major goals. These included "value maximization," enhancing the value of the portfolio with respect to return-on-investment; "balance," obtaining the best mix of low-risk and high-risk projects, long- and short-term projects; and "strategic direction," the fit of the portfolio to business strategy in terms of market selection and niche. With the exception of the balance criteria, none of these objectives fit well (except perhaps by strained analogies) with government R&D missions.

But something approaching portfolio development and evaluation is appropriate to government-funded research, even in cases of basic research intended to advance fundamental knowledge. In fact, it is often the case that government R&D managers, consciously or not, practice a form of portfolio management. These practices can be distinguished as: (1) output maximization portfolio and (2) balanced portfolio management.

Output Maximization Portfolio. In many instances, government R&D managers seek to maximize the output or impact of one or a few categories of scientific and technical knowledge. For example, several funding units in the National Science Foundation and the National Institutes of Health seek to support research that advances fundamental scientific knowledge without near-term consideration as to the applications that may flow from that knowledge. Even if there is some general expectation that the knowledge will ultimately lead to application, if the application is, essentially, a black box, then maximizing fundamental research is not about application.

Other R&D managers in government have an explicit mission to support projects that lead to technology development and commercialization and to economic development impacts. Earlier studies (Kingsley, Bozeman, and Coker, 1996) of the New York State Research and Development Authority provide a nice contrast to studies of basic research impacts (Rogers and Bozeman, 1997)

because the managers in the organizations examined are seeking to maximize quite different outputs and production functions.

Balanced portfolio. Many public managers are as concerned with building up scientific and technical capacity as they are with producing discrete impacts from particular projects. Some public managers, including those at BES, speak of their roles in nurturing science. This approach leads to different assumptions about program management and to a different portfolio approach. The concern in the balanced portfolio is to integrate discrete outputs with an emphasis on maintaining and extending the research community's capacity, especially its scientific and technical human capital.

BES projects generally include multiple output types and, in that sense, provide one sort of balance. Indeed, this approach resembles the type of balance (Baker, Green and Bean, 1986) urged for most private sector portfolios——balancing "downstream" and "upstream" projects and balancing degree of technical risk. Even if it is not the explicit intent of project managers or researchers to provide a mix of basic research outputs and technology "spin-offs" from basic research, it occurs with surprising frequency.

A more limited approach to government portfolio management and evaluation, then, seems appropriate and would entail:

1. A recognition that government-funded R&D has highly diverse outputs.

2. An interest in understanding the project and management attributes that are likely to lead to various output types.

3. A concern with some balance of output types and an awareness of the opportunity costs associated with pursuing particular portfolio mixes.

4. A dual investment orientation, aimed not only at understanding, at least in an approximate way, the costs of outputs, but also an interest in longer-term investments (e.g., scientific and technical human capital) to help sustain the portfolio.

In considering scientific and technical human capital development as a component of R&D portfolios, it is perhaps useful to note that it includes not only the formal educational endowments usually encompassed in traditional human capital concepts (e.g. Becker, 1958), but also the skills, know-how, "tacit knowledge," and experiential knowledge embodied in individual scientists (Gaughan and Bozeman, 1998). Scientific and technical human capital is the sum total of scientific and technical and social knowledge and skills embodied in a particular individual. It is the unique set of resources that the individual brings to his or her work and to collaborative efforts.

Since the production of scientific knowledge is by definition social, many of the skills are more social or political than cognitive. Thus, knowledge of how to manage a team of junior researchers, post-docs and graduate students is part of scientific and technical human capital. Knowledge of the

expertise of other scientists (and their degree of willingness to share it) is also a part. Most important, the scientific and technical human capital enhances the ability of R&D groups and collectives to produce knowledge. Thus, the object of evaluation is best viewed in terms of capacity, not discrete product.

Knowledge Value Communities[6]

A *knowledge value collective* is a set of individuals connected by their use of a particular body of information for a particular type of application. Collectives have the practical merit of being well suited to the measurement scientific and technical capacity. They are loosely coupled communities of knowledge producers and users (e.g. scientists, manufacturers, lab technicians, students) who pursue a unifying knowledge goal (e.g., understanding the physical properties of superconducting

---

[6] See for example: Rogers "Researcher mobility as a way to transfer scientific knowledge." to appear in a special issue of the *International Journal of Technology Management.*

Bozeman and Monica Gaughan. "Models of Scientific Careers: Using Network Theory to Explain Transmission of Scientific and Technical Human Capital." to appear in *International Journal of Technology Management*.

Bozeman and Rogers. 1998. "Knowledge Value Collectives: A Theory of Knowledge for Research Evaluation."

Bozeman and Rogers. 1998. "Information Use as a Criterion for Knowledge Value."

Rogers and Bozeman. 1998. "Modeling the Creation of Knowledge Value: Comparisons and Types of Knowledge Value Alliance."

Rogers and Bozeman. "Knowledge Value Communities: The Proof is in the Putting," paper presented at Society for the Social Studies of Science Annual Conference, University of Arizona, Tucson, Arizona, October 23-26, 1997.

Rogers. "Models of the Creation of Knowledge Value," invited lecture, Workshop on R&D Evaluation, Ecole des Mines, Paris, France, June, 1998.

Rogers. "Career Paths as Inter-Sector Feedback Loops in R&D," paper prepared for presentation at the Annual Meeting of the Institute for Operations Research and Management Science, Seattle, October, 1998.

Rogers. "Knowledge value networks: A use-and-transformation approach to R&D valuation," paper prepared for presentation at the 20th annual research conference of the Association for Public Policy Analysis and Management, New York, October 1998.

materials) but to diverse ends (e.g., curiosity, application, product development, skills development).

A *knowledge value alliance* is a more tightly concentrated set of individuals from multiple institutions who contribute resources and interact with each other directly in pursuit of a transcendent knowledge goal, i.e., a "knowledge covenant." Inherent in this concept is the objective of generating multiple *uses* and multiple *types* of use (e.g., technology development, skill enhancement, understanding of fundamental phenomena).

Knowledge value alliances grow and decay in a manner similar to what M. Callon (1997) calls an emerging network. They appear fairly soon after the very first research efforts take place on some scientific or technological problem and grow in size and complexity until most parties to the alliance either withdraw because of waning interest or form new alliances that sprout from old as new research directions emerge.

The main focus of an alliance is the pursuit of knowledge, and that is precisely what brings its members together. In this regard, the knowledge value alliance is similar to any scientific research project. However, the multiple use focus of knowledge value alliances highlights the relevance of program managers, industry advisors or partners, and other participants that would

not ordinarily be referred to as members of a research team.

The need to postulate the existence of an entity such as a knowledge value alliance, rather than continue to explain knowledge production activities by referring to research teams, projects and programs, arises from the fact that the latter do not capture the diversity and heterogeneity of knowledge production found in the RVM case studies. For example, research programs are often administrative units of convenience that reflect the jurisdiction of managers rather than the relevant dynamics of the knowledge production process. The boundaries may seem identifiable and clear in research proposals and budget documents, but frequently upon further inspection, they reveal themselves to exist only for the purpose of securing resources for a larger set of research activities with dynamics of its own.

Of crucial importance to research evaluation, is the danger that the value of research is gauged mainly by measuring payoffs at the project level. When this happens, most of the important activities simply go unnoticed and uncounted——resulting in a very distorted picture of the knowledge production process.

Conclusion

In general, the RVM project's findings suggest that traditional modes of evaluation the impacts of R&D projects leave much to be desired. Just as important, by revising some common assumptions

about evaluation of R&D and by implementing new methods, it is possible to derive assessments that are, at the same time, more encompassing and valid.

Among the major drawbacks of conventional R&D impacts assessment, one stands out: the tendency to fit inappropriate models based on requirements to monetize benefits. By focussing on monetary benefits (usually measured indirectly) and discrete outputs, the dynamism of R&D projects often is lost. Research is not discrete and even when research produces such discrete products as articles or patents, any approach that does not understand the long-term nature of science and technology is open to question. It is no surprise that the benefits of science accrue uncertainly over a long period. But, more important, the “outputs” of science often occur of similarly long, unpredictable periods. The “project” is, in some ways, a bureaucratic fiction (albeit a necessity). Scientists have career in which they continually interact with other scientists, technicians and commercial and governmental actors. In pursuit of those careers, scientists not only produce “goods,” they also enhance their own capacity to perform scientific tasks and, in the day-to-day work with others, enhance the scientific, technical and commercial capabilities of other persons in their knowledge value collective (or network). An assessment on that dynamic process depending on a time-bound snapshot, on discrete products and on such artificial categories as projects will necessarily distort the impacts of scientific

and technological work, usually underestimating impacts. Our studies show that the chief value of the scientific and technical work funded by BES is not contained in individual studies or technologies but in the support of scientific, technical and commercial capabilities. In the long term, this support for expanding capabilities goes will beyond the life of any single project and, indeed, is an investment from which the nation benefits from one scientific generation to the next.

