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INVESTMENT-ORIENTED R&D PLANNING AND EVALUATION FOR DOE'S CLEANUP

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PREFACE AND ACKNOWLEDGEMENTS

This paper was supported jointly by the Office of Science and Risk Policy and the Office of the Deputy Assistant Secretary for Planning, Policy and Budget within the Department of Energy's Office of Environmental Management (EM). It is addressed to the senior manager who must make decisions as to the structure and content of EM's programs of science, research, development, and demonstration (R&D). It is one of a series of reports by the Joint Institute for Energy and Environment (JIEE) that seeks to probe alternatives to EM's status quo and identify new strategic options available to EM. By design, this series adopts a perspective more general than the project-specific focus often found describing the cleanup program and more behavioral than the technical discussions that typically underlie waste cleanup planning. In doing so, it seeks to stimulate a dialogue over the benefits and costs of alternative approaches to R&D planning and evaluation that is realistic about the cleanup mission and the uncertainties and constraints faced by the program.

A central theme of the JIEE's work is that cleanup management should adopt explicit goals and organize activities across the Complex in an integrated manner. This requires central leadership from DOE Headquarters, which must ultimately assemble cleanup budgets and represent the cleanup activity to Congress and the national constituency. Given these goals and leadership, it must also be recognized that cleanup is a site-specific activity with legal obligations to regulators and stakeholders and unique local physical circumstances. An integrated cleanup program must accommodate this unique character. We have written extensively about how this might be accomplished.

This paper extends this concept to the management of the R&D function. It is based on the belief that R&D is an investment in the future and should seek the highest possible rate of return within relevant uncertainties and constraints. Building from this concept we propose a value-driven, integrated approach to R&D planning and evaluation. Throughout the paper two themes are juxtaposed. One is that planning and analysis requires a common, investment-based template from which to assemble data and permit common calculations to guide decision making. The second is that information-based decision making must be buttressed by compatible incentives so the behavior of the various players in the system will reinforce the decisions. We develop these themes from first principles and discuss how they might be implemented through a pilot program.

This paper follows in the footsteps of a number of earlier efforts to examine the DOE-EM R&D program. One, the Galvin Commission report, called for a more refined scientific base and led to the formation of the Environmental Science Program.[1] A second, "Building an Effective Environmental Science Management Program," by the National Research Council, addressed the organization and management of the Environmental Management Science Program.[2] Third, a second National Research Council report, entitled "Decision Making in the U.S. Department of Energy's Environmental Management Office of Science and Technology," addressed many similar topics to the current volume while focusing on current practices, and recommended a number of general principles that could be implemented to improve decision making.[3]

We would like to take this opportunity to thank the many individuals who have contributed to this report. Mark Gilbertson and Dan Berkovitz provided support throughout the course of the study. Milton Russell of JIEE provided many insightful comments on the various drafts the report went through. Ker-Chi Chang of DOE-EM organized an internal review within EM that helped ensure the report was accurate and targeted. This was particularly valuable, because the EM R&D programs have undergone numerous reorganizations and improvements, even as our research was being carried out. Within JIEE, Sherry Estep edited the report and Kathy Ballew produced the report in final form. The authors, of course, retain final responsibility for any remaining shortcomings.

Under the terms of our agreement with DOE, the authors are accountable for the contents of the document. Neither DOE nor its employees have had control over or bear responsibility for the views expressed herein.

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[1] Secretary of Energy Advisory Board, *Alternative Futures for the Department of Energy National Laboratories*, Task Force on Alternative Futures for the Department of Energy National Laboratories, Washington, D.C. 1995.

[2] National Research Council, *Building an Effective Environmental Management Science Program*, National Academy Press, Washington, D.C. 1997.

[3] National Research Council, *Decision Making in the U.S. Department of Energy's Environmental Management Office of Science and Technology*, National Academy Press, Washington, D.C. 1999.

I. INTRODUCTION AND EXECUTIVE SUMMARY

This paper uses an "investment analogy" to examine the program of research and development (R&D) carried out by the Department of Energy (DOE) in support of its cleanup mission. It asserts that the role for cleanup R&D is straightforward—to lower costs and to create new cleanup options. Targets of opportunity include storing wastes in different ways, treating wastes to different levels of hazard or stability, and remediating sites to different end-states. An effective R&D program at the appropriate level is a key part of a strategy to reduce the national burden of risks and costs imposed by the nuclear legacy.[4] Potentially, new technologies can also create options to attack previously intractable cleanup situations.[5] Even recognizing the value that fundamental science and new knowledge can indirectly contribute to social well-being, DOE's specific challenge is to identify and pursue the options offering greatest value to the cleanup mission.

R&D comes at a cost. Technological change occurs because DOE "invests" in R&D, by making the deliberate decision to treat less waste in current periods in order to treat more in future periods. From the perspective of a planner, such a tradeoff makes sense if the overall program becomes more productive. However, under these circumstances less current cleanup occurs, and more confidence in program management is required. Thus, DOE requires a method to convey the logic of its planning process to interested parties—such as Congress, its regulators and stakeholders—as well as a management system that will permit it to evaluate if it is making good on its promises.

Cleanup R&D also occurs within a context, specifically, within the boundaries of the "DOE Complex." The Complex includes national laboratories, weapons laboratories, uranium enrichment facilities, weapons production facilities, and numerous smaller and/or special purpose facilities. Individual members of this group have long carried out research dealing with weapons, nuclear fuels and technologies, energy technologies, and a broad array of basic research. Undertaking cleanup R&D (hereafter simply R&D) can require these groups to direct efforts away from traditional, often basic, avenues of enquiry and toward new, and often more applied, topics. Decisions over cleanup technology choices are also multi-layered, with cleanup managers, stakeholders, and regulators each having a role that leads to long

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[4] M. Russell, *Reducing the Nuclear Legacy Burden: DOE Environmental Management Strategy and Implementation*, JIEE 2000-01, April 2000.

[5] DOE carries out a variety of waste-related operations that deal with past and ongoing weapons development, past and ongoing research, the decontamination and decommissioning of buildings and facilities, and the remediation of lands and soils. We simplify all of this by referring to it simply as "cleanup," but we recognize that there are a multitude of activities that constitute the DOE environmental management program.

deliberations over the assignment of cleanup technologies to cleanup tasks. As a result, at the site level, the program tends to "lock in" to existing technologies. Thus, in addition to identifying the benefits and costs of R&D alternatives, DOE must anticipate behavioral barriers to developing and deploying new technologies.

A system that casts R&D as an investment is attractive to address both issues. It provides a means for systematically organizing the variables needed to plan and evaluate cleanup-targeted R&D, to calculate paybacks from alternative R&D strategies, and to identify circumstances when behavioral incentives come into play. From a planner's perspective, R&D creates options for future actions without requiring that the options actually be exercised, thereby creating flexibility. But from the banker's perspective, at least some of these options must be implemented if their production is to be justified.[6] R&D also incurs greater and different sorts of uncertainty than the typical investment. These uncertainties include the likelihood that innovations will be successfully developed and, if developed, the likelihood they will be acceptable to stakeholders and regulators.

One major barrier in developing a system to identify the R&D choices contributing the greatest value to cleanup is that DOE has not developed clear-cut measures of cleanup value. Value must be approximated through surrogate measures, referred to as metrics. Instead of placing a value on specific cleanup tasks, DOE has implemented its cleanup as a set of individual, site-specific, hazard-based activities, the completion of which will lead to a set of end-states acceptable to stakeholders and regulators. Within this context, and over the scheduled lifetime of the cleanup—some seventy-five years— there is little information available to differentiate among tasks or between sites. Data on uncertainties and behavioral incentives are also less than perfect, though we argue that data imperfection should never be taken as a reason to delay or avoid analysis. Nevertheless, for the program to succeed it is imperative to construct output metrics that distinguish among degrees of success over time, by measuring the extent to which risks have been reduced and identifying future requirements for continued stewardship.

More generally, we believe that R&D should be integrated within a larger cleanup management system. A single, central logic for defending specific cleanup choices would provide the strongest basis for defending specific R&D choices. In this paper, we organize our rationale for R&D planning and evaluation within the logic of the integrated cleanup management program we have described elsewhere and, in

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[6]In financial management, options are used as part of a larger risk-bearing strategy. Because options are sold over limited price ranges and for limited periods of time, they sell for much less than their target instrument and offer a cost-effective tool for the financial analyst to limit or extend risk. For a time, some investors viewed options as an end in themselves and used them as an inexpensive means to leverage the purchase of financial assets. This period gave rise to many financial disasters, including the bankruptcy of Orange County, California.

doing so, extend our overall management system.[7] Our approach requires that participants throughout the Complex adopt a single set of goals, a common definition of cleanup task value, a shared data base describing technical options, and a set of incentives that motivates them to pursue the goals actively. None of this is to say that each site should place the same value on the same physical activity, but rather that they should establish value and undertake site sequencing in the same fundamental manner.

Some would argue that this ignores reality. Cleanup managers at DOE's operating activities have painstakingly negotiated cleanup plans with stakeholders and regulators, which once adopted have the force of a legally binding obligation. A first consideration may be to ask whether or not cleanup plans have sufficient flexibility to benefit from new technologies.

From one perspective, cleanup plans are firmly set, with regulatory standards driving the level of cleanup and compliance agreements driving the schedule. In this context, R&D serves primarily to supply technologies for situations where no sufficient technology previously existed and, perhaps, to exert a general influence on the overall technical base. This view predicts a limited role for R&D. A second perspective views cleanup as much more flexible and the opportunities for performance-enhancing R&D as much more substantial. As a first instance, unmet technical needs will always be an important target of R&D. Accordingly, compliance agreements can be, and frequently are, renegotiated as circumstances change. One example of changed circumstances would be the development of technologies that offer advantages over the existing technical base. A second would be tighter budgets that would leave some activities undone. A third instance would be the discovery that some circumstances warrant more cleanup and others less cleanup than was previously contemplated. Each of these and other circumstances renders the situation more fluid and offers opportunities to consider new technologies that were previously unavailable.

In fact, there is validity to each view, but more importantly, both ignore the responsibilities of the headquarters planners who must rationalize the cleanup to a critical audience. Compliance provides these planners with a very weak base from which to argue priorities. Even though DOE is obligated to seek a budget that meets its legal obligations, Congress views its oversight role as ensuring that DOE is using budget dollars efficiently and effectively. Thus, apart from simple compliance, DOE is continually faced with the need to present evidence that it has identified new, more efficient alternatives to current practices, evaluated tradeoffs among the new and old

[7] D. J. Bjornstad, D. W. Jones, M. Russell, K. S. Redus, and C. L. Dümmer, *Outcome-Oriented Risk Planning for DOE's Clean Up*, JIEE 98-01, October 1998; M. Russell, *Reducing the Nuclear Legacy Burden: DOE Environmental Management Strategy and Implementation*, JIEE 2000-01, April 2000; and D. J. Bjornstad, D. W. Jones, M. Russell, and C. L. Dümmer, *Implementing Outcome-Oriented Risk Planning: An Overview*, JIEE 98-02, September 1998; C. L. Dümmer, D. J. Bjornstad and D. W. Jones, *Opportunities for Regulatory Reform for DOE Cleanup*, JIEE 00-03, April 2000.

approaches, and sought out the most mutually beneficial terms among itself and its regulators and stakeholders. If current practices are less than fully efficient, Congress typically demands to know the opportunity costs of current choices, even if these choices reflect legally binding, past agreements. Therefore, even when legal obligations partially constrain DOE's path, an investment-based approach to R&D management offers clear benefits for articulating how the programmatic choices of a centrally-housed R&D management team are both responsive to the needs of the field and are adopted by the field. Rather than ignoring reality, our proposed approach to R&D management allows the integration of R&D with the reality of the field cleanup tasks.[8]

We present our arguments in seven sections and an Appendix. Section II presents the investment principles that are used to link R&D planning and evaluation to management practices. This section introduces the basic conceptual model, the changes that are needed to adapt it from evaluation to planning analysis, and the data that the model requires. In particular, the need for cleanup values, R&D uncertainties, deployment uncertainties and incentives are described. These data inputs are taken up in successive sections that describe concepts of value, the logic of R&D planning under uncertainty and in pursuit of value, the need to consider practical issues of deployment, and the behavioral basis for incentives. These are contained in Sections III through VI, respectively. Section VII demonstrates that even if this admittedly ideal system could be put into place, it still would require integration with other cleanup management systems. It indicates the importance of goals, complex integration, incentives, and the kinds of results that would occur if the system were fully in place. Finally, Section VIII takes up the policy implications of this analysis and the steps that might be used to implement the system. The Appendix describes the mathematical programming model used to generate the data presented in Section VII.