We have developed, in preliminary fashion, some means for a more expansive analysis of the impacts of scientific work. While these methods do not yield a precise cost-benefit number and do not associate themselves with particular “products,” we feel they nonetheless provide an account of science and technology that is somewhat closer to the nature of the work and the outcomes that unfold over time.

In the next phase of the RVM project we seek to refine these approaches, examining in particular the career trajectories of scientists, the capacities of networks of scientists and commercial actors, and the ways in which BES-funded projects contribute to these multiple actors’ ability to harness knowledge for scientific, commercial and social gain.

APPENDIX

Research Products of the RVM Project

Papers Published or Submitted for Publication

[7]Barry Bozeman and Gordon Kingsley. 1997. "The Research Value Mapping Approach to R&D Assessment." *Journal of Technology Transfer*, 22, 2: 33-42.

Barry Bozeman and Gordon Kingsley. 1997. "Charting the Routes to Commercialization: The Absorption and Transfer of Energy Conservation Technologies." *International Journal of Global Energy Issues*, 9, 1/2: 8-15.

Juan Rogers and Barry Bozeman. 1997. "Basic Research and the Success of Federal Lab-Industry Partnerships." *Journal of Technology Transfer*, 22, 3: 37-48.

Juan Rogers "Researcher mobility as a way to transfer scientific knowledge." to appear in a special issue of the *International Journal of Technology Management.*

Barry Bozeman and Hans Klein. forthcoming. "Government's Role in Performing Research." chapter in Chris Hill (ed.) *Science and Technology Policy in the U.S.: A Time of Change* (London: Longman).

Barry Bozeman and Hans Klein. forthcoming. "The Case Study as Research Heuristic: Lessons from the R&D Value Mapping Project." *Evaluation and Program Planning*.

Gordon Kingsley and Barry Bozeman forthcoming. "Commercial Interactions with Federal Laboratories." *Materials Technology*.

Barry Bozeman and Dennis Wittmer. "Technical Roles and Success of Federal Laboratory-Industry Partnerships," *Research Policy*, revised, resubmitted for publication.

Monica Gaughan and Barry Bozeman. "Models of Scientific Careers: Using Network Theory to Explain Transmission of Scientific and Technical Human Capital." to appear in *International Journal of Technology Management.*

Barry Bozeman and Juan Rogers. 1998. "Knowledge Value Collectives: A Theory of Knowledge for Research Evaluation."

[7] This paper was awarded the Technology Transfer Society's *Lang-Rosen Award for Research Excellence*.

Barry Bozeman and Juan Rogers. 1998. “Information Use as a Criterion for Knowledge Value.”

Juan Rogers and Barry Bozeman. 1998. “Modeling the Creation of Knowledge Value: Comparisons and Types of Knowledge Value Alliance.”

Barry Bozeman and Juan Rogers. “Strategic Management of Government-Sponsored R&D Portfolios: Lessons from Office of Basic Energy Sciences Projects.” November 20, 1998

Barry Bozeman and David Roessner. “Prototype Case Studies for R&D Value Mapping: Assessment of Basic Research Impacts.” October 23, 1995.

Gordon Kingsley and Michael C. Farmer. “Using Technology Absorption as an Evaluation Criteria: The Case of a State R&D Program."

Juan D. Rogers and Barry Bozeman. “Obstacles and Opportunities in the Application of Network Analysis To the Evaluation of R&D.”

Conference and Symposia Presentations

Barry Bozeman. “Knowledge Value Collectives and R&D Evaluation,” invited lecture, Workshop on R&D Evaluation, Ecole des Mine, Paris, France, June, 1998.

Barry Bozeman. “Empirical Results from the R&D Value Mapping Project,” invited lecture, University of Copenhagen, September, 1998.

Barry Bozeman and Monica Gaughan. “Scientific and Technical Human Capital and R&D Evaluation,” paper prepared for presentation at the Annual Meeting of the Institute for Operations Research and Management Science, Seattle, October, 1998.

Barry Bozeman and Juan Rogers. “Research Value Mapping Project Overview,” Advisory Board, Office of Energy Research, June, 1998.

Barry Bozeman and Dennis Wittmer. “Technical Roles and the Success of Federal Laboratory-Industry Partnerships,” paper presented at the EASST/43S Conference: Signatures of Knowledge Societies, Bielefeld, Germany, October, 1996.

Juan D. Rogers and Barry Bozeman. “Knowledge Value Communities: The Proof is in the Putting,” paper presented at Society for the Social Studies of Science Annual Conference, University of Arizona, Tucson, Arizona, October 23-26, 1997.

Juan D. Rogers. “Models of the Creation of Knowledge Value,” invited lecture, Workshop on R&D Evaluation, Ecole des Mines, Paris, France, June, 1998.

Juan D. Rogers. “Career Paths as Inter-Sector Feedback Loops in R&D,” paper prepared for presentation at the Annual Meeting of the Institute for Operations Research and Management Science, Seattle, October, 1998.

Juan D. Rogers. “Knowledge value networks: A use-and-transformation approach to R&D valuation,” paper prepared for presentation at the 20th annual research conference of the Association for Public Policy Analysis and Management, New York, October 1998.

Technical Reports

"The Research Value Mapping Project: Qualitative—Quantitative Case Studies of Research Projects funded by the Office of Basic Energy Sciences" *Final Report.* February 19, 1998.

"Research Value Mapping Analysis: Quantitative Case Study of Basic Energy Sciences-Funded Research Projects" *Interim Report.* June 23, 1998

Barry Bozeman and Juan Rogers. "RVM Project Highlights and Conclusions: "What We have Learned" *Mid-Term Report.* June 19, 1998

Case Study Reports

Case 97-01, Montaser, George Washington University, "He Inductively Coupled Plasmas for Emission and Mass Spectrometry."

Case 97-02, J. Sengers, University of Maryland, "Critical Phenomena in Fluids."

Case 97-03, P. Barton, Massachusetts Institute of Technology, "Synthesis and Optimization of Chemical Processes."

Case 97-04, L. Tolbert, Georgia Institute of Technology, "The Organic Chemistry of Conducting Polymers."

Case 97-05, M. Adams, University of Georgia, "The Metabolism of Hydrogen by Extremely Thermophilic Bacteria."

Case 97-06, D. Pollard, Stanford University, "Rock Fracture Networks and Clusters and Fluid Flow Properties in Reservoirs and Aquifers."

Case 97-07, A. Pines, UC Berkeley and LBL, "Nuclear Magnetic Resonance Spectroscopy."

Case 97-08, G. Somorjai, UC Berkeley and LBL, "CAM Surface Science and Catalysis Program."

Case 97-09, S. Bruemmer and E. Simonen, PNNL, "Irradiation Assisted Stress Corrosion Cracking."

Case 97-10, J. Delmore, INEL, "Chemical Materials and Processes: SIMS."

Case 97-11, J. Fredrich, Sandia National Lab, "The Micromechanics of Failure in Brittle Geomaterials."

Case 97-12, G. Swift, Los Alamos National Lab, "Thermoacoustic Engines."

Case 97-13, B. Hawsey, Oak Ridge National Lab, "Rolling-Assisted Biaxially Textured Substrates (RABiTS)."

Case 98-14, Larry Rahn, Combustion Research Facility, Sandia-Livermore National Laboratory.

Paper Abstracts

R&D Value Mapping:

A New Approach to Case Study-Based Evaluation

BARRY BOZEMAN

GORDON KINGSLEY

ABSTRACT

This study presents an approach to harnessing the power of case studies for research evaluation called *R&D value mapping (RVM)*. While this method uses case studies in the traditional manner to provide in-depth insights, it also structures case studies through an analytical framework that yields quantitative data and less subjective "lessons learned." When properly applied, RVM can yield an inventory of outcomes and empirical generalizations regarding the determining variables. A particular advantage of the approach is that it not only provides an indication of the type and amount (though not a single numerical index) of outcome, but also gives insight into the reasons outcomes are achieved. Thus, RVM is useful for policy management strategies seeking to replicate success. The specific steps associated with the RVM method are illustrated through studies that have applied the technique.

Basic Research And The Success Of Federal Lab-Industry Partnerships

JUAN D. ROGERS

BARRY BOZEMAN

ABSTRACT. This paper examines the role that basic research plays in the strategies pursued by industry in their interactions with federal labs. It draws on questionnaire-based data of 229 federal laboratory-industry joint R&D projects with 219 companies and 27 laboratories. The study documents the relative importance of basic research in the success of the interactions by comparing the incidence of basic research on several indicators of success. The study shows that, even though projects involving basic research tend to have higher costs, they also have a high percentage of product outputs in the short term. Typical high payoff strategies for partnership were those in which the company performed several technical roles and the federal laboratory was more narrowly focused.

The Case Study as Research Heuristic:

Lessons from the R&D Value Mapping Project

BARRY BOZEMAN

HANS K. KLEIN

ABSTRACT. How can case studies be used as a research heuristic? If prototype case studies are performed, what can researchers expect to learn from them and how can they be structured to enhance their learning value? This paper considers that question and the learning from one case study intended to inform multiple case studies undertaken later in the project. Two prototype cases are presented, one Brookhaven National Laboratory, the other from Los Alamos National Laboratory, each having as its objective providing information about how to design and execute the subsequent 30 case studies to be undertaken. This paper summarizes the cases, presents some of the lessons learned for the subsequent larger project and then considers more generally the use of prototype case studies and the preconditions for their successful deployment. Prototype case studies are particularly useful for helping set boundaries for later studies, identifying the ways in which the research setting affects research findings, making judgments about the accessibility and availability of data, and determining respondents' reactions to the research and the researchers.

Scientific Careers and their Social Contexts: A "Scientific and Technical Human Capital" Model for R&D Evaluation

MONICA GAUGHAN

BARRY BOZEMAN

ABSTRACT. So long as government supports science and technology, the productivity of scientists remains a crucial concern for policy-makers and evaluators. These evaluation concerns manifest themselves in many ways, ranging from the need to make merit review-based decisions for the allocation of grants to the need to bring some semblance of rationality to the allocation of resources among science agencies and national laboratories. Regardless of the breadth of the R&D evaluation objective, models for evaluation tend to have the same individualistic bias one finds in theory-seeking social studies of science. Most sociological and economic studies of scientific production begin with assumptions about production functions, individual utility maximization or economic returns to the individual. Even evaluation-oriented studies often fail to consider the social environment of science and scientists, except perhaps as a predictor of productivity. The notion of the social environment of the scientists *as the dependent variable* or as the evaluation criterion variable is quite uncommon.

Having recently conducted extensive case studies of more than 20 public-sponsored basic research projects we have developed some ideas about what is missing in standard R&D evaluation studies, whether qualitative or quantitative in approach. And, in this paper we outline a different sort of model, one focusing on productivity, but socially-embedded productivity. We refer to this model as "scientific and technical (S&T) human capital." Before outlining the model and its premises we begin by elaborating the reasons for individualistic bias in analysis of science and then turn our attention to the three bodies of theory contributing to S&T human capital: life course theory, human capital theory and social capital theory. A considerable body of empirical work leads us to the conclusion that a scientific and technical human capital model is required that (1) is longitudinal, (2) examines networks or some other conceptual apparatus implying social connection, and is (3) capacity-oriented rather than product-oriented.

Strategic Management of Government-Sponsored R&D Portfolios:

Lessons from Office of Basic Energy Sciences Projects

BARRY BOZEMAN

JUAN ROGERS

ABSTRACT. While strategic management of R&D portfolios is common practice in private sector R&D, government R&D management tends to be more discrete and ad hoc, focusing on generating maximum output from individual projects. Oftentimes there is no clear notion of the desired public sector output. Whereas private sector R&D evaluation is generally straightforward, with the function of R&D being measured in terms of company's internal return on investment, the benefits of public sector-sponsored R&D tend to be more diffuse with respect to both type and impact.

In this study, we contrast two types of "portfolios": (1) R&D output portfolios (focusing on one type of scientific output, such as, for example, fundamental knowledge or technology development); and (2) a balanced portfolio that considers both R&D outputs and "scientific and technical human capital," the capacity created by R&D projects.

Drawing from our case study evidence we show different approaches to achieving each portfolio type. In addition to the case study evidence, we provide analysis of the relationship of aspects of the projects to the output types generated by the project. In this analysis we focus on those aspects of projects potentially under the control of strategic public managers, including, for example, magnitude of funding, degree and type of management oversight, and inter- and intra-organizational linkages.

Based on the cases presented, we suggest that a balanced approach to government R&D portfolio management is appropriate for many government agencies. That is, government managers may wish to consider the extent to which their projects produce both traditional outputs such as articles and patents, as well as provide contributions to scientific and technical human capital, the growth of which makes discrete outputs possible.

Prototype Case Studies For R&D Value Mapping

Assessment Of Basic Research Impacts

BARRY BOZEMAN

DAVID ROESSNER

ABSTRACT. The chief objective of this paper is to report on prototype case studies used to further develop an approach to assessing the near-term commercial and socioeconomic benefits of government-sponsored basic research projects (specifically, projects of the Department of Energy's Basic Energy Sciences program). While the case studies provide some free-standing information about the benefits of three projects, their chief value is as a feasibility study for large-scale application of the "R&D Value Mapping" (RVM) approach to the understanding of the commercial impacts research projects.

The RVM approach is, fundamentally, a quantification of a relatively large number of case studies. As such, the approach requires multiple, linked cases studies, in sufficient number to make statistical inference. *Given the number of cases (n = 30) required for actual application of RVM, the cases do not constitute and application of RVM,* rather they highlight special problems in application of RVM for basic research projects.

The three cases studies developed include “Whisker-reinforced Ceramics at Oak Ridge National Laboratory,” “Understanding Thin Film Deposition at the Stanford Synchrotron Radiation Laboratory,” and “Brookhaven National Laboratory, Superconducting Materials and Magnet Technology.” Each of the case studies presents particular challenges, but the issue permeating the three case studies is setting boundaries. As is well known, basic research is unpredictable in its impacts, both with respect to timing and and range of impacts. These three cases well illustrated the boundary-setting issues in basic research case studies and the “conclusions” section discusses lessons learned and possible approaches to mitigating this and other research problems.

Knowledge Value Communities and Science Evaluation:

The Proof is in the Putting

BARRY BOZEMAN

JUAN D. ROGERS

ABSTRACT. Until recently, serious discussions of the value of science have generally been relegated to the safe confines of academic discourse. In many respects, the social compact developed briefly after World War II and symbolized by Vannevar Bush's Science: The Endless Frontier (1945) sufficed as a statement of the value of science. Science policy documents of the 1950s (President's Science Advisory Committee, 1958; 1960; U.S. Congress, 1986) gave the underpinning for the equation "science=technology=economic growth."

What constitutes value in R&D? Traditionally, value has been judged by economic benefit (see Link, 1987, for an overview) or perceptions of scientific and technical progress (e.g. Laudan, 1977). While each of these general approaches to valuation (which we term, respectively, *economic valuation* and *valuation of state-of-the-art)* has many uses, we feel that the two do not fully capture all the dimensions of value important to either the scientific and technical enterprise, economic desiderata or to policy-makers and their clients.

In this paper, we present an alternative approach to valuation, *valuation by use and transformation,* and an evaluation theory to accompany the approach. The crux of our argument is that the best approach to valuing scientific and technical information is to simply observe repeated instances of its use- that continued use and transformation of information is, in many respects, the best available index of value.

Using Technology Absorption as an Evaluation Criteria:

The Case of a State R&D Program

GORDON KINGSLEY

MICHAEL C. FARMER

ABSTRACT. The R&D portfolio of states tends to be concentrated in applied projects designed to address the competitiveness of local industries. However, evaluation standards are often those used at the federal laboratories where the highest good is achieved by the diffusion of newly developed technologies. This diffusion of innovation standard undervalues one of the primary goals of state programs--involving local industry in projects as a means of stimulating the adoption of technology. In this study, this type of adoption by a project participant is identified as technology absorption. It is distinguished from technology transfer which is the process by which outcomes are adopted by organizations outside the project (i.e. non-participants).

While absorption outcomes are common in state projects, they have rarely been studied. This research analyzes eight case studies of R&D projects whose outcomes are limited to absorption. The cases are drawn from 31 case studies of projects sponsored by the New York State Energy Research and Development Authority (the Energy Authority). Each case examines the development of a different energy conservation technology from inception to impacts. Comparison of the absorption cases with projects having different transfer impacts suggests that states place great value on absorption outcomes.