In the process of developing our logic, we have reached a number of conclusions. These may be summarized as follows.

- The system for R&D prioritization that we propose shares many attributes with DOE's current system, and for virtually each topic we raise, some process or procedure is already in place. We have chosen not to dwell on these existing activities. Instead we develop a substitute approach based on investment principles and on a common integrating logic. Our approach is intended to make transparent all facets of R&D management. The approach highlights the tradeoffs among the costs and benefits of R&D, uncertainties and incentives. It

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[8] We further believe that compliance-based regulation holds considerable flexibility to consider new technical options. See C. L. Dümmer, D. J. Bjornstad and D. W. Jones, *The Regulatory Environment Guiding DOE's Cleanup: Opportunities for Flexibility*, JIEE 98-04, September 1998; and C. L. Dümmer, D. J. Bjornstad and D. W. Jones, *Opportunities for Regulatory Reform for DOE Cleanup*, JIEE 00-03, April 2000.

describes the need to integrate R&D management with other aspects of cleanup management. It also recognizes the realities of a complicated cleanup program with multiple players and a long history.

- DOE's current means for R&D prioritization is a bottom-up approach in which site level managers match cleanup tasks and technologies, and R&D managers use this information to set the R&D agenda. To tighten the relationship between tasks and technologies, we propose developing more explicit measures of cleanup task value. We discuss value in detail below, but it should be generally thought of as a goal-related metric that can be compared to the costs of undertaking R&D. Our concept of value is incremental, because it is the change in value that results from a technical innovation, as distinct from the entire benefit that accrues to some cleanup task, that must be compared to R&D costs. Adopting this format would provide explicit guidance as to which opportunities offered greatest net value and were therefore the logical targets of R&D emphasis. This approach would permit R&D managers to argue the basis for the R&D agenda using information that reflected overall program goals, as well as the site level applications described in *Paths to Closure*.

- Grounding R&D in the pursuit of cleanup value would provide a basis for transforming the cleanup R&D program to a wholly use-driven system. Our proposed approach to this is to extend the R&D review process into what we term a 360 degree system in which information on cleanup needs and scientific opportunities would flow seamlessly between R&D managers and researchers. Within a 360 degree system, users would articulate cleanup needs, but equally, researchers undertaking basic or foundational studies would bear the burden of articulating needs for fundamental enquiry. The Galvin Commission properly recognized the necessity of investments in the intellectual infrastructure required for technical breakthroughs, but did not endorse enquiry for its own sake. Again, to a degree these practices are already being pursued, and our suggestions are intended to make the process more explicit.

- Our formulation for setting the R&D agenda is based on managing uncertainty, much like a financial manager manages financial risk, and draws on many similar tools. One source of uncertainty to be made explicit is the risk that technologies may not be deployed for reasons ranging from timing to changes in cleanup priorities to stakeholder or regulator reluctance, to preemption by better alternatives. Unacceptable technologies should be recognized as such, but opportunities to "tune" technologies to local needs should not be overlooked. A second source of risk is the fact that not all R&D enquiries will bear fruit. For these reasons, the R&D agenda will logically initiate many more activities than it will actually complete. Without advocating "day trading," we believe that an R&D technology portfolio must have a reasonable amount of turnover, based on information that was unavailable or conditions that changed after individual technical pursuits were initiated.

Explicit attention should be paid to circumstances where negative incentives could weaken or defeat the system we propose or where the lack of positive

of site level managers to adopt new technologies once cleanup plans are set. A second is that central R&D managers may not be attentive to the explicit needs

naturally to some projects being canceled for programmatic, rather than technical, reasons. Negative incentives should be replaced by positive

- The approach we propose is consistent with a fully integrated cleanup

  elsewhere. Adopting such a management system would provide a basis for prioritizing cleanup tasks according to system-wide goals and then linking R&D to the prioritized tasks. Such a system would provide an objective basis

  budget should be larger or smaller.

- practices and procedures linked to these concepts will determine the system's ultimate utility. We describe the practical implications of our analysis in some

  never be available. None of this should be taken as an excuse for inaction.

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II. PRINCIPLES OF R&D MANAGEMENT

Viewing research and development as an investment highlights the tradeoff between giving up current cleanup dollars to gain greater future benefits, and provides a method for estimating the relative dimensions of this tradeoff. In principle, the process is straightforward. If a dollar today spent on R&D can produce more than a dollar of future cleanup, properly discounted to reflect rate of return on investment, it is logical to carry out the R&D.[10] This section seeks to develop principles for measuring these values.

Our approach to R&D prioritization draws upon two tools of investment analysis. The simpler of the two, conducted *ex post* or after the fact, asks the question: "How well did we do?" We refer to this as evaluation. Evaluation seeks to measure rates of return, with a positive rate of return indicating an improvement in the overall value of cleanup.[11] Measuring a dollar rate of return would require knowing the dollar value of the set of cleanup tasks, the costs of conducting them with the existing technical base, and the dollar improvement to cleanup or the dollar reduction in costs that R&D contributed. From this gross return would be subtracted the total cost of producing the new innovation. The time periods during which R&D takes place and innovations are put into place would differ, and discounting would be required. In general, the costs and benefits attributable to each year would be discounted and summed. Carrying out this calculation would yield a present discounted value from which could be calculated a rate of return or other measures of investment performance.[12] The key element of this calculation is some measure of the relative values of different cleanup tasks. We take up issues of value in Section III, immediately below, but note here that precise measures of value may never be known and that the value of successful cleanup of a given target may change over time.

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[10]See M. Russell, *Reducing the Nuclear Legacy Burden: DOE Environmental Management Strategy and Implementation*, April 2000, JIEE 2000-01. Russell's paper develops the thesis that the national goal for the cleanup program should be to reduce the combined burden of the risks that the legacy presents and the costs (defined broadly) of reducing these risks, with both aspects of the burden considered cumulatively over time. R&D funding and management as discussed here provides one element of the strategy that Russell develops to guide DOE in meeting this goal.

[11]If investment returns are calculated properly, using an appropriate discount rate, it can be argued that any investment with a positive present value should be undertaken. However, funding for specific types of investment, like R&D, may be capped or rationed by category. When this is the case, ranking R&D opportunities by rate of return can provide a means for prioritizing investments within categories. It can also provide evidence of where opportunities exist to gain efficiency by moving funds between categories.

[12]It can also be argued that after the fact evaluation of successful R&D projects neglects the costs of unsuccessful ones. Thus, the total costs of successful R&D should include these costs. More generally, it may be desirable to evaluate the entire R&D program, rather than individual projects.

The second tool deals with before the fact or *ex ante* analysis, and asks the question: “What R&D choices will yield the best expected rate of return?” We refer to this as planning. During the planning stage, R&D managers have incomplete information concerning the future, and must deal with a number of uncertainties that govern whether or not an innovation will yield value. We divide these uncertainties into two types. First is the likelihood that the R&D will lead to a successful cleanup innovation. We refer to this as *discovery uncertainty*, and take this topic up in Section IV. Second is the likelihood that if R&D is successful the resulting innovation will be acceptable and deployed. We term this *deployment uncertainty*, and discuss it further in Section V.

Planning and evaluation must be based on the same principles. An agency of government loses credibility if it sets plans using one set of criteria yet judges the success of those plans using different criteria. Nevertheless, *ex ante* and *ex post* analyses will necessarily differ in the quantity and quality of available information when they are conducted. It is a simple fact that future events are uncertain. What is sometimes less obvious is that this uncertainty is a normal cost of doing business, whether for the private sector or for government, and that a number of tools have been developed to help “manage” uncertainty. Managing uncertainty is less concerned with forecasting future events than it is with identifying opportunities to hedge against unfavorable outcomes. Hedging means taking actions that provide insurance. However, DOE cannot typically purchase insurance in secondary markets like households purchase fire insurance. Instead, DOE must assess the range of likely uncertainties that will lead to different technical requirements, determine these requirements, and develop an R&D portfolio that provides insurance against a range of outcomes. Like households and businesses, DOE runs the risk of being “insurance poor.” Thus DOE should attempt to assemble the best available information, update it frequently, and make changes to the R&D portfolio based on the newest information.

In this sense, the R&D portfolio is almost precisely equivalent to the purchase of financial options. A financial option is a derivative instrument that guarantees its owner the opportunity to buy or sell some primary financial instrument at a fixed point in time at a given price. It does not, however, obligate the owner to do so. If conditions, uncertain at the time of purchase, do not come to pass favorably, the owner simply allows the option to expire, and writes off the purchase price as a cost of insurance. If they do come to pass the owner exercises the option and buys or sells the underlying financial asset. Because financial options expire frequently, buyers must constantly update their expectations concerning uncertain events and make decisions over whether to allow options to expire, to repurchase them, or to purchase different options than before. Firms view options as a form of insurance. Thus, a decision to purchase, for example, crude oil futures, limits the range of prices a refiner must pay for future shipments. If the prevailing market price falls below the option strike price, the refiner buys at market and allows the option to lapse. If not, the option is exercised. In either case, the price paid for the option is the price paid to manage uncertainty.[13]

DOE's R&D planning process should follow a path parallel to this financial analogy. To apply this approach, DOE should consider the various uncertainties it faces for each R&D target and undertake R&D that leads to innovations appropriate for each eventuality. It should then periodically update its expectations, based on R&D results, deployment likelihood, and the value of the cleanup targets, and decide whether or not to renew the option, that is, whether or not the individual R&D task should be continued. Thus, individual R&D tasks are evaluated on their own merits and on their expected contribution to the overall R&D portfolio. For example, if it becomes clear that a given technology, however technically attractive, could not be deployed, DOE may not want to "renew its option." Similarly, if an alternative technology is more attractive, DOE may also wish to cancel. Over time, cleanup priorities may also change, and DOE may wish to redirect its resources toward tasks of higher value and away from tasks of lower value. The point is not that DOE should engage in "day trading," by rapidly moving in and out of R&D topics. But DOE should be able to justify its R&D plans at any given point of time on both the merits of its technology targets and on their relationship to the larger R&D portfolio and should make the adjustments needed to maintain this justification.[14]

Naturally, the range of possible outcomes is large, and not all avenues of enquiry can be followed with equal intensity. Specific choices thus become a matter of R&D policy. For example, DOE might emphasize technological improvement for the most likely outcomes, or it might emphasize improvements for the most high value tasks. The point is, by using this information, a specific policy can be followed and articulated. DOE is, in essence, developing a diversified R&D portfolio that can be modified as new information becomes available. In doing this, DOE prepares for a number of contingent outcomes and need not start over if its "best-guess" about the future proves incorrect. In other words, like a wise investor, DOE should avoid putting all of its eggs in one basket.

One particular issue of policy is the choice of a discount rate. Using a high discount rate means that benefits occurring in the future will figure less heavily in the present value calculation, whereas choosing a smaller discount rate would lead to

[13]Financial options have also been used by some investors as a means to leverage the purchase of financial instruments for speculative purposes. Our analogy to options should not be taken as an endorsement of blindly undertaking excessive levels of untargeted R&D on the hope that something positive will emerge.