This research examines absorption outcomes in terms of the types of impacts achieved, the management practices that produce these outcomes, and in the standards by which project success is determined. Absorption projects tend to be distinctive from other types of projects because: 1) they develop technologies that are very large in scale and very complex; 2) project leadership typically is provided by an end-user who attempts to employ the technology for commercial purposes; and 3) success is measured through the technological accomplishment and on-going commercial venture, rather than by transfer standard, i.e., the number of adopting organizations.

Knowledge Value Collectives:

A Theory of Knowledge for Research Evaluation

BARRY BOZEMAN

JUAN D. ROGERS

ABSTRACT. Familiar theories of the political economy of science and technology, while useful in their traditional domains, offer little guidance for the task of more explicit valuing of science. For example, production function theories, intended originally for assessing the contribution of nations' science and technology to economic growth (e.g. Solow, 1957; Griliches, 1979), fare poorly as models for more narrow-gauged evaluation. Our paper presents an alternative approach to valuing knowledge, one based on the range and repetition of uses of scientific and technical knowledge. Ours is not a new economics approach; indeed, is not grounded in economics at all. In a sense, as we explain below, it is "pre-economic." We are concerned with the value that economists seek to monetize, not with the economic reflections of value. After elaborating this approach, we explore its implications for social theory of science and for policy-making and evaluation.

We present a new framework for analysis and evaluation of scientific and technological activities. We suggest the need for a new way of understanding knowledge value creation and proposed a "use-and-transformation" approach. It is based on a distinction between information and knowledge such that knowledge is created when information is transformed in use. That very process is evidence of value attribution.

In the final section of the paper we offer an example of a KVC in the area of "Synthesis and Optimization of Chemical Processes.." We determine the members of the KVC and the multiple types of uses that occur within it. We also determine the composition of one important KVA and showed its single knowledge focus, the diversity of the members of its "knowledge covenant" and the large number of types of uses of information and knowledge creation that originate from it.

Modeling the Creation of Knowledge Value:

Comparisons and Types of Knowledge Value Alliance

JUAN D. ROGERS

BARRY BOZEMAN

ABSTRACT. When looking at more than one or two cases of knowledge production in science and technology, the observer is almost immediately struck by the relatively large variety of ways in which these knowledge producing activities take place. There is neither a single pattern of organization of research teams, nor a typical career path, nor a set of personality traits, nor a single motivating factor that characterize groups and individuals that produce scientific and technological knowledge.

This paper presents an analysis of data from 13 case studies of research sponsored by the Office of Basic Energy Science of the US Department of Energy, which has led us to conclude that, even though basic science was essential to almost all the research activities, knowledge creation could not be adequately explained with the traditional notion of disciplinary science. Many factors intrinsic to the content of research, such as the choice of research problems, the patterns of collaboration, the career paths of researchers, as well as institutional and organizational arrangements to carry out the work showed a diversity that cannot be captured by the disciplinary structures.

The question of what the relevant entities or units of analysis for studying the dynamics of R&D is central not only for adequate characterizations of the system of scientific and technological knowledge production but also for determining the correct focus for evaluation of R&D activities. Typically, R&D performance evaluations have focused not only on the wrong thing, but have looked in the wrong place. Most evaluations have been project or program based. Often this focus is misleading.

This paper contains (1) a brief summary of the main concepts of the knowledge value framework, (2) a comparison of the main concept of that framework, the Knowledge Value Alliance, with other constructs presented in the literature, and (3) a typology of KVAs and the main features of each type. An appendix contains summaries of the case data to illustrate the categories with empirical data.

Information Use as a Criterion for Knowledge Value:

Tools for Evaluating Knowledge Production Activities

BARRY BOZEMAN

JUAN D. ROGERS

ABSTRACT. Traditionally, value in R&D has been judged by economic benefit or perceptions of scientific and technical progress. The former valuation has led us to a variety of assessment approaches, ranging from cost-benefit analysis to production function studies seeking to ascertain the impact of technological growth on national economies. The latter has resulted in a focus on a wide variety of quality indicators, ranging from Nobel prize awards to citations. In our view, the study of R&D impacts pre-supposes a theory of knowledge (and its value) and most R&D impact evaluations have used the wrong one. Absent an appropriate concept of knowledge's value, R&D evaluators will become more and more adept at measuring the wrong thing.

We present an alternative approach to valuation, *use-and-transformation,* and an evaluation theory to accompany the approach. The crux of our argument is that the best approach to valuing scientific and technical information is to simply observe repeated instances of its use--that continued use and transformation of information is, in many respects, the best available index of value. The focus of the paper, then, is in describing how use and transformation valuation can be understood and applied within the context of "knowledge value communities"--between the micro-world of scientists and engineers producing research and the macro-world of other scientists and engineers, commerce, and social institutions that use and transform the work.

Obstacles and Opportunities in the Application of Network Analysis To the Evaluation of R&D

JUAN D. ROGERS

BARRY BOZEMAN

ABSTRACT. Networks have been used for several decades in the study of science and technology (Schrum and Mullins, 1988). They serve both as guiding metaphors for conceptualizing the relationships between actors and as techniques to measure structural properties of the ensemble. All network studies share the assumption that the ties between actors, which connect them into a system, are more important than their individual attributes. The network studies available in the literature collectively make a persuasive case for the importance of such ties for understanding the development of science and technology. Arguably, this conclusion would lead one to believe that if these structural properties are important for giving an accurate account of the nature of science and technology they would somehow translate into evaluation criteria for their assessment. We raise this question in this paper and examine the relevance and usefulness of existing network approaches to science and technology for the evaluation of government funded R&D activities.

We have found a number of obstacles for the application of network analysis to the problem of R&D evaluation. Not all these observations are of the same kind. Some have to do with the practical aspects of the application of network techniques. Others have to do with the legacy of R&D evaluation as it has been practiced to date. Others have to do with the use of network analysis for describing and characterizing structural properties of the social systems involved in R&D. And still others have to do with conceptual issues that must be addressed if there will be a more fruitful use of network approaches in the evaluation of R&D. In the paper, we explore ways to overcome these obstacles.

Research Value Mapping Analysis: Quantitative Case Study of Basic Energy Sciences-Funded Research Projects, Draft Interim Report to the Office of Basic Energy Sciences Department of Energy

ABSTRACT. The set of analytical tools for assessing the social and economic impacts of R&D has expanded significantly during the past ten years. Yet despite advances in application of such research evaluation techniques as cost-benefit analysis, benchmarking and bibliometrics, one set of obviously relevant techniques, case studies, has remained somewhat stunted in its development. Case study approaches to research impact evaluation generally have credibility with policy-makers and officials and are popular among evaluators and policy analysts.

The objective of this report is to employ a new approach to case study analysis, one which examines both the qualitative and quantitative aspects of cases. The method, termed ***R&D value mapping*** yields an inventory of benefits and empirical generalizations of the determinants of those benefits and has been applied in several studies. A particular advantage of the approach is that it not only provides an indication of the type and amount of research outcomes, but also gives insight into the reasons outcomes are achieved. Thus, R&D value mapping (RVM) is useful for policy management strategies seeking to replicate success.

Research Value Mapping (RVM) Project Highlights and Conclusions:

"What We have Learned"

BARRY BOZEMAN, JUAN ROGERS, DAVID ROESSNER, AND

JONGWON PARK

ABSTRACT. This paper summarizes five broad lessons from research on the economic and social impacts of 30 research projects funded by the Department of Energy's Office of Basic Energy Sciences (BES). Lessons include: (1) the importance of a stable, sustained source of funding in stimulating research fecundity, (2) the contribution of various innovative institutional and organizational designs to research project outcomes, (3) the role of "spill-overs" and other beneficial outcomes of basic research with respect to the larger technical enterprise, (4) the development within BES of effective management approaches for promoting multidisciplinary, multifocus research, and (5) the differences (or lack of differences) between research projects based at universities as compared with those based in federal labs.

Case Summaries

Adams, M.

"The Metabolism of Hydrogen by Extremely Thermophilic Bacteria"

UNIVERSITY OF GEORGIA

Extreme thermophiles or "hyperthermophiles" are a unique group of microorganisms that have the remarkable property of growing optimally near and above 100°C. They have been isolated mainly from marine volcanic environments, including deep sea vents. The researchers grow some of these organisms in large scale culture (600 liters) and study their pathways of hydrogen (H_2) metabolism. Since molecular H_2 plays a central role in the commercial production of many chemicals, a long term objective of this research is to assess the utility of hyperthermophilic hydrogenases and oxidoreductases in industrial energy conversions. Techniques used in this project include growing high temperature organisms (600 liters), anaerobic protein purification, various biochemical and molecular biology techniques.