[14]This approach is similar to "Bayesian Updating," and is described more fully in T. R. Curlee et al., *R&D to Reduce Greenhouse Gases—The Importance of the Government's Role*, JIEE 97-7, October 1997; and R. C. Lind, *Global Warning Policy: The Need to Consider Real Options and Take a Sequential Approach,* Environmental Protection Agency Report, May 1992.

future benefits counting more in the calculation. A number of considerations go into

receive smaller weight than current ones. One would not be indifferent to receiving a dollar's worth of benefits today and a year from now. A dollar today would be

indifference. Paying in the future would be preferred. The specific rate to be used is much less clear. Some, especially those who prefer more R&D, would argue for lower [15]

Because discounting places greater weight on near term costs and benefits and

that it shifts burdens from present to future generations, the so-called intergenerational equity issue. This is a complicated issue that cannot be fully addressed here, but which

that is, the greatest value for any given resource expenditure. Since consumers prefer present purchases over future purchases, a payment is necessary to compensate them

achieve to justify borrowing money to invest in some activity expected to produce a return. Thus, the interest rate is a price that allocates consumption across time

positive rate of return to defer current consumption in favor of future consumption. Making investment decisions in this way ensures that society compensates future

One should not assume, therefore, that all costs passed to the future violate the equity criterion. First, the benefits that accrued to "winning the Cold War" accrue to the future, as well as the past. Thus, in a sense, the future bears some responsibility for paying these costs. Second, whatever the cause, legacy wastes are a sunk cost. Spending resources to deal with them deprives the future of the alternative products that the same dollars could have produced. Thus, to the extent that greater spending on cleanup means less spending on (say) medical research, there is a tradeoff to be faced. Finally, not all cleanup tasks fall within the scope of the current technical base. Undertaking a less than satisfactory current cleanup that precludes future cleanup with superior technologies also has equity as well as efficiency implications.[16]

A complete discussion of the choices underlying the discount rate is beyond this paper. A good summary of the issues is found in "A Primer on the Major Issues Related to the Discount Rate for Evaluating National Energy Options," in R. C. Lind, ed., , Washington, D.C., The Johns Hopkins University Press, 1982. The Office of Management and Budget deals with

[16]We add for completeness the following argument. Even under a pure intergenerational equity criterion,

suggests that dollar-for-dollar transfers from the present to the future mean transferring wealth from a poorer to a richer generation. Equalizing transfers in utility terms would thus call forth the use of a positive

Ensuring that all benefits and costs are represented is as important as choosing the discount rate, and to do this the unique aspects of the cleanup program must be taken into account. For example, some cleanup values are dynamic, in the sense that the value of cleanup increases over time because the risks associated with some hazards are increasing. In others, if hazards dissipate naturally, cleanup values decrease over time. Some types of DOE hazards may pose special costs beyond direct risks to health and the environment. For example, the public has typically associated a risk premium for nuclear materials that exceeds objective measures of risk. Sometimes large overheads, termed "mortgage costs" within the Complex, are associated with maintenance and surveillance of sites over time and must be taken into account. It is important to recognize that these choices are ultimately matters of policy, but until they are isolated and explicated, they cannot be fruitfully addressed.

In creating an R&D insurance policy, DOE should view its R&D program as a series of small steps, rather than a once-and-for-all commitment. Then it can undertake alternative courses of action with explicit plans to cancel those that prove less viable than others. By doing this, DOE is managing the risk of having undertaken a more limited set of activities and having "guessed wrong" about which would be successful. It is also managing the risk of having circumstances arise for which there is no appropriate technology. Its cost for doing this is the cost of initiating more R&D activities than will actually be completed.

It is sometimes suggested that DOE can engage in risk sharing with the private sector and thereby limit its costs of making the wrong R&D guesses. This is typically possible only when private firms have markets beyond DOE in which to sell similar R&D products. When DOE makes up the entire market, and when DOE and the private sector each make decisions based on the same information set, they should reach the same conclusions as to the riskiness of an R&D investment. In making bids, private firms cushion their cost estimates to account for uncertainty, just as they account for any other normal business expense. Under these circumstances DOE will save money only when firms calculate the costs of uncertainty improperly or when DOE fails to provide full information. In either case, the courts have often converted fixed-price contracts to cost-plus contracts under these circumstances. This not to say that DOE cannot benefit from using the private sector in its cleanup. By doing so it can gain proprietary information, hire new expertise, and draw upon the powerful performance incentives that market forces provide. We deal with these opportunities at length in our work on privatization.[17] But DOE cannot, in general, force or

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discount rate to maintain equity.

[17]D. J. Bjornstad, R. C. Cummings, C. L. Dümmer, D. W. Jones, M. Russell and G. Valdez, *Risk Reduction and the Privatization Option: First Principles*, JIEE 97-04, September 1997; and D. J. Bjornstad, D. W. Jones and C. L. Dümmer, *DOE-EM Privatization and the 2006 Plan: Principles for Procurement Policies and Risk Management*, JIEE 97-08, July 1997.

otherwise convince firms to absorb normal costs of doing business, beyond a reasonable level of profit, and uncertainty is such a cost.

It should also be recognized that ideal data for planning and evaluation are unlikely to ever be available, and that waiting for better data can lead to perpetual inaction. DOE should accept data weaknesses, while moving ahead. The private sector faces similar challenges in its own R&D planning. For example, a firm's bottom line is contribution to profits, but direct measures of R&D rate of return are not always obtainable. One can evaluate the contribution of a new product line to a firm, but it is more difficult to measure the role of continuing technological change on profits. How much should Corporation X credit to the development of a new operating system, given that X already dominates the market for its product? How much should an automaker credit to an updated vehicle in maintaining market share? Corporation X may not compute a precise rate of return, but it knows the response of the market place to its products, and it ultimately knows its own profitability. Likewise, the automaker knows its market share, even if it doesn't fully understand the linkage between R&D and share. Thus, even though DOE may not fully understand the dollar-denominated rate of return from R&D dollars, it can still collect and analyze the information available on the success of its R&D programs, taking into account the fact that data are always imperfect and incomplete.

We close this discussion by noting that failure to bring R&D activities to closure is a wholly unattractive prospect to the researchers whose tasks are canceled, particularly when the reasons for canceling are non-technical. DOE may wish to consider implementing management practices that cushion the blow of project cancellations to avoid creating ill will or other responses that might lower the overall productivity of its R&D program. For example, DOE could rearrange priorities within an R&D organization's larger program, essentially holding the organization harmless for forces outside its control. It might also reserve dollars from canceled programs for new activities. It should, in particular, avoid stigmatizing researchers whose programs are chosen for cancellation because, in a very real sense, these researchers may contribute significantly to overall rates of return by having provided the information needed to judge their programs' contributions within the context of cleanup. Nevertheless, following this approach would necessarily lead to canceling some programs and, potentially, to enlarging others, and there will be concomitant individual winners and losers, even though the cleanup program as a whole would benefit. We discuss these topics in more detail in Section VII.

To summarize, viewing cleanup R&D as an investment is an attempt to clarify the various benefits and costs associated with spending fewer current dollars on cleanup to achieve greater future cleanup value. R&D should thus be evaluated on the basis of its success in creating greater future cleanup values, net of R&D costs and discounted appropriately. R&D planning should be based on the same principles as evaluation, but should seek to manage uncertainties associated with "discovery" and deployment. This can best be accomplished by viewing the R&D program as a series of small steps, analogous to financial options. Periodically, information as to

R&D progress and deployability should lead to changes in the R&D portfolio. These changes are key to successful management of R&D and should not be judged failures.

III. THE IMPORTANCE OF VALUE

Despite the fact that cleanup is driven by environmental statutes, there is an implicit concept of value that underlies the decision to undertake some cleanup activities, postpone others and ignore others altogether. This concept rests on the notion that even though society could use the resources that go into cleanup in many different ways, the choice to use them in cleanup implies that social well-being is greater from additional cleanup than additional purchases of other goods government might provide. This is similar to the reflections of value that occur when a household chooses to purchase one auto over another or, more generally, chooses its particular budget allocation over alternative allocations. The fact that cleanup choices are guided by environmental rules and regulations, rather than by specific studies that seek to value the parameters of each cleanup choice, reflects the fact that rules and regulations can, in some circumstances, reduce the costs of implementing general policies. The general policies are, nonetheless, intended to maximize the net value of government activities.

Value is different than cost. Sometimes a relatively inexpensive cleanup activity can provide a highly valued result, just as a very expensive activity may contribute little to well-being. The nation's environmental regulations are intended to produce the highest possible level of *net* well-being. Stated differently, they are intended to produce the greatest increment of benefits over costs, that is, the greatest net benefits.[18] Clearly, it is easier to measure costs of cleanup than it is to measure the value of cleanup, especially when the aim is to compare the two in dollar terms. Nevertheless, thinking in dollar terms helps to clarify the kinds of considerations that should go into cleanup choices if society wishes to achieve the greatest net benefits.

The value of any individual R&D project is derived from its impact on net benefits for the cleanup task at which the R&D is targeted. More specifically, net benefits can change because total values increase, because costs decrease, or because of any combination of cost and benefit changes that increase net well-being. When there is no technology available to carry out the task, the entire task value, net of costs, can be assigned to the technology, though care should still be taken to choose the most favorable net benefit result. When there are existing technologies, and if the innovation produces the same cleanup product, the proper measure to assign is the net

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[18]The notion of using net benefits as an input to decision making is well established in government. As early as the Nixon Administration, and on through the Ford and Carter Administrations, Executive Orders called for economic analyses of major rules implementing legislation. President Reagan issued Executive Order 12291 calling for the explicit use of benefit- cost analysis in rule making, a practice that has been reenforced by each administration since then. The Office of Management and Budget provides instructions for carrying out benefit-cost analysis in its circular A-94, dated October 29, 1992. The Clinton Administration has done this through Executive Order 12866.

cost savings over the best currently available technology. To the extent that technologies are robust and can be applied broadly, this attribute should be factored into the value calculation. It is also possible for an innovation to lower total task value, while increasing its net benefits. This would occur when an innovation lowers both costs and benefits, with cost decreases exceeding benefit decreases. Under this circumstance, total benefit increases could still be realized if cost savings were used to undertake additional activities.

Cleanup value estimates that were measured in the same metric as cleanup costs would thus simplify the task of R&D managers greatly. Although values can take many forms, dollar values defined by the willingness to pay by the relevant constituent group to avoid some damage, harm or other cost due to contamination would be most relevant. If this information were available to R&D managers, R&D planning could easily identify the tasks that offered the highest rate of return. They could then seek to manage risks due to other uncertainties, and choose R&D agendas that delivered the greatest expected values. They could also evaluate the tradeoff between more or less R&D and address directly the opportunity costs accruing to thinking versus doing. Moreover, if the planning system through which tasks were sequenced were also value-driven, innovations that modified cost-benefit relationships could lead to a resequencing of projects and in turn to a larger programmatic net value. In a sense, R&D in search of value creation could be the engine that drove cleanup.

Properly organized, the process of establishing a research agenda would draw information from some management functions and supply inputs to others. There is clear advantage to allowing different management functions to be specialized. For example, one group could establish cleanup task values. Naturally, this practice would have to take into account legal obligations, but we have argued elsewhere that there may exist significant flexibility within the larger program context.[19] Ideally, value estimates could be arrayed by end-state. This would allow the comparison of technologies that produce different cleanup levels. R&D managers could supply information on cost alternatives, given different R&D objectives. They would in turn arrange R&D agendas to take into account the highest valued targets. Planners responsible for sequencing would use both cost and value information to schedule activities to accomplish the greatest net value accomplishments. The result from this would be a fully integrated management structure. We demonstrate the attributes of such a system in Section VII.

However, DOE has not established value estimates for cleanup tasks. Private firms have similar problems estimating specific R&D contributions to individual business activities, but can ultimately relate R&D to the firm's net revenue position.

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[19] C. L. Dümmer, D. J. Bjornstad and D. W. Jones, *The Regulatory Environment Guiding DOE's Cleanup: Opportunities for Flexibility*, JIEE 98-04, September 1998.

To complicate this task further, DOE does not have a market test, like profits, and must substitute some other measure of performance. Several candidates for surrogate benefit measures, each of which has advantages and disadvantages, are available.

One attractive measure that we mentioned above is the use of risk reduction as a metric for cleanup performance.[20] In its purest form, risk reduction can be defined as the value of avoiding harm or damage due to contamination. Other risk-related measures might describe damages in physical terms, such as deaths, illnesses, lost natural resource and land services, degree of contamination and the like. Such measures could provide R&D managers with an independent means for targeting their activities. At present, risk measures do factor into cleanup management, but they are not employed in ways that could guide R&D in the manner we describe.

A second measure characterizing individual cleanup tasks is the cost for cleanup using current technology. In this case R&D value is measured as the savings from an innovation, relative to some baseline technology. Clearly this is a less desirable measure because it fails to discriminate among different levels of cleanup, and specific choices about task sequencing if budgets are tight. Again, one's view of costs depends on the degree of flexibility one assigns to cleanup activities. Some would argue that cost savings is the most relevant measure, because DOE should be committed to clean each site to the greatest degree possible. Following this reasoning, it might even be argued that while sequencing should reflect cleanup priorities, each task is of sufficient value that cleanup should continue until all tasks are completed. In this sense, sequencing is of minor import. Unfortunately, such reasoning is ultimately self-defeating. As noted above, Congress includes DOE's ability to achieve cleanup efficiencies among its budget criteria. If DOE plans its program without accounting for budget ceilings and without describing the opportunity costs of its actions, Congress is likely to respond with reduced budgets. This is not to say that DOE should stand ready to renege on past commitments, but rather that DOE should be prepared to describe the benefits its actions purchase.

There are also a set of "yes-no," or binary measures of R&D relevance. One such measure is simply to target unmet technical needs. Another is to target potential needs, that is, cleanup tasks where improvement over baseline technologies is possible. Yet another might target robust technologies that would meet a variety of needs. Sometimes these criteria are presented in the form of a "gated" decision process. Each such measure, while of value, is essentially descriptive, increases reliance on the subjective judgements of program managers, and, thus, is more difficult to explain to program critics.

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[20]D. J. Bjornstad, D. W. Jones, M. Russell, K. S. Redus, and C. L. Dümmer, *Outcome-Oriented Risk Planning for DOE's Clean Up*, JIEE 98-01, October 1998.

Overall, the largest gap in the R&D planning information set is the lack of comparable measures of value by cleanup task.[21] Numerous difficulties arise from this defect and from the use of value surrogates. Cost-based measures can focus R&D away from unmet needs and toward short-term savings. Such savings are likely to be marginal, and if tight time schedules are followed, technologies may not be completed in time for use, especially if an extended decision process must precede deploying a new technology. Cost measures fail to reflect technological improvements that offer more desirable end-states. For tasks without existing technologies, a lack of baseline value estimates leaves R&D planners without guidance as to priority. Thus, without some programmatic indication of value, R&D planners must be prepared to create and defend their own implicit or explicit values as they undertake R&D prioritization.

[21] Arguably, the lack of a measure of cleanup value is also the greatest barrier to efficient project sequencing and to other aspects of cleanup management.

IV. DISCOVERY UNCERTAINTY AND THE LOGIC OF R&D PLANNING

The question next arises of how best to manage uncertainty attendant to the process of R&D discovery. In other words, how should the sequence of R&D projects leading up to the desired set of innovations be chosen and managed? By tradition, the logic of knowledge accumulation has been described as a linear continuum running from most basic to most applied. If followed literally, this view would imply carrying out basic research with little or no regard for its use. This contrasts with our investment-based argument that R&D should target value. The alternative to this is to aim basic, as well as applied research, toward specific, value-related end points. We argue that for a program with specific goals, like the cleanup program, both basic and applied research should be clearly directed in this way. This is not to say that all Federal research should be use-driven, but that cleanup R&D should be.

The linear view of R&D causality was expressed by Vannevar Bush in his landmark report, requested during World War II by President Franklin Roosevelt, *Science— the Endless Frontier*.[22] According to Bush, scientific progress occurred as knowledge-driven basic research, exogenously motivated, was fed into more applied research that was problem-driven. In this view, problem-driven research was made possible by basic research, but not the reverse. This view cautioned Federal R&D managers to be wary of applied research. If permitted, excessive amounts of applied research could draw resources away from more fundamental research, and stifle the process arguably responsible for the nation's economic and technical growth. This view is expressed in Figure 1, which shows the arrow of discovery running from left to right. This argument became the basis for the logic underlying research planning at the National Science Foundation and the Pentagon. It has become known as the linear hypothesis and remains a strong force in promoting a "hands-off" approach to research funding. In extreme forms, this approach leaves enquiry totally unconstrained, save for the most general directions. In less extreme applications, the linear model implies

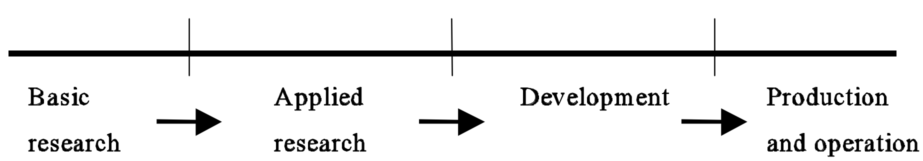

Figure 1. Linear Model of Scientific Research.

[22]V. Bush, *Science—The Endless Frontier: A Report to the President on a Program for Post-War Scientific Research*, Washington, D.C., National Science Foundation, reprinted, 1990.

review by peers, and in still others, steps in research processes

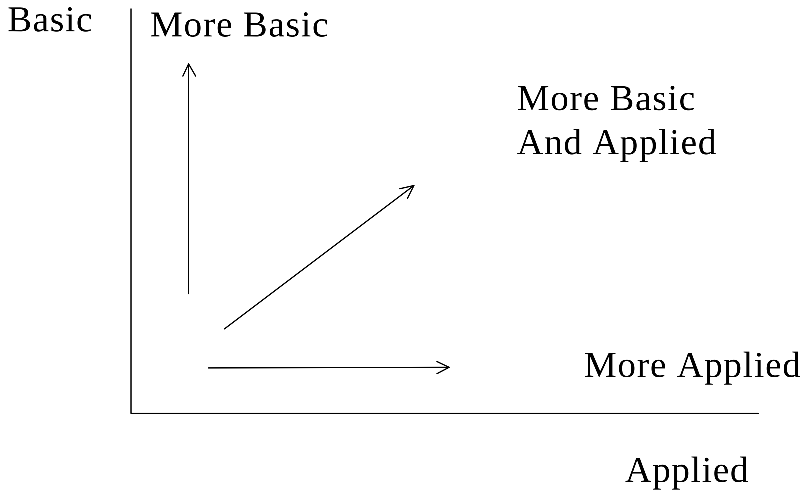

Figure 2. Two Dimensional Model of Scientific Research.

are separated by "gates" representing the achievement of threshold criteria. In all cases enquiry is intended to advance knowledge, rather than to feed application.

Over the decades since Bush delivered his report, it has become apparent that research guided by the linear hypothesis is not the sole source of contributions to basic knowledge. The evidence indicates that a large set of fundamental discoveries have been inspired by highly practical needs. This is not to say that curiosity-driven research has not led to fundamental knowledge, but rather, that use-driven basic research has also led to fundamental discoveries. Perhaps of greater relevance, when there is a clearly definable, applied target guiding basic research, it may be the case that required fundamental discoveries can obtained more directly. This approach is expressed by Donald Stokes who suggests that a more informative way of viewing research projects is by juxtaposing them on a graph, the axes of which denote greater or lesser degrees of "basic-ness" and "applied-ness," as is shown on Figure 2.[23] Whereas in Figure 1, basic research is defined as knowledge-driven, and applied research is defined as use-driven, Figure 2 suggests that any given project can have both basic attributes, i.e., be focused on the accumulation of fundamental knowledge, and yet have considerations of use associated with its design. Figure 3 depicts these relationships in simplified form, by dividing the continuum shown on Figure 2 into dichotomous basic-applied dimensions, with each further subdivided into whether or not the target of enquiry is fundamental understanding or use. In the upper left quadrant, Stokes places basic research driven by curiosity; in the upper right, basic research driven by needs; in the lower right, applied research driven by needs, and in the lower left applied research driven by curiosity. The book takes its title, *Pasteur's*

[23]D. E. Stokes, *Pasteur's Quadrant*, Washington, D.C., The Brookings Institution, 1997.

Research is inspired by:

		Considerations of use? No	Considerations of use? Yes
Quest for Fundamental Understanding?	Yes	Pure basic research	Use-inspired basic research
	No	Pure applied research	Use-inspired applied research

Figure 3. Quadrant Model of Scientific Research.

Quadrant from Stokes' conclusion that Pasteur's use-inspired studies into fermentation and other topics laid the fundamental foundations for the field of microbiology. He likewise notes numerous other instances where use-driven feedback leads to very fundamental findings, not the least of which were the basic outputs associated with the Manhattan Project. The conclusion is that the arrows of Figure 1 go both ways. This process of identifying basic research through use-related feedback effects is sometimes called the non-linear model.[24]

The non-linear model squares with our investment-based approach to R&D planning and evaluation, because in our approach no credit is given to cleanup technologies that are not deployed. Using the purely science-driven approach it would be mere happenstance that a technology would be deployed. Using a casual use-driven approach whereby scientists speculated informally on which ideas might ultimately be deployed begs the question, would not using a more formal, integrated approach driven by cleanup values maximize the value of R&D? We conclude that managing discovery uncertainty for the DOE cleanup R&D means focusing on the two right-hand quadrants of Figure 3.

[24]It should be noted that the bottom left quadrant of Figure 3 also has meaning for the DOE cleanup. This quadrant contains information of an applied nature, collected for curiosity's sake, rather than for purpose. The systematic collection of facts without regard for specific use, as is done in encyclopedias and other reference materials, can make an important contribution to knowledge. But it can also prove more costly than directed research when a specific use can be called upon to guide data collection. The costs accompanying the extensive collection of data characterizing DOE sites subject to cleanup, the nature of the wastes thereon, and many other physical attributes of surrounding territories, illustrates the need to discipline the collection and use of data for program planning.

In sum, our approach seeks to direct a significant amount of management energy to choosing the right topics. Following our earlier arguments, innovations should be tied to project values. Then, looking "upstream" from the innovation toward the string of R&D activities on which it rests, scientific proposals should be subject to "applied" review for relevance, "peer" review for quality control, and "basic" review to ensure applied activities take full advantage of fundamental knowledge. We refer to this as a "360 degree" review process.[25]

[25]This recommendation is sharply different from that contained in the NRC report *Building an Effective Management Science Program*. That report recommended consulting with the ultimate users of research but specifically excluded them from the review process. Such a perspective views science as foundational rather than enabling. Clearly, it is easy to overstate the ease with which enabling basic research can be identified, but this report responds to the intent of Congress that the EMSP be targeted at cleanup and reducing its costs, an outcome that requires the active participation of technology users in the review process and clear measures of cleanup value.

V. DEPLOYMENT UNCERTAINTY

DOE does not have sole discretion over the specific manner in which it carries out its cleanup. It cannot unilaterally determine which technologies will be used for legacy waste cleanup and which will not. It shares this responsibility with its partners —Congress, regulators, and local and other stakeholders. Deployment uncertainty arises over the fact that any of these parties can potentially veto the use of a specific technology in a specific application, or can at least increase the effective cost of using any given technology sufficiently to make an alternative more attractive. To increase the probabilities of a technology being acceptable to the various parties, DOE must manage its relationships with each party appropriately.[26] Whereas an extended discussion of how best to interact with each party over acceptability is beyond the scope of this paper, having a well structured means for planning and evaluating the DOE R&D program would clearly provide a framework for this interaction. We examine issues with Congress, regulators, and stakeholders, in turn.