This project led to the first description of the purification of enzymes from high temperature organisms, the first insights into their metabolic pathways, the first structural information on high temperature proteins, and the discovery of a new class of metal (tungsten)-containing enzymes. The researchers discussed technological application of the high temperature organisms with many industrial researchers both informally and as part of formal consulting agreements. Dr. Adams' lab supplied materials (enzymes, proteins) to 16 other laboratories throughout the U.S. for collaborative research projects.

The major impact of this project is theoretical in understanding basic biochemistry and metabolism of high temperature microorganisms which provides the basis for the development of related technologies. This project supported (in part) six Ph.D. theses, nine post-doctorates (in addition to two current post-doctorates), and two Ph.D. candidates. The BES grant enabled Adams to bring nine visiting researchers to join the project (including from Germany, England, Italy, and Hungary) and has provided training for 19 undergraduate students.

Alper, M. D.

"Enzymatic Synthesis and Biomolecular Materials"

LAWRENCE BERKELEY LABORATORY

The goal of this project is to use natural biological processes and molecular variants of them to synthesize new materials. One component focuses on the use of naturally engineered and "created" enzymes to synthesize new materials. This project is funded jointly by the Division of Energy Biosciences and the Division of Materials Sciences of DOE.

The most important contribution of this project is the publication of more than 100 articles in a number of areas related to biomolecular materials. The project has also commercialized a new material and filed approximately ten patents. It has a license to commercialize a new sensor pending, and continues to participate in a CRADA that has led to patent applications and the potential of a new biomaterial.

Barton, P.

"Synthesis and Optimization of Chemical Processes"

MASSACHUSETTS INSTITUTE OF TECHNOLOGY.

The main concerns of this research are the flows of energy in industrial chemical plants. It seeks to develop systematic methods to synthesize industrial chemical processes and provide optimal solutions for the required overall energy flows. The visible products of this research are specifications and software packages that implement the methods and algorithms to reach optimal solutions. The project—first led by Larry Evans from around 1976 to 1991—has been directed by Paul Barton since 1992.

The most interesting features of this research are, on the one hand, the great impact it has had in the chemical industry by providing methods and software implementations that are widely used, allowing it to save hundreds of millions of dollars in production efficiencies. On the other hand, the career paths of graduate students who were part of the sponsored research have very peculiar patterns. This is due mainly to the significant role of a spin-off company, Aspen Technologies Inc. that hired and re-hired a number of them at various stages of their professional career. A virtual "traffic in students" helped both the company keep abreast of developments in basic research and the research team obtain direct experience of the problems that the industry faces.

Bruemmer, S.

"Irradiation Assisted Stress Corrosion Cracking"

PACIFIC NORTHWEST NATIONAL LABORATORY

This research project addresses basic science issues dealing with radiation effects on material microstructure and microchemistry, and their influence on interfacial and environmental dynamics. Employing a high-resolution electronic microscope and computer simulation, this project is investigating what happens to materials under radiation and hostile environments. Mechanistic understanding of irradiation and environmental effects on materials performance have direct implications for the safe operation of nuclear reactor systems and the temporary and long-term storage of nuclear waste.

The most important impact of the project is the development and refinement of analytical techniques, the refinement of a high resolution microscope, and numerous computer programs. Though the focus of the research has been on basic understanding of the cracking process, most contributions of this research originated through collaboration with industry, which utilized the tools and techniques developed over the course of the basic research process. The coordination of basic and applied research and management of the funding from various sources deserves much attention. Interestingly, the lab performed much of its research as a contractor to industry which is rare among federal laboratories. Collaboration with different types of organizations resulted in different research orientations and outcomes.

Chandler, D.

“Photo-fragment Imaging, Combustion Research Facility”

SANDIA NATIONAL LABORATORY

The goal of this research is to understand the details of fundamental chemical processes that occur in combustion. Experiments in chemical kinetics use approaches such as laser-photolysis/laser-induced fluorescence, long-path IR absorption, mass spectrometric and laser diagnosed flow-reactor studies, and high-temperature shock-tube measurements. Recent systems of interest have included the reactive systems OH + CH4 and NH2 + NO and the collisional quenching of electronically excited NO. These experimental studies are aided by quantum chemical and statistical theoretical calculations.

Experiments in chemical dynamics emphasize collecting data for elecmentary processes and individual molecules resolved to a quantum-state level. Techniques utilized include ion imaging of unimolecular and bimolecular reactions, femtosecond time-resolved aproaches (transient absorption, photoelctron spectroscopy, and stimulated Raman scattering), and linear and nonlinear laser spectroscopies. Recent applications have included ion-imaging studies of the product angular distirbutions from the H + D2 reaction and the speed and internal state distribution of the HI product from the H + HI reaction. Femtosecond time-resolved applications include investigations of internal conversion, virational energy redistribution, and dissociation. Recent spectroscopic studies have emphasized the application and development of two-color resonant four wave mixing and laser-induced grating techniques for molecular spectroscopy and photodissociation dynamics.

The technique provides a visual representation of how a molecule dissociates. This research made a significant impact on strengthening the nation’s scientific infrastructure in two ways, one is the findings of this research on combustion chemistry systems and the other is the transfer of techniques to other labs that applies the same technique in studying different phenomena such as atmospheric chemistry, laser control of chemical reactions,etc. Because Chandler is at the Combustion Research Facility, which is a National User Facility, Chandler have the mandate and the support to help others learn about the technique and help them set it up in their laboratories. As a result of the PI’s active role in technology transfer, aproximately 30 other research groups worldwide are now adopting the technique to study similar systems.

Cullen, D.

"Molecular Genetics of Ligninase Expression"

UNIVERSITY OF WISCONSIN - MADISON.

In addition to playing a key role in the carbon cycle, lignin-degrading fungi have demonstrated potential in emerging technologies such as biomechanical pulping, bleaching and otherwise improving chemical and mechanical pulps, converting lignin to useful chemicals, effluent treatments, and remediation of contaminated soils. These processes involve mechanism(s) which are poorly understood, and this represents a barrier to further development. Long term objectives of this research are to elucidate the basic genetics and physiology of the degradation of lignin and related aromatic compounds.

Toward these goals, the structure, genomic organization and regulation of genes involved in lignin degradation are under investigation. Emphasis is on the genes encoding extracellular peroxidases and glyoxal oxidase of the white-rot fungus *Phanerochaete chrysosporium*. A variety of experimental techniques will be employed to construct detailed integrated maps. The role of glyoxal oxidase in lignin degradation will be determined by gene disruption techniques. Identification of specific transcripts in wood and soil samples will help to identify the key genes in the degradation of lignin and organopollutants. Efficient heterologous expression systems will be developed for the production of pure isozymes for biochemical investigations.

This research will contribute to understanding the mechanism(s) of the degradation of lignin and related aromatic compounds, and will also provide insight into lower eukaryote genome organization and genetic regulation. The identification of specific genes in wood and soil provides a framework for genetic improvement of strains used in biomechanical pulping and in soil remediation. Further, the methodology is broadly applicable to a other fungal species and substrates, including plant pathogens and mycorhiza.

Delmore, J. E.

"Negative Ionization Mass Spectrometry"

IDAHO NATIONAL ENGINEERING LABORATORY

This project involves analysis of ions and the development and application of computer models of ions. The Delmore and his project team began the search for computer models of ions in 1982-83. The contributions of this work can be classified into three groups: (1) theory of a branch of chemistry dealing with

high temperature (900 to 1500 degree centigrade) materials, especially their ionization properties; (2) ion optic modeling programs, and (3) ion optic systems. Since about 1986, the the team has been analyzing contaminants as they are absorbed into organic materials. A software tool, SIMION, was developed and distributed to scientists interested in the characterization of materials in this nation and in other countries.

The team is interdisciplinary in nature and has pursued a number of basic research avenues in the study of ions. The interests and expertise of the five to six project investigators and emerging research opportunities have helped to shape these research directions. Many of the most important “lessons” drawn from the work pertain to the development and execution of a basic research program within a laboratory setting where limited basic research is performed. The project has thrived by bringing together a group of scientists well-versed in their respective specialties, while compatible in their interests. The project has yielded two patents, resulting in about $60,000 per year in revenues to the laboratory. Three students were supported.

Ewing, R. C.

“Particle-Induced Amorphization of Crystalline Silicates, Complex Oxides and Phosphate”

UNIVERSITY OF NEW MEXICO

This research investigates irradiation effects on transition from crystalline to aperiodic state in naturally occurring materials (complex oxides, silicates and phosphates) and ion-irradiated ceramics. The research also covers the irradiation effects on structure and bonding, cascade energy, defect accumulation and temperature on the amorphization of complex ceramic materials. Techniques used in this study include X-ray diffraction, high-resolution transmission electron microscopy (HRTEM), extended X-ray absorption fine-structure (EXAFS) and near-edge spectroscopy (XANES).

According to Ewing, this research changed the basic approach used in the field, and led to the development of multi-user Microbesm Analysis Facility and $ZnSiO_4$ as a better nuclear waste form. Roughly 65 articles have been published in academic journals and five students have been supported.

Feldberg, S.

“Electrochemistry and Photoelectrochemistry”

BROOKHAVEN NATIONAL LABORATORY

The objective of this project is to provide new insights into the mechanisms of electrochemical and photoelectrochemical phenomena. The experimental objective is to understand the role of interfacial structure and organization in a variety of interfacial processes [e.g. double-layer relazations, charge (ion or electron) transfer between the solution and the electrode, electron transfer between electrode and immobilized or adsorbed redox moieties]. A focus is on heterogeneous electron transfer and, in particular, on the measurement of very fast (submicrosecond) heterogeneous processes. The experimental approach utilizes an indirect laser-induced interfacial temperature-jump (ILIT) technique. At its present level of development, ILIT can access interfacial rate processes occuring in the nanosecond time domain, arguably a leading-edge experimental approach exceeding the capabilities of other state-of-the-art electrochemical approaches. Theoretical analyses and computer simulations attack a broad range of electrochemical and photoelectrochemical problems that may be generally described as electron transfer coupled with homogeneous chemical reactions.

Fredrich, J.

“The Micromechanics of Failure in Brittle Geomaterials”

SANDIA NATIONAL LABORATORY

BES funded research has been the basis for the development of geomaterial pore imaging analysis software which creates 3-D rock specimen reconstructions. This 3-D imaging technique that resulted in publication in *Science*. Researchers expect that the investigation provides a detailed understanding of the micromechanical processes associated with the failure of brittle Geomaterials. Knowledge of the failure behavior of rocks is not only relevant to oil and gas exploration, there are additional application to the underground disposal of nuclear waste, and drilling technology.

Fredrich’s modeling technique provided a way to transfer complex physical material data to a computer. Computational Physics collaboration took Fredrich’s Geophysical modeling technique from computer visualization to computer simulation. Computational modeling and simulation work has been conducted using the supercomputing capabilities of the teraflop computer at Sandia National Laboratory.

Goodman, D.

"Correlations between Surface Structure and Catalytic Activity/ Selectivity"

TEXAS A&M UNIVERSITY

This is addressing issues that are key to understanding the relationship between surface structure and catalytic activity/selectivity. The primary research questions are related to the origins of enhanced catalytic properties of mixed-metal catalysts and critical active site requirements for molecular synthesis and rearrangement. The preparation, characterization, and determination of the catalytic properties of ultra-thin metal and metal oxide films are also being explored.

Based on this research, about 200 journal articles have been produced. The project was first funded by BES in 1982, and since then, 12 students have been supported. Currently, the project is pursuing three goals: (1) the study of the unique catalytic properties of ultrathin metal films, (2) the investigation of the critical ensemble size requirements for principal catalytic reaction types, and (3) the modeling of supported catalysts using ultra-thin planar oxide surfaces.

Gregg, B. A.

"Photoconversion Processes in Liquid Crystal Porphyrin films and Other Molecular Semiconductors"

NATIONAL RENEWABLE ENERGY LABORATORY

The primary mission of this project is to understand the relationship of three photoconversion processes: those in organic systems, in inorganic semiconductors, and in biological photosynthesis. The project team is pursuing this goal by investigating photochemical and photophysical properties of thin films of liquid crystal porphyrins.

The project is theoretical in nature, placing little emphasis on technological application, and is small in size——five researchers and no students have been involved since its start in 1991. The project team has produced fifteen published articles, and a patent.

Hawsey, B.

"Rolling-Assisted Biaxially Textured Substrates (RABiTS)"

OAK RIDGE NATIONAL LABORATORY

The objective of the Rolling-Assisted Biaxially Textured Substrates (RABiTS) case is to develop a superconducting wire that has characteristics desirable for industrial development and application. Deposits of YBaCuO (YBCO) on textured substrates has promise of enabling high-field electric power devices at liquid nitrogen temperatures. The project has thus far developed prototype wires that display desirable properties at 65 Kelvin. Much of the work has involved developing a "backbone," or substrate, for the superconducting wire.

The project is an excellent example of a national laboratory project that has successfully teamed multiple divisions within the lab. The RABiTS case has strong scientific implications, including publications in *Science* and other top rank journals, but also strong commercial implications, including partnerships with 3M, Southwire and a number of other firms.

Ho, P.

"Chemical Vapor Deposition Sciences"

SANDIA NATIONAL LABORATORIES

This project focuses on vapor-phase and surface reactions during chemical vapor deposition (CVD) under conditions used to fabricate photovoltaic cells, wear and corrosion-resistant coatings, and semiconductor devices. Ho and his colleagues' approach to understanding the fundamental mechanisms of CVD—along with some of the tools that were developed for basic science—are now proving extremely useful to crystal growers. Specifically, the rotating disk CVD reactor and the reflectance monitor provide growers working on metal-organic CVD of compound semiconductors with unprecedented control over their processes. The CVD allows the crystal growers to grow complex structures, such as vertical-cavity surface emitting lasers, that were, in the past, nearly impossible to produce reliably.

This project has resulted in more than 180 journal articles and four patents. According to Ho, the project showed that CVD could be understood on a basic scientific level, which changed how people think about CVD, and thus how industry develops new processes and equipment. The CHEMKIN and Surface-CHEMKIN software developed from this project have become the de facto commercial standard for chemical kinetics modeling. In addition,

the project produced a reflectance monitor, commercialized by Filmetrics, that won a 1997 R&D 100 Award. This project has included many CRADAs with industry giants such as, SEMATECH, SRC, Motorola, GM, Intel, Texas Instruments, and others.

Israelachvili, J.

"Molecular Properties of Thin Organic Interfacial Films Materials Sciences"

UC-SANTA BARBARA.

This project measures structural, adhesive and tribological properties of thin organic films on solid surfaces. The research focused on the use of a Surface Forces Apparatus (SFA) for measuring directly the forces acting between solid surfaces as a function of separation with a distance resolution of 0.1nm. Adhesion and surface energy of metals coated with surfactant and polymer films are measured by SFA in both gaseous and liquid environments. The study developed new measurements of dynamic forces acting on two laterally moving surfaces, recording the normal (compressive) and tangential (frictional) forces while simultaneously monitoring the plastic deformation.

On practical side, this research led to the development of new lubricant systems that reduce wear on solid surfaces. Israelachvili reports collaborations with many industry labs including 3M, IBM, Exxon, Mobil, Shell, etc. This project produced about fifty articles and supported ten students.

Jones, K. W.

"Measurement of Fluid Flow and Fluid-Rock Interactions Using Synchrotron Computed Microtomography"

BROOKHAVEN NATIONAL LABORATORY

The objective of this project is to study microgeometry, fluid flow, and fluid-rock interactions in geological specimens using the nondestructive technique of synchrotron computed microtomography (CMT). An area X-ray detector makes it possible to obtain volume images with up to 10^9 voxels and a spatial resolution better than 10 m. The experiments are intimately linked to the development of a CMT system which provides integration of data acquisition, tomographic section reconstruction, and visualization with a three-dimensional viewing system.

The project produced new data on the microgeometry of sandstones and other rocks as well as new methods for analysis of these structures. Some data have been used by Mobil——one of two major companies that participate in a project CRADA——for proprietary consideration of particular reservoirs. And, the work will continue to be the foundation of a systematic study of fluid flow through geological materials in the future. Project-developed tomography techniques have been applied in areas other than the geosciences, such as in studies on catalysts, polymers, and biological specimens.

Mesmer, R.

"Basic Aqueous Chemistry at High Temperatures and Pressures"

Oak Ridge National Laboratories

The aim of this project is to establish basic principles governing chemical and thermodynamic behavior of aqueous solutions of broad classes of solutes at high temperatures and pressures through experimental studies. Advancement in experimental methods and the development of new models for exploring and representing behavior over wide extremes of conditions are important parts of this research. Results from this study are important for not only advancing theoretical understanding in basic solution chemistry, basic hydrothermal geochemistray, and environmental chemistry, but also in developing practical applications such as steam generation technology, geothermal resources, and nuclear waste disposal.