First, DOE receives an annual budget but faces a cleanup estimated to last seventy-five years. This time period was developed by arraying cleanup tasks, comparing them with available technologies and likely budgets, and negotiating activities and schedules with regulators and stakeholders, a process that effectively defines compliance with relevant laws and regulations. Over time, it has become apparent that the commitment to cleanup extends much beyond this, because some long-lived contaminants will require at least some very long-term attention. In an effort to make planning more tractable, DOE has proposed a planning horizon of ten years, but Congress has never approved the elements of this process. How long and how intense the final cleanup will actually be is closely related to DOE's ability to justify its annual budget and relate the items in it to cleanup progress. To obtain steady funding for its R&D program, DOE must convince Congress that the cleanup is being conducted cost effectively, according to plan, employing "acceptable" technologies, and developing new technologies in an integrated manner. Thus, one source of deployment uncertainty lies in DOE's need to obtain annual budgetary and planning approval from Congress.

Second, DOE's cleanup is largely derivative of obligations defined by the nation's environmental, health and safety laws and regulations. These are administered by EPA and other Federal agencies, as well as by DOE orders and special legislation

[26]DOE has often viewed technical acceptability as synonymous with technical sophistication on the part of those evaluating the technology. Following this conclusion, it has viewed the creation of technical acceptance as an exercise in education. That is, if Congress, regulators, or stakeholders find a technology unacceptable, it is because they do not understand it. Thus, educating them will lead to acceptance. We reject this view and argue that technical acceptance is a much more complicated issue. See A. K. Wolfe, D. J. Bjornstad, and M. Russell, *Public Acceptability of Controversial Technologies (PACT): An Application to Genetically Engineered Microorganisms (GEMs)*, JIEE 2000-05, April 2000.

governing DOE. Some responsibilities may be delegated by EPA to states. As noted elsewhere, the nature of the DOE cleanup places it outside the bounds of the common application of most regulations.[27] Whereas the law and implementing regulations call for a thorough and speedy cleanup, DOE has scheduled a long-term cleanup for which many required technologies are not now available.   Consequently, DOE is virtually always "out of compliance" and has negotiated a series of consent decrees that guide much of the timing and character of the cleanup. To a large degree, these agreements define the cleanup program in a rigid manner, increase the costs of inserting new technologies into the process, and generally provide incentives for cleanup managers to avoid renegotiation that might lead to missed deadlines and fines or other penalties. This leads to a circumstance in which new technologies may be ignored for the sake of expediency. Thus, the regulatory process contributes a second source of deployment uncertainty.[28]

Third, DOE has delegated a significant degree of decision authority over technology deployment to local stakeholders. These individuals and groups both live in the communities subject to E,S&H hazards and also benefit from cleanup spending. We have argued elsewhere that stakeholders are subject to conflicts among their incentives.[29] On the one hand, they have personal interests in seeing risks and other costs arising from contaminants reduced to the lowest possible level. On the other hand, cleanup dollars have tended to replace dollars from other programs that have been curtailed or scaled back as a result of the reduced threat of nuclear war. Negotiating cleanup technologies is at once negotiating risk reduction and negotiating continued spending. Given this complicated arena, stakeholders may have multiple incentives to consider when judging the acceptability of different technologies, a circumstance that directly affects deployment probabilities.[30]

In sum, whether or not DOE ever attempts to implement a formal system for deployment uncertainty planning, the issues embedded within the concept are real and

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[27]C. L. Dümmer, D. J. Bjornstad and D. W. Jones, *The Regulatory Environment Guiding DOE's Cleanup: Opportunities for Flexibility*, JIEE 98-04, September 1998.

[28]For instance, states have a fair amount of discretion in determining how and if technologies are used. A state may license a given technology, but restrict its use, as Tennessee has done in restricting out of state shipments to a DOE incinerator located in Oak Ridge. Failing to use a technology efficiently is somewhat less costly than failure to deploy it at all, but is still a clear loss in rate of return to the R&D program.

[29]M. Russell (1998). Toward a productive divorce: separating DOE cleanups from transition assistance. *Annual Review of Energy and Environment, 23*: 439-463.

[30]One difficulty with the stakeholder process is that it has developed its own inertia and leads the public debate over DOE's funding of cleanup to be separated from other budgetary considerations. Hence, while net local funding might even be rising, if cleanup funding is threatened, the natural tendency of the stakeholder process leads to public outcry. This militates against separating cleanup funding from other transition funding. See ibid.

require attention. As noted above, uncertainty impacts costs, and thereby reduces the net benefits of the R&D process. Congress, regulators, and stakeholders can all influence whether or not a technically feasible cleanup innovation meets the test of practical deployability, and it would be disingenuous to suggest that R&D planning should take place without considering their roles. A planning system for R&D should include ways to track issues in deployment uncertainty. In this way R&D could target technologies that would have a high probability of acceptability and could factor concerns by regulators and stakeholders into new technologies early on.

VI. INCENTIVE PROPERTIES RELATED TO R&D PLANNING AND EVALUATION

It was stated above that even though private firms could not always calculate rates of return specific to their R&D activities, they could always observe a bottom line profit or loss figure. The potential for increased profits provides incentives for firms to modify their behavior to increase revenues and/or reduce costs. Private sector managers also attempt to use incentives to motivate their staff to do their best. Thus, an outside salesman who is on commission has a greater incentive to make sales than one who is on a fixed salary, because the salesman's rate of compensation is higher the greater the number of sales. Firms use any number of such devices to tie compensation to performance. Profit sharing plans, bonuses, and stock options are all examples of ways that firms attempt to motivate employees to increase their performance. In general, any feature, intentional or accidental, of a management system that causes a firm or the managers and workers within a firm to modify their behavior in pursuit of their own betterment is an incentive.

Not all incentives lead to desirable ends. Workers respond as quickly to unintended incentives as they do to carefully designed incentives. A salesman whose commission is keyed to some surrogate measure other than sales, like number of presentations made, or number of miles traveled will respond as directly to these measures as to the measures most relevant to the firm. Thus, surrogate measures must be carefully chosen to avoid distorting behavior into unproductive paths.

More troublesome are cases in which incentives provide workers with conflicts of interest. A salesman may, for example, be empowered to offer price reductions if necessary to close a sale. If commissions are based on numbers or sales or gross sales, the salesman will have an incentive to drop prices quickly, to permit a quick close, even though this practice may erode profits. Likewise, firms sometimes believe that their sales staff are most closely linked to their customer base and are the best source of counsel as to the level of next year's sales. Sales forecasts, in turn, become the basis for production planning, materials negotiations, and the like. The problem is that salesmen's compensation is often based on their exceeding a quota. Salesman who predict high sales run the risk of having their quotas increased and have an incentive to understate future sales. Firms that base plans on understated sales face production shortfalls and higher costs. More generally, conflicts of interest arise when a higher level manager (the principal) cannot fully monitor a subordinate (the agent). In these cases, the higher level manager must design the system of incentives to compensate for the fact that the agent has a greater amount of information concerning his or her activities than does the principal. For example, tying the salesman's commission to profits on the sale rather than gross sales provides an incentive against price cutting. Unbundling the setting of quotas from sales forecasts accomplishes the same result.

It is important to note that within the private sector, the role of incentives is two-fold. First, the firm observes that net revenue (profit) increases result from some combination of lower costs and additional sales and makes choices that position it to increase sales and reduce costs. These choices govern its relationships with buyers and sellers outside the firm itself. Second, the firm develops internal incentives that lead its employees to adopt behaviors that increase sales and/or lower costs. Observing profits is a relatively simple task. Thus, the challenge to the firm is to develop incentives that lead to greater profits.

The Department of Energy faces similar issues in setting incentives as does the private sector, but has the more difficult task. DOE has no measure of profits. DOE must thus independently set its own goals and position itself relative to outsiders that affect its ability to meet these goals. Outsiders include Congress, regulators, stakeholders and contractors. Next, based on its goals it must also set internal incentives to achieve them. To an extent, it is the existence of profits that permit firms to extend incentives to its employees through bonuses, profit sharing, stock options and the like. DOE, having no automatic source of dollar incentives, must align other aspects of its salary plan, compensation package and program attributes to accomplish this. To the extent that the measures of net revenues are absent, DOE must create surrogate measures or metrics to measure progress toward goals. In doing so, it runs the risk of creating unintended incentives.

One major opportunity to employ incentives lies in achieving program integration between the field and headquarters operations. At present, the field may have limited incentives to deploy new technologies. It operates under a series of legally binding consent agreements that have been painstakingly negotiated. Switching technologies can mean renegotiation and can disrupt carefully planned schedules. Often technologies are unproven so the field manager runs the risk of unpleasant surprises. The field, moreover, often receives little or no return from modest cost reductions or end-state improvements, and there is, in any event, no measure of value to differentiate among sites. To overcome this lack of incentives to deploy new technologies to high valued targets, DOE must link local cleanup budgets to local success in some positive way. For example, program savings must be returned to sites or even supplemented with incremental funds. This both rewards site program managers and interested local parties, such as regulators and stakeholders who find that increasing productivity rewards rather than penalizes them.

At headquarters, the situation may be reversed. R&D managers typically have long term agendas that emphasize the discovery of new knowledge over its application. Modifying R&D plans to respond to site level concerns is both disruptive and costly, especially insofar as each site has specific technical needs and specific stakeholder requirements. A central R&D program would thus prefer to develop technologies to some generic level and then turn them over to prospective users for fine tuning. Local managers, however, typically do not have budgets for this purpose and would prefer to stick with their existing plans in any event. Unless there is a means for tying the knot between local needs and R&D outputs, the outputs of the centrally directed R&D activity may be both mis-targeted and go unused. Tying the knot simply requires that R&D be directed at high value targets, with consideration given to the portfolio and deployment needs discussed above. Taken in sum, local cleanup managers are rewarded for applying the best available technologies, R&D managers are rewarded for developing the right, i.e., the high value, technologies, and DOE achieves its overall goal by both developing and deploying high value technologies. Again, in both cases, individuals' performance incentives must be tied to these same goals.

A separate case of inadequate incentives concerns the management of research itself, most of which is funded by headquarters, carried out by the field, and has been traditionally knowledge-driven, basic research. Traditional criteria for success center around scientific success, reinforced by peer approval. Hence, technical success ensures continued funding. This paper examines a number of R&D management changes that depart from this norm. We call for cleanup R&D to be application-driven, for researchers to undertake the burden of additional reviews, and for the results of these reviews to be used to determine future levels of funding, including the possibility of cutting off funding. All of these circumstances dilute the relationship between the researcher and his or her peers, introduce elements of uncertainty into the funding process that are beyond the control of the researcher, and generally refocus the R&D process on R&D success coupled with field application. This weakens the researcher's incentives to move quickly toward that point at which the research can be evaluated and possibly discontinued. It may also weaken researchers' incentives to participate in the 360 degree review process. To correct this, DOE needs to ensure that research programs and individual researchers are not penalized for moving ahead quickly and being discontinued. Doing this means decoupling total program funding and individual researcher rewards from being discontinued due to portfolio criteria.

To close, we should anticipate the criticism that notes that ineffective or improper incentives do not necessarily imply that the actors in the system will ignore policies and protocols and engage in behavior detrimental to the overall cleanup effort. Many team players will accept the goals of the larger organization, even when they conflict with their own goals and conflict with the reward system. However, one need not count on altruism to ensure success. There is no arguing with the fact that creating incentives which provide all actors in the system with a consistent message and with reason to excel would be the more desirable strategy.

In sum, DOE must develop consistent incentives among internal organizations and their staffs by creating goals against which to measure success, providing consistent information measuring progress toward these goals, and linking reward structures to the progress each individual organization makes toward these goals. Because DOE does not earn profits it must identify other measures of success than the private sector and must find other ways to reward success. Examples of rewards include program stability and growth, increased responsibilities, and staff compensation packages. Disincentives include reductions in program size and growth for meeting goals, and separating decisions concerning responsibilities and compensation from meeting goals.

VII. MEASURING THE VALUE OF INFORMATION PRODUCED BY R&D

Thus far we have been critical of the lack of integration throughout the cleanup effort, the lack of clear-cut measures of task worth, and the lack of incentives to deploy new technologies. The reasons for these criticisms are clear. Without integration, the R&D manager must set and defend an agenda more or less independently of headquarters managers who set general DOE policy and of field cleanup managers who sequence projects and make specific technology choices. For their part, cleanup managers have a site-specific perspective and are predisposed to ignore the products from the R&D shop. Certainly, the cleanup manager does not welcome new developments that might require renegotiating the sequencing strategy. There is, moreover, no gradation in project priority. About half are of highest and presumably equal priority.[31] The schedule is unfolding over the next seventy-five years, with little sense of urgency. It would be difficult to imagine Intel, with ten percent of its gross revenues devoted to R&D, finding itself in a similar situation.

We take the time to discuss these results to emphasize three points. First, as we turn to implementation issues in the next section, we believe that it is fully possible to implement the approach we describe using extant data. This is not to say that the program should not seek better data, but neither should it postpone further analysis. Second, we wish to demonstrate the power of incentives and the importance of proper incentives. In this example the model responds optimally, in response to whatever goal is set. Third, these responses mean that integration is required. We demonstrate that under different goals, very different site responses occur to the same, very general, cost-reducing stimulus. Under more specific technical changes, we would expect even more diverse responses. This emphasizes the need to key the R&D program to both site needs and to overall goals to achieve integration.

To illustrate the best of all possible worlds, we employ a mathematical programming model, described further in the Appendix, to choose project sequences in response to specific technical changes that reduce costs, given budget and technical constraints. The model seeks to allocate a fixed budget to a series of cleanup tasks, over a ten year period, with tasks divided into phases and by waste types in a way that maximizes the goal built into the model. The point of this analysis is to show how the simplest type of R&D result would be implemented in a fully integrated system that responds to incentives. Data to make the system operational were taken from the

[31] In its November 1998 Environmental Management Research and Development Program Plan, DOE reports that the sites have identified that 46 percent of their activities are of highest priority, including those on the critical path to site closure and those that represent major technology gaps in project completion.

"Paths to Closure" data base for the Oak Ridge National Laboratory,[32] and the types of cleanup tasks contained in the model reflect those on the ORNL reservation.

The nature of a model of this sort is that "everything matters." The model thus responds to all changes in input variables. If budgets increase, the model expands the cleanup in an efficient way. At the margin the next most beneficial activity is undertaken. Likewise for budget decreases: the least valuable project, that is, the project that makes the smallest contribution to the goal, is dropped. Models demand logical completeness. For the model presented here, this takes the form of a number of constraints that relate individual tasks to the goal, be they cost relationships, risk relationships or others. Sometimes changes in these relationships lead to surprising or non-intuitive results, which upon reflection become quite sensible. But whatever else, the model is integrated and everything matters.

Our analysis divides cleanup into three processes—storage, treatment, and disposal—and assumes that the task of project sequencing consists of moving each of three types of waste (low-level, mixed low-level, and transuranics) from storage to treatment to disposal, given constraints, and according to the site goal over a ten year planning horizon. We consider three hypothetical sites which are identical, in wastes, technologies and budgets, except for the goal that each pursues. It is assumed that the waste is "in compliance," in the sense that the site can leave all wastes in storage if that best meets its goals. The goal of Site 1 is to minimize the pool of risk at the end of a ten-year planning period that includes risks due to wastes in storage and in disposal. We call this pool terminal risks. In general, treatment reduces terminal risks, but increases total costs. The goal of Site 2 is to minimize the total risks over the ten-year period, that is, storage and disposal risks in each period, plus the risks due to treatment in each period. Treatment risks are typically higher than either storage or disposal risks. The goal of Site 3 is to reduce life-cycle costs of the operation, including the present value of storing risks perpetually at the end of the period. Constraints include a total budget of $200 million per annum. For Site 2, an additional set of constraints is added. Because treatment risks always increase total risks above the amount of risk reduction gained from treatment, a "site treatment plan" is used to constrain the site to a certain minimum level of treatment. Site 3 focuses on cost savings. It only treats wastes when the sum of treatment costs plus the present value of disposal costs is less than the present value of storage costs.

Before proceeding, a few comments are in order. First, risk data for this analysis are drawn from the "Risk Data Sheets" used in site planning. They tend to reflect levels of contamination to a greater extent than the "value of harm" concept that underlies classical risk analysis. Second, the goal of Site 2 is in many ways the

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[32] In creating this model, we have made numerous simplifying assumptions and have not attempted to fully meet the legal requirements under which ORNL operates. Thus, our results should not be interpreted as "second-guessing" the ORNL cleanup.

most typical goal across the Complex. Without the agreement of regulators and stakeholders, and the force of compliance agreements, site managers seem to be reluctant to undertake any action that increases risk temporarily, even if it means delaying the overall cleanup. This is consistent with our earlier discussion of incentives, insofar as managers stand to suffer more harm from the occurrence of "bad" events, like accidents, releases, or deaths, than they stand to earn rewards from making progress toward some ten-year goal (let alone a seventy-five year goal). Third, the goal of minimizing life-cycle costs is arguably unavailable under current regulatory practices. We discuss the potential to overcome it at length elsewhere, but note that our storage costs include the outlays necessary to maintain RCRA (storage) risk goals, but not RCRA treatment schedules.[33] Finally, the model used to analyze the data exhibits "non-linearities" in the sense that increasing one activity without increasing others leads to decreasing returns to scale. Thus, unit costs of storage, treatment, and disposal, all increase with volume.

We assume that R&D is successful in achieving an across-the-board decrease in either storage, treatment, or disposal of ten percent. In other words, the reduction occurs for only one of these activities at a time, but for all waste types and time periods. We further assume that the metric of cleanup success applied by headquarters is terminal risk reduction, and the impacts of cost decreases are measured against terminal risk reduction. For simplicity, we apply the cost reduction to each of the waste types. Table 1 reports the results of carrying out this analysis. In reporting the data, we assume that headquarters (like Site 1) adopts a goal of reducing terminal risks, and present the impact on terminal risk given cost reducing technical change coupled with the pursuit of site-specific goals.

For Site 1, which seeks to minimize terminal risks, the ten percent reduction in costs leads in each case to greater progress toward the goal. Table 1 should be read as follows: Reducing storage costs at Site 1 by ten percent leads to a reduction in terminal risk at the end of the period by 2.6 percent, or, on average, by .26 percent per one percent of storage cost reduction. The ten percent reduction for treatment costs has twice as large an impact on terminal risks and a reduction in disposal costs has a smaller impact. Note that for Site 1, the goal of the field and the headquarters is the same. Once cost reductions are available they are factored immediately and fully into sequencing schedules in the manner that achieves the greatest reduction in terminal risk.

[33] C. L. Dümmer, D. J. Bjornstad and D. W. Jones, *The Regulatory Environment Guiding DOE's Cleanup: Opportunities for Flexibility*, JIEE 98-04, September 1998.

Table 1. Impact of a Ten Percent Cost Reduction on Terminal Risk Minimization, by Cleanup Activity and Site Goal (data presented as terminal risk elasticity*)

	Site 1- Goal: minimize terminal risk	Site 2 - Goal: minimize total risk	Site 3 - Goal: minimize cost
storage cost	-.26	+.46	0
treatment cost	-.52	+.82	+.06
disposal cost	-.17	+.18	-.06

*Terminal risk is defined as the sum of risks in storage and in disposal. The elasticity reported is the percent change in terminal risk divided by the (ten) percent decrease in cost.

Very different results occur for Site 2, which seeks to minimize total risks and is constrained to meet minimum treatment schedules. For Site 2 a reduction in storage costs leads to an *increase* in terminal risks. Additionally decreases in treatment and disposal costs lead to increases in terminal risks. In essence, the storage cost reduction leads the site to store greater amounts of wastes. Reductions in costs of managing stored wastes and disposed wastes lead managers to resequence in ways that meet site goals, but that are contrary to the headquarters goal. Changes in costs have virtually no impacts on the risk reduction behavior of Site 3, which is concerned with cost minimization rather than terminal risk reduction. It does, of course, help to meet the cost-reduction goal of the site.

Naturally, the results of a model exercise should not be accepted uncritically, but the findings are nonetheless clear and striking. First, for R&D to have a positive impact, it must be closely linked to programmatic goals. In this case, we assume that the goal of R&D was a more rapid reduction of terminal risks through cost reduction, but only one of the three sites sequenced projects following this same goal.[34] Second, for innovations to be deployed, there must be a mechanism to ensure that sites have incentives for deployment. In this case, sites were fully incentivized to integrate new technology into sequencing plans, but pursued their own goals rather than a common goal. As a result, the impact of R&D on those sites was very different. Thus, for R&D to have a uniform impact, supportive of central goals, the sites must share the goal underlying headquarters action. In this exercise, only Site 1 shared that goal. More generally, one should not assume that simply undertaking successful R&D will lead to an improved cleanup.

[34]We note that terminal risks in this context are planning risks, because cleanup will not be completed within the ten year planning horizon we postulate. Their minimization is, nevertheless, a reasonable goal.

VIII. IMPLICATIONS FOR R&D MANAGEMENT

1. Overview

Our goal in this paper has been to develop a stand-alone approach to cleanup R&D management that is also integrated with other phases of cleanup management. We describe a system that draws upon information and decisions made in other aspects of cleanup planning and, in turn, feeds information and decisions back into them. To this point, our focus has been on the broadest designs of research management—the investment analogy, establishing cleanup value, issues in technology acceptability, the logic of R&D planning, and relevant incentives. We now summarize the conclusions we have reached and describe a process for implementing them.

The driving assumption behind our approach is that viewing cleanup R&D from an investment template provides the best way to organize the various benefits and costs that will ultimately determine if the R&D program is a success or failure. The investment model calls for examining the benefits and costs of innovations, by year, and discounting them to a present value. In its simplest form, this basic approach identifies the variables needed to evaluate past program activities. For planning purposes, uncertainties associated with developing successful technologies and deploying successful technologies must be added. Planning should view R&D as creating options that will be used if the payoff is sufficient. Uncertainty requires creating more options than will ultimately be used. Recognizing this, the review process must take care to initiate the proper range of activities and to terminate activities that do not show promise within the specific context of DOE cleanup. To apply this approach, one must assemble information on benefits, costs, discovery uncertainty, and deployment uncertainty.

We consider separately the fact that information is necessary, but not sufficient, to conduct the R&D program successfully. Success requires that the various agents in the system be motivated to implement the steps the system indicates. One part of motivation is having the proper set of administrative relationships and other management tools to disseminate information and otherwise tell the agents what is expected of them. We do not address this topic. We do, however, consider the fundamental incentives that motivate behavior within the system. One set of incentives deals with the need to focus R&D on targets of value to the program. Another set of incentives deals with the need to deploy technologies that are developed. Finally, we consider the incentives that the scientific and technical researchers experience under the changes we propose.

Within a fully integrated cleanup program, R&D managers have access to information on task value and have incentives to produce new technologies that are responsive to value. Cleanup managers have complete information on the new technologies and have incentives to deploy the new technologies. Under such a system, optimal deployment of technologies occurs. Abstracting from real world frictions, we demonstrate how such a system would support program goals, using a computerized model that ensures immediate responsiveness in matching new technologies to cleanup needs. From this we demonstrate the need for complex integration. Unless the sites and the central offices share goals, the impacts of even successful R&D are severely diluted.