This highly productive project that has published more than 400 articles since its inception in 1972. More than fifty algorithms were developed, most of which are based on equations of chemical states that describe the behavior of numerous solutes in water. One CRADA on supercritical water oxidation of hazardous wastes has been signed. Many contributions to the power industry have been made by defining water chemistry at high temperatures. Results are used in waste disposal, steam generator guidelines,and chemical processing. Extensive databases for reaction thermodynamics and thermodynamic properties of electrolytes have been produced in a sustained program that markedly changed our basic understanding of chemical processes in water at high temperatures and pressures.

Montaser, A.

"The Inductively Coupled Plasmas for Emission and Mass Spectrometry"

GEORGE WASHINGTON UNIVERSITY

Emission and mass spectrometry represent one of the primary tools available to the analytical chemist for identifying the composition of unknown materials. Not only is spectrometry important for investigation of fundamental phenomena as part of basic science, but it is also applied to a wide variety of practical problems such as detection of pollutants in air and water, identification of toxic substances in tissues and body fluids, detection of impurities in ultrapure materials, determination of the composition of food and drugs, and many others.

Since 1984, a research team at George Washington University under the direction of Akbar Montaser has been attempting to develop new high temperature plasmas and new sample introduction systems for rapid elemental analysis of solutions and solids using atomic emission spectrometry. Emphasis has been placed on: 1) generation and fundamental investigation of annular, helium inductively coupled plasmas that are suitable for the excitation of high energy spectra lines, with the intent of enhancing the detecting powers of a number of elements; 2) generation of plasmas that require low gas flows and low input power, with the intent of decreasing the cost of analytical determination; 3) development of simulation and computer modeling of He CIPs to ease the hunt for new helium plazmas without incurring the enormous cost for extensive experimental studies; 4) development and characterization of new sample introduction systems that consume microliter or microgram quantities of samples.

Over the course of the project, which began in 1984, 10 Ph.D.s have been produced; the team has generated 260 publications and presentations; three books were written; a network of some 50 collaborators worldwide has developed, including other university researchers in the U.S. and abroad, researchers in federal agencies and laboratories, and industrial researchers; and four patents and copyrights have been granted.

Pines, A.

"Nuclear Magnetic Resonance Spectroscopy"

UNIVERSITY OF CALIFORNIA - BERKELEY AND LAWRENCE BERKELEY LABORATORY

The Nuclear Magnetic Resonance Spectroscopy project is pursuing research on NMR techniques for the study of solids and quasi-solids. The research team, led by Pines, was able to overcome inherent limitations of NMR technology for chemical analysis of materials other than liquids by increasing it sensitivity and resolution by several orders of magnitude. It now has numerous applications in materials sciences, electronics, biology, the oil industry, and for general analytical chemistry instrumentation. More than 50 Ph.D. students have worked with Pines——many have been hired by top academic institutions and private industry.

The bulk funding for this stream of research originally came from the National Science Foundation, with supplemental support from the university. In 1978, the program received full funding from BES and has continued in that fashion to the present. It is a good example of a multifaceted research program that includes important fundamental science with implications for many disciplines, and yet holds great potential for private industry.

The enormous diversity of scientific and industrial dimensions of this projects is chiefly due to the central role of a single person over the span of 25 years——Professor Pines. He has led several teams of researchers and students at his own lab, and has conducted collaborations with many scientists at other institutions in the country and abroad.

Pollard, D.

"Rock Fracture Networks and Clusters and Fluid Flow Properties in Reservoirs and Aquifers"

STANFORD UNIVERSITY

This project seeks to describe and document the geometry of opening-mode fracture networks and clusters in sedimentary rock in order to understand the mechanics of their development in relationship to faults and folds. The project team is developing a methodology for the prediction of spatial variations of permeability in fractured aquifers and reservoirs using an integrated program of field mapping, laboratory simulation, and theoretical analysis.

This is a somewhat typical, university based, small science project, yielding five doctoral dissertations and two masters' theses. A computer code, PRED2/3D, was developed for use in petroleum and hydro-geological applications. The project led to the development of new conceptual models and geomechanical analysis tools for the characterization and prediction of structural heterogeneities in oil and gas reservoirs and aquifers that have major impact in the flow of groundwater and hydrocarbons.

Sengers, J.

"Critical Phenomena in Fluids"

UNIVERSITY OF MARYLAND

The concept of a critical phenomenon in fluids comes from thermodynamics and refers to the behavior of a fluid near a state transition point, such as the transition point of water from liquid to steam. Critical phenomena in fluids have unusual properties such as the rapid dampening of sound waves, the extreme scattering of light, and the divergence of heat capacity and thermal conductivity.

Sengers and colleagues have made important contributions in theoretical explanation of phenomena, in experimental investigation, and in engineering applications through the research papers published in refereed journals. Their work also has industrial impacts, particularly in the areas of standard-setting in properties of water and steam. Since 1989, the project team has published fifty-five papers from their DOE-supported research. This research has contributed to the establishment of viscosity and thermal conductivity of water and steam that is currently used in the power generation industry throughout the world. The project also produces and distributes the diskettes containing the equations for the properties of water.

Shanklin, J.

"Characterization of Fatty Acid Desaturases and Related Lipid Modification Enzymes"

BROOKHAVEN NATIONAL LABORATORY

Understanding the architecture of the soluble plant fatty acid desaturase enzyeme and successfully redesigning the enzyme for functions previously unknown in nature act as paradigms for enzyme engineering in general. At the same time, the

introduction of double bonds into the acyl chains at desired positions and the production of a new generation of biomaterials are sources of the materials (currently obtained from fossil fuels). These materials will help a transition from finite fossil reserves to a renewable biological source.

This has obtained two patents that will likely enable biotechnology companies to engineer new oil crop plants. Based on this project, a CRADA was finalized with DuPont Corporation to develop basic research related to oil crop development. Cooperative projects were established with several large universities worldwide to investigate the materials developed in this project.

Somorjai, G.

"The Center for Applied Materials' Surface Science and Catalysis Program"

UNIVERSITY OF CALIFORNIA - BERKELEY AND LAWRENCE BERKELEY LABORATORY

The objective of this project is to pursue basic research in major areas of surface science and catalysis that have potential impacts on existing and emerging technologies. The research has focused on the synthesis, atomic level surface characterization (structure, composition, energy states), and the relationships between performance (chemical or mechanical) and molecular level properties. When the research began in 1971, the team utilized a new set of experimental methods for investigating various surface level phenomena.

Based on this project, over 750 articles were published and 110 students were supported. Although the research was originatlly focused on surface sciences of catalysis, the project expanded into diverse areas such as pollution prevention, biomedical devices, computer memory devices (disk drives, silicon chips), petroleum production, and polymer sciences. This project represents cross-fertilization through collaboration, not only among different disciplines in the university, but also among the formation of strong research capabilities in fundamental sciences. According to Somorjai, the training of students is the project's single most important contribution.

Sturchio, N. C.

"Mineral-Fluid Interactions: Experimental Determination Of Atomic-Scale Processes Using Synchrotron Radiation"

ARGONNE NATIONAL LABORATORY

The objective of this program is to advance basic understanding of rock-fluid interactions through experimental studies of atomic-scale processes at mineral-fluid interfaces. This is crucial to establishing the relationship between atomic-scale processes and macroscopic geochemical transport in large-scale natural systems. Sturchio and colleagues have demonstrated the ability to perform *in situ* X-ray reflectivity, diffraction, and standing wave studies of reacting mineral surfaces in chemically controlled conditions.

Of the ten journal articles produced by this project, one published in *Science* in 1994 has led to several additional successful collaborative projects. Two Ph.D. students have pursued degrees based on this project.

Sturge, M. D.

"Excitons and Plasmas in Semiconducting Microstructures and Ternary Alloys"

DARTMOUTH COLLEGE

This project focuses on spectroscopic investigations on three types of semiconductor systems. The research investigated type II indirect gap superlattices, strain confined quantum structures, and partially ordered ternary semiconductors in order to improve the understanding of optically excited states of such structures. Experimental tools such as time-resolved tunable laser spectroscopy, magneto-spectroscopy, and spatially resolved spectroscopy were employed, with and without external perturbations such as magnetic field, electric field, and uniaxical stress.

The most important findings of the project have been mainly theoretical, resulting in 33 articles published in scientific journals.

Swift, G.W.

"Thermal Physics"

LOS ALAMOS NATIONAL LABORATORY

This project seeks to apply the insights of thermal physics to develop a new means to achieve a well-established thermal transformation: heat transfer——the process at the heart of all heat engines. Most heat engines achieve heat transfer with the use of moving parts, but the approach of Swift and colleagues uses acoustic standing waves to achieve displacement without moving parts. This research drew on and contributed to foundational theory, yet has also contributed to the design of the heat engine.