The context in which these relationships take place is summarized in Figure 4. First, we divide DOE cleanup responsibility between what we have characterized as cleanup planners and cleanup managers. In general, planners are headquarters staff and managers are field staff, but this need not always hold true. This is not to suggest in any way that these two groups have separate missions, are rivals, or disregard guidance passed between them. But they have been assigned different cleanup roles, are subject to different pressures, have access to different information, and respond to different incentives. Second, we assume that cleanup planners have the responsibility for developing and managing the cleanup R&D agenda and for establishing the value of cleanup for different sites in a comparable manner. They do this by imposing a "national" perspective on the process. Cleanup managers, in turn, have been assigned the responsibility of setting the cleanup sequence and deciding which technologies to use for each cleanup task.

The two groups are influenced by different constituencies. Planners interact with Congress and the non-local stakeholder community. As we have discussed, Congress serves as a banker for R&D by providing funding and oversight as to whether or not the overall portfolio provides an "adequate rate of return." To do this it examines virtually every detail of R&D planning. Non-local stakeholders serve as a surrogate for national willingness-to-pay for DOE cleanup. Together these two groups may be viewed as setting and monitoring all aspects of cleanup spending, though we focus only on R&D at present. The managers interact with regulators and with local stakeholders. Regulators interpret the legal requirements of cleanup and monitor the manner in which the managers are discharging their cleanup responsibilities as recorded in consent degrees. Local stakeholders play both formal and informal roles. Formally, they interact through site specific advisory boards and other legally chartered bodies. Informally, they represent local interests through a variety of avenues, including interactions with regulators.

The relationships depicted in Figure 4 are as follows. Responding to Congress and non-local stakeholders, planners determine a central view of cleanup priorities, denoted here as values. Using these values, input from the scientific community, and input from field users, planners set an R&D agenda. We will discuss the exact nature of this information in detail below. In general, planners should seek a 360 degree review from the scientific community and information on local technical

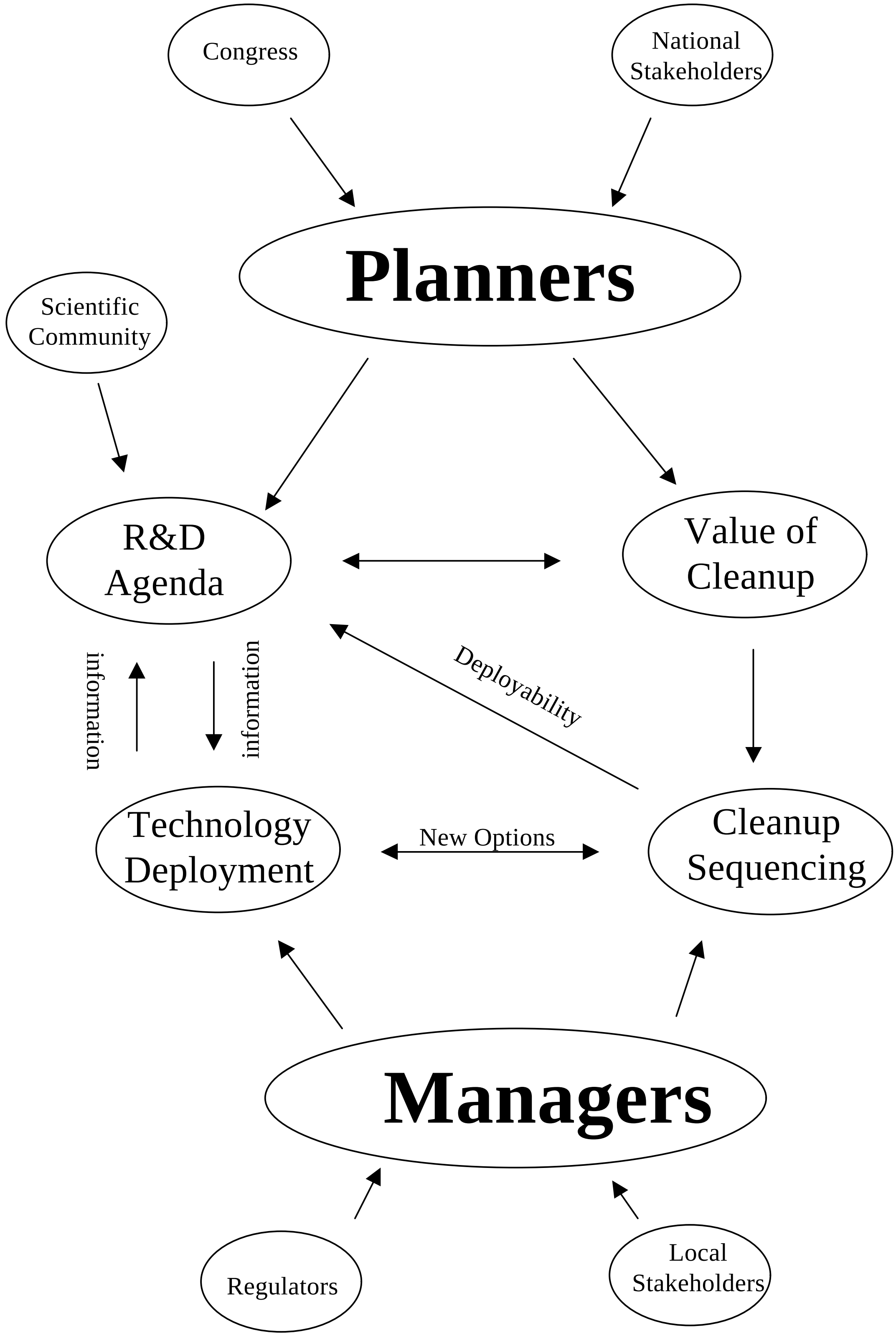

Figure 4. Fundamental Relationships in R&D Planning and Evaluation

considerations and deployability from the field. The managers match technologies with cleanup tasks and determine a cleanup sequence. Typically this process will involve regulator approval and stakeholder concurrence. As noted, the result of what is essentially a negotiation is given the force of law as the site treatment and cleanup schedules are embedded in a variety of binding legal agreements.

The process is dynamic, and any number of specific events can serve to trigger changes, including budget changes, new information, new technologies, changes in regulations, court cases, and overall DOE policy changes. Two types of changes in particular were singled out above. The planners must manage the R&D agenda so as to take full advantage of the information they receive from various input sources, especially the cleanup managers and the scientific community. The managers must integrate new technologies into cleanup schedules. Figure 4 highlights these information flows and decision points.

2. Setting Cleanup Values

We stated above that in making investment concepts operational, it was likely that less than perfect information would be used, and further, that this should not be a barrier to attempting the sort of analysis we propose. In no case is this more true than for value. To the extent that no value measures exist, surrogate measures must be created, a process sometimes referred to as developing "metrics." Though metrics may be imperfect, they often take on a life of their own, in the sense that they become benchmarks against which performance is measured and rewarded or punished. Thus, to create metrics is to create incentives. A carefully developed system of metrics can highlight desirable (and undesirable) technical attributes and through a system of rewards (or punishments) provide incentives to produce certain types of outcomes.

For *cleanup task valuation* it is useful to consider a hierarchy of information by overall utility to prioritization.

Dollar value of cleanup task

Dollar values for individual cleanup tasks would provide a clear estimate of the amount of resources society would be willing to spend to complete some specific task to some specific end-state. They would contain similar information as the prices that a household was willing to pay to obtain, for example, housing services. A variety of elements might be included in cleanup value, for example, the value of the land reclaimed, or the stewardship costs avoided through cleanup, or simply the willingness of the general public to spend dollars to restore contaminated lands to their original condition. If the costs for a cleanup task far exceeded the value of the task, it would call into question the wisdom of carrying out the task. Implicitly this happens frequently in cleanup, but rather than stating that the benefits from a task fall short of costs, the circumstance is commonly described as "having no adequate affordable technology available." Thus, an implicit set of values is inherent in the cleanup program, but it fails to support the type of analysis we propose.

The difficulty in assigning values to issues like cleanup is that the market provides little guidance, because no market transactions occur. For example, a family can look in the newspaper to find asking prices of apartments or houses and can consult with friends or relatives to gather information on what they spend for similar accommodations. In contrast, no such guidance for environmental amenities or cleanup activities is available. Economists have developed tools to provide estimates of willingness to pay that depend on survey techniques that query respondents about spending preferences. Although these techniques are at an early stage of development, are sensitive to individual incomes and proximity to the topic of the survey, and can evoke emotional responses, they have been accepted as a useful first step in litigation and other types of environmental decision making. At present DOE has not prepared estimates of dollar cleanup values, though it may wish to lay the groundwork to do so.

Risk management/reduction

The concept of risk is very similar to that of value because, in their most general form, risks are viewed as the *expected value* of damages caused by some sort of environmental hazard. Setting risks as a primary cleanup metric would make it possible for DOE to draw upon an extensive and well-developed set of methodologies known as risk planning that includes risk analysis, risk management and risk communication components. EPA in particular has based a good deal of its formal decision making and budgeting on these concepts and has found a receptive ear on Capitol Hill.[35]

In general, risks are said to arise from a combination of a hazard, pathway, and receptor. Hazards are toxic, radioactive, hazardous or other materials that can cause harm. A pathway is a means for the hazard to travel from its place of rest to the receptor. Pathways include ground water, soil, and air. Receptors include humans, animals, and plants, and the physical environment. Even though there is no "big book of values" through which risk analysts can attach dollars to risks, the set of tools provides a useful approach to measuring cleanup progress, as we have argued at length elsewhere. The fact that the environmental rules and regulations driving cleanup are implicitly or explicitly based on risk analysis also argues for DOE to adopt these measures in its planning process.

In fact, DOE has developed risk data bases and uses them as an element in its planning process. While these data bases fall short of the "risk ideal," are more

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[35]Note our work, mentioned above, that describes how to do this.

focused on hazards than on expected damages, and vary in quality from site to site, they provide an excellent point of departure for setting cleanup values in more objective ways, but they fall short of the controversy of assigning dollars to tasks by end-state.[36]

Cost reduction potential

DOE has developed what is essentially a baseline technology set for each cleanup task in the Complex and has cost estimates for dealing with most cleanup tasks. A measure of the value of a new innovation is the cost advantage it offers over an existing technology. Note that this departs from benefit analysis because it does not address the issue of task value. On the other hand, DOE does have a well developed plan in *Paths to Closure*. If one accepts this baseline as fixed, cost savings provide a valuable metric for calculating rate of return to R&D.[37] Of course, when no technology exists, no baseline cost exists. Using this metric could therefore provide a disincentive to develop technologies that deal with currently intractable problems. This should not prove insurmountable, because cost baselines could always be assigned, regardless of existing technologies.

Meets an unmet need

The remainder of the metrics discussed are binary in the sense that they can be answered yes or no. As such, they provide much less information than values, risks or costs. Nevertheless, some cleanup tasks do not have available cleanup technologies. One measure of value is to meet a previously unmet need. One could also record in this category new cleanup options, such as technologies that permit more desirable end-states to be reached.

Meets a need

A minimal test of a cleanup technology is that it meets a cleanup need without reference to existing technologies or other circumstances.

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[36]The Consortium for Risk Evaluation with Stakeholder Participation has recently conducted a review of the use of risk in the DOE's cleanup prioritization process which describes DOE's use of risk and recommends ways to strengthen the role played by risk in cleanup management. See Consortium for Risk Evaluation With Stakeholder Participation, Peer Review of the U.S. Department of Energy's Use of Risk in its Prioritization Process, New Brunswick, New Jersey, December 15, 1999.

[37]Were value data available, new technologies might cause net benefits to shift thereby implying that a different cleanup schedule might be more desirable.

3. Deployability

Deployability is the set of attributes that describes the circumstances under which a cleanup innovation would be acceptable to relevant decision makers. It does not necessarily mean that the technology would be chosen as a cleanup tool, but rather that the technology would be eligible for use. One way to characterize deployability is to enumerate the required conditions for acceptability and then cost them out as add-ons to the technology's base price, but doing this may oversimplify the rather complex deliberations that underlie technology acceptance by society.