The most promising output of the project to date is a large-scale collaboration with an industrial firm to develop a natural gas liquefier. Although this project developed 10 patents, Swift concludes that the impact of patent and licensing, in their current forms, are minimal. He emphasizes the importance of the theoretical advance above all else. The project trained a couple dozen postdoctoral fellows and many graduate students.

Tolbert, L. M.

"The Organic Chemistry of Conducting Polymers"

GEORGIA INSTITUTE OF TECHNOLOGY

This project pursues fundamental studies in the mechanistic organic chemistry of conducting polymers. Oligomers of defined length have been synthesized and their spectroscopic properties as they converge with those of the associated polymers have been compared——resulting in a validation of solid state theory. The outcomes obtained in this project expanded basic concepts in physical organic chemistry to include electroactive polymers.

This project has also researched charge distribution in polymer molecules and the mechanisms of charge transfer in these materials. The work was conducted, until very recently, under the supervision of a single investigator, Dr. Laren Tolbert. DOE support began in 1985, but the foundations of the research were set during the previous eight years work by Tolbert in carbanion chemistry while at the University of Kentucky and with NSF support.

The project is fairly typical of “small” basic science in an academic setting led by a single highly productive university professor. Two important characteristics of the research stream are noted. First, the main scientific impact was the result of cross-disciplinary fertilization occasioned by communication between the investigator and various audiences. Second, the career paths of students lead, almost exclusively, to industry.

Wagner, A.

“Artificial Photosynthesis: Chemical Dynamics of Combustion”

ARGONNE NATIONAL LABORATORY

The object of this project is to characterize the gas-phase chemical reactivity of small molecules and radicals, especially those of importance in combustion. This is achieved by combining theoretical studies in the energetics and dynamics of chemical reactions with experimental studies in chemical dynamics and kinetics.

The major contribution of this project has been the rich intermingling of theoretical and experimental approaches to understanding elementary reactions in combustion. The focus of this project is more on theoretical aspect; its major product is over 300 articles published in scientific journals. From 8 to 10 investigators worked on the research over its 15 years of existence.

Walsh, P.

“PERF, Combustion Research Facility”

SANDIA NATIONAL LABORATORY

The objective of this project is new basic understanding of the chemical kinetics of formation and destruction of hazardous air pollutants in flames. Based on this project, new techniques for laser-based imaging of industrial natural gas flames were developed. This research enabled to measure hazardous air pollutant emissions from natural gas combustion in an industrial scale furnace under well-controlled conditions. The results are under consideration in the U.S. EPA's Industrial Combustion Coordinated Rulemaking Process, by which emissions standards are to be agreed upon by regulators and industry.

This study demonstrated that combustion products from existing industrial natural gas burners, both conventional and low-NOx, when operated within normal ranges of excess air, contain negligible concentrations of hazardous air pollutants, even under severely upset operating conditions. The importance of this result is that it enables regulators to focus their attention on other, significant sources of pollutant emissions, not waste limited resources requiring changes in equipment on sources making no contribution to air pollution.

Weinert, M.

"First Principles Theory Of High And Low Temperature Phases"

BROOKHAVEN NATIONAL LABORATORY

The objective of this study is to show that first principle techniques can be used for determining the electronic and structural properties of metals, complex crystalline structures, liquids, and amorphous materials. This project has demonstrated that it is possible to accurately model materials properties from first-principles and that the results are often as accurate as those derived from experiment. The project team demonstrated that the long-standing disagreement between electronic structure theory and phase diagram constructs arose because of invalid assumptions of the phase diagram constructs. This has forced a reevaluation of the whole CALPHAD procedures that been successfully used in industry for 20-30 years. Other impacts include an increased understanding of impurities and phase stability of different systems as a result of the research.

Several of the algorithms developed in this project are now being used as a standard by other researchers in the field. Since the beginning, the team has collaborated with SUNY-Stony Brook which has provided human resources for the project. The research done on the instability of excited phases was the most important output as it required a reexamination of a number of assumptions underlying the field of phase diagrams. This work has extended beyond the standard materials physics community in academia into the materials community in industry.

Wigley, D.

“A Model Approach to Hydrodenitrogenation Catalysis”

UNIVERSITY OF ARIZONA

Available mechanistic information regarding metal-mediated hydrodenitrogenation (HDN) catalysis is not extremely detailed. This research explores soluable model compounds that stimulate HDN substrate/catalyst interactions. The primary focus is on the six-membered heterocyclic compounds such as pyridine and its derivatives, bound to mid- or high-oxidation state tantalum centers. The results of this research offer new insights in HDN related processes, including the manner by which nitrogen heterocycles may be further degraded after C-N bond clevage. Furthermore, this information is especially relevant to reactions of pyridine, since pyridine HDN often provides only a minor fraction of C5 products.

This research discovered and developed fundamental reactions in Hydrodenitrogenation (HDN) catalyis that help explain how the currently operating petroleum hydrotreating processes work, and point the way to new and more efficient catalysts that may be developed in the future. According to Wigley, this work will allow new catalysts to be developed on a more rational basis than has been done in the past.

One postdoctoral associate is now employed in the chemical industry as a result of his work on this project. Five Ph.D. dissertations and one masters thesis have been prepared based on this BES project. Although Wigley believes that this project has a significant impact on industry, Wigley emphasizes that the project’s most significant contribution to industry has been the education of graduate students who have been highly sought after.

References

Baker, N., S. Green, and A. Bean (1986) “The Need for Strategic Balance in R&D Project Portfolios.” *Research Management*, 29, 2: 38-44.

Becker, G. S. (1964) *Human Capital: A Theoretical and Empirical Analysis, with Special Reference to Education.* New York: Columbia University Press.

Bullock, R. J. and M. E. Tubbs (1987) "The case meta-analysis method for OD." *Research in Organizational Change and Development*, 1: 171-228.

Callon, M., P. Laredo, and P. Mustar (1997) *The Strategic Management of Research and Technology*. Paris: Economica International.

Cooper, R., S. Edgett, and E. Kleinschmidt (1997) “Portfolio Management in New Product Development.” *Research/Technology Management*, Sept.-Oct.: 16-28.

Gaughan, M. and B. Bozeman (1998) “Scientific Careers and their Social Contexts: A “Scientific and Technical Human Capital” Model for R&D Evaluation.” Paper prepared for presentation at the Institute for Operations Research and the Management Sciences, Seattle, WA, October 25, 1998.

Gear, A. E. (1974) "A Review of Some Recent Developments in Portfolio Modeling in Applied Research and Development." *IEEE Transactions on Engineering Management*, EM-21, 4: 245-248.

Illinois Institute of Technology Research Institute [IIT] (1968) *Technology in retrospect and critical events in science.* Washington, DC: National Science Foundation.

Kingsley, G., B. Bozeman, and K. Coker, K. (1996) “Technology transfer and absorption: an ‘R&D value-mapping’ approach to evaluation.” *Research Policy*, 25: 967-995.

Larsson, R. (1993) "Case survey methodology: Quantitative analysis of patterns across case studies." *Academy of Management Journal*, 36, 6: 1515-1546.

Laudan, L. (1977) *Progress & Its Problems: Towards a Theory of Scientific Growth*. Berkeley, CA: University of California Press.

Link, A. (1987) *Technological Change and Productivity Growth*. New York: Harwood Academic Publishers.

Link, A. (1996) *Evaluating Public Sector Research & Development*. New York: Greenwood.

Oehmke, J. (1990) "Optimal Evaluation of Research Portfolios." *American Journal of Agricultural Economics,* 72, 5: 1374-1374.

Rogers, J. and B. Bozeman (1997) “Basic Research and the Success of Federal Lab-Industry Partnerships.” *Journal of Technology Transfer*, 22, 3: 37-48.

Sherwin, C. W. and R. S. Isenson (1967) “Project Hindsight: Defense Department study of the utility of research.” *Science*, 156: 1571-1577.

Science Policy Research Unit [SPRU] (1972) *Success and Failure in Industrial Innovation*. London: Center for the Study of Industrial Innovation.

Tassey, G. (1997) *The Economics of R&D Policy.* Westport, CT: Quorum.

Vonortas, N. and H. Hertzfeld (1998) “Research and Development Project Selection in the Public Sector.” *Journal of Policy Analysis and Management*, 17, 4: 621-638.

Wolf, P. J. (1993) "A case survey of bureaucratic effectiveness in U.S. cabinet agencies: preliminary results." *Journal of Public Administration Research and Theory*, 3, 2: 161-181.