On the one hand, there are circumstances under which virtually any technology might be used, just as terminally ill patients willingly participate in tests of experimental drugs. Thus, a community may accept a waste incinerator as a means of treating local wastes that would otherwise be stored in more hazardous forms, but reject the notion of collecting wastes from other sites for incineration. Under other circumstances, technology acceptance may depend more on "process" than on the technology itself. Certain controversial technologies may require special monitoring groups to assure locals that a technology is performing as promised. In other circumstances, community characteristics may come into play. Public attitudes toward nuclear materials differ between "atomic communities" and other communities. The presence of some minority or cultural groups may also affect technology acceptance. Native American groups, for example, are said to have unique cultural perspectives on bioremediation. Sometimes deployability hinges on the credibility of the group that will be responsible for operating the technology. In other circumstances secondary considerations, like impacts on local labor markets, may come into play.

Deployability conditions should be part of the information set used to organize the R&D agenda. DOE should not cavalierly dismiss local concerns as ignorance or lack of information, and neither should it presume that "educational programs" will overcome local resistence. By the same token, DOE should not assume that opinions will not change over time. Further, given sensitivity to potential concerns, changes to cleanup or treatment technologies or their implementation could be built into the R&D process to increase their acceptability. Some technologies may simply be unacceptable at certain times and in certain places while being acceptable in others.

Note also that deployability is a binary metric and is limited. The fact that a technology is, *ex ante*, deployable and, *ex post*, deployed, still begs the question of rate of return. Thus, simple quotas on deployment are undesirable and may create improper incentives. A recent GAO report cites a DOE Headquarters requirement that a site deploy one new innovation for each $100 million of budget.[38] This is a weak test of R&D program effectiveness.

4. 360 Degree Review

DOE has a great deal of experience in managing R&D activities, a large part of which concerns carrying out scientific merit reviews of proposed and ongoing activities. Merit review is a generic term that refers to a process in which panels of experts judge R&D projects and proposals according to predetermined criteria. The information content of the review is dependent upon the degree to which the expertise of the panel matches the criteria. We have noted above the desirability of having "upstream" researchers comment on the scientific foundations of the work, peers comment on the application of that science, and "downstream" users comment on the applicability of the R&D to their needs—our so-called 360 degree review.

The difference between the process we propose and the current practice lies largely in the use to which the data gathered from reviews are put. At present the review process is dominated by the "linear model," a practice leading to a review process in which the headquarters management team can be viewed as a facilitator for the scientific community. In this process, the headquarters team drafts a program statement, chooses review panels, and ensures the integrity of the process. The panels meet, evaluate the proposals based on scientific merit, and report their findings. Based on the scores and within the topical boundaries of the program statement, headquarters funds those proposals scoring highest in the process. Of course, within the whole of DOE, there are gradations of this process. For the basic sciences, like physics, the scientific community is the primary decision maker, whereas for more applied cleanup projects more attention is given to the end use than to peer review. But the process is still distinguished by a directionality from basic to applied knowledge and by a lack of connectedness among R&D activities. Naturally, we generalize. Many programs sponsor annual reviews at which principal investigators brief one another, and others have professional organizations that serve a similar process. There is overlap among headquarters people who bring different backgrounds and different experiences as they serve simultaneously on different topical panels. In the cleanup technology program, end users "certify" the applicability of technologies as they undergo development. In the Environmental Management Science Program, headquarters teams judge topical appropriateness. Nevertheless, there is no single point at which the R&D agenda for cleanup is brought together, evaluated and restructured on a periodic basis.

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[38]U.S. General Accounting Office. (1998). *Nuclear Waste: Further Actions Needed to Increase the Use of Innovative Technologies* (GAO/RCED-98-249). p. 39.

5. Assembling the Information

The steps in creating a single assemblage of R&D information are, in principle, similar to those now undertaken in generating technology roadmaps. They differ primarily in their focus on task value, technology acceptability and merit review. Undertaking them would also require a significant, but certainly not prohibitive, resource commitment.

The database that could potentially be assembled as a guide to task values is at once overwhelming and disappointing. DOE, through its Office of Environmental Management, has assembled a *Paths to Closure* data base, available on the DOE website and updated annually, which indicates project level activity by cleanup site, for example, by the Oak Ridge Reservation. These sites are in turn disaggregated into successively smaller units until the operating unit is reached. Specific information dictated by headquarters guidance is presented for each site: generally a task description, points of contact, and some level of scope and scheduled progress over time. Risk information is not reported. A related database entitled *Cleanup Criteria Decision Document Database* contains a variety of information on the criteria underlying legal decisions regarding cleanup. Some information on type of contaminant and risk profiles is included. DOE-EM also supports a series of site technology deployment plans, a lessons-learned database, and a program integration website.

Not surprisingly, none of this information is useful in its present form for the analysis we describe. It has been developed to support a series of management functions that exclude technology planning, or, indeed, a centrally organized, goal-oriented cleanup. Information from each site follows a common format, but content and coverage differ from site to site. Cleanup tasks tend to be defined geographically, and emphasize budgetary considerations over operational ones. Of course, at some level and in some place all of the needed information does exist and could be assembled.

There are many ways to do this. For the sake of example we describe one approach that might be undertaken, understanding that the institutional details would necessarily be keyed to the DOE culture. To do this, EM headquarters might undertake a special exercise in which a baseline database would be created for a limited number of cleanup activities across a minimum of the four large sites, Hanford, Oak Ridge, Idaho and Savannah River. This would be carried out as a test rather than a budgeting exercise. The first step might focus on several large-value activities and would require a single lead person or group to meet personally with staff from each site. Information would be gathered on initial conditions, targeted end-states, current technology plans, current cost estimates, and relevant temporal milestones. The principal goal would be to relate the activity needed to convert initial conditions to planned end-states with specific technology options and costs. A key aspect of this task would be to establish a value metric. This could be some comparative index, pseudo-dollar values, risk estimates, or some other representation of the importance of each task relative to others. As stated, this would be a top-down process relating activities across sites. Holding constant the site total value, it might be a useful exercise to reallocate value among tasks to express local preferences.

The second step could be to develop a "cross-walk" between the set of technical needs derived from the task database and the existing technology program. In other words, one would match existing activities with needs. One might plug in these technologies to the tasks to determine the result of successful completion. At the same time, "windows of opportunity" could be verified and other aspects of deployability considered. This would determine whether or not technology development schedules were consistent with technology deployment opportunities. It should identify which types of tasks would be amenable to different sorts of R&D timetables.

The third step could create a technology roadmap for each amenable technology, in essence, reversing the arrow on Figure 1. Each roadmap should be complete in the sense that all required developmental activities would be noted and compared temporally. Data should be organized to facilitate ease of comparison. It should be able to answer such simple questions as whether some more basic activities fed into several downstream technical needs or whether they were unique.

The fourth step could build this information into the 360 degree review process. For example, if technologies were critically time-dependent on other activities, review could focus attention on key assumptions. Any number of programmatic issues could be examined in this way.

Finally, the system could be "exercised" for scenario analysis. The model-based discussion of the previous Section demonstrates the kinds of considerations that could go into such analysis. Current activities could be subject to portfolio tests, redundancy tests, tests of timing, and expected rate of return. Emerging technologies such as bioremediation could be examined for relevance to high-value targets. Queries about changes or additions that might add value could be explored. These in turn could be compared in rough terms to the financial commitment required to conduct the research and more generally on the shares of the R&D budget allocated to different shares of value. Doing these things would develop a rough cut at the needed information set.

Companion to the information exercise would be an incentive exercise. The information exercise should indicate the feasible set of activities. The incentive exercise should indicate the dollar charges at the relevant points shown on Figure 4 and to whom they would accrue under current practices relative to what might be called "best" practices. For this to be useful the scenario analysis noted above should provide a range of realistic decision points and alternative decisions. For example, what would be the consequence of canceling an R&D project for portfolio reasons under current practice? Under best practice? What would be the consequence of substituting superior technology for an inferior one in the baseline under current and best practices? What would be the consequence of allowing sites to determine cleanup task values independently of other sites.

In the first case, the researchers might perceive that they were canceled for reasons beyond their control, and perhaps were identified as having failed. If research dollars were shifted to other sites as a consequence, future researchers might view cleanup research as less desirable, leading the best researchers (or at least those with viable alternatives) to leave thereby reducing the quality of the program. Researchers engaged in the 360 degree review process might balk at giving unfavorable reviews, other than on scientific merit. In general, the quality of the information supplied through review might decline. Best practices would seek to allocate research dollars to the best programmatic uses without creating negative incentives for the participants. One way to do this would be to hold researchers "harmless" when research was canceled for portfolio reasons by funding other activities within the same administrative unit.

In the second case, replacing a current technology with a superior technology could lead to a variety of outcomes. One could be to increase costs. Another might be to change the ability to meet compliance deadlines. Another might be to move projects to other contractors or to make use of different or differing amounts of labor. The cost issue points out the importance of understanding task value. Unless added costs were offset by added benefits so that net benefits increased, substituting a superior technology would be questionable. On the other hand, if the new technology saved dollars that were transferred to other sites, local decision makers would soon learn that saving dollars led to smaller budgets. Using a superior technology that led to a violation of compliance orders might expose sites or even individuals to civil or criminal penalties. In each case, best practices would attempt to make sure that sites or individuals were not penalized for making decisions beneficial to the overall cleanup. Such practices would also anticipate impacts of incentives on the deployability of technologies. As an example, a new technology, such as bioremediation, that replaced a large number of workers might be the subject of attacks unrelated to its technical attributes.

Finally, establishing values independently would provide a significant incentive for sites to inflate values. This suggests that some sort of top down discipline must be imposed. This does not suggest that local preferences are unimportant to valuation, or even that sites might not sequence projects in different ways than a literal interpretation of headquarters might imply.

6. Conclusion

From a broad concept of investment theory we have arrived at a series of small steps that could lead to an operational test of the ideas developed in this paper. As stated repeatedly, our goal is to make use of existing information rather than await ideal information and to sensitize administrators to incentives that may conflict with programmatic aims. In closing, we wish to highlight the very significant differences between the assumptions underlying the current cleanup design and the design we espouse.

Current cleanup is organized as a bottom-up plan through which hazardous, radioactive and toxic materials are characterized, stabilized to prevent outright harm, and scheduled for some sort of treatment or final disposition. The philosophy driving this plan is *closure*, an end-state in which the technical base and public willingness to pay are reasonably exhausted. The plan emphasizes local control through the field, sound budgeting, and attention to detail. The process relies heavily on technical expertise and experience, learning-by-doing, and stakeholder guidance disciplined by resource constraints and regulatory requirements. One arrives at program totals by adding up the parts.

Our approach is top-down. We start with a budget and a technical base and propose the development of metrics that measure program progress against some objective set of goals. In other words, how do we allocate the budget across the Complex to do the most good? In this format, budgets are assumed to be fungible and can be shifted, for example, into R&D if doing so increases cleanup value. By design, this approach contrasts with current practices, because we seek to determine if looking at the same set of facts through a different filter will yield new insights. We believe that much useful guidance can be gained through this process, even if present practices continue to prevail, or that the system could form the basis for a new approach to R&D prioritization. Clearly, no cleanup system could be totally top-down because local preferences and concerns for specific cleanup issues are built-in to the legislation governing cleanup. Top-down planning, instead, seeks to ensure that for a fixed budget the greatest possible amount of resources are available to satisfy local preferences and concerns.

APPENDIX: VALUING CLEANUP COST REDUCTIONS DUE TO R&D

1. Introduction

In discussing rates of return to R&D, it was recognized that direct estimates of dollar value contributions to cleanup were unlikely to be calculable, but that other estimates of program outputs could provide the information required to organize R&D around cleanup goals, in other words, to integrate the R&D program with the cleanup. We now illustrate how this could be done by calculating how R&D that reduces costs affects explicit cleanup goals. We do this by drawing on a formal non-linear programming model of the Oak Ridge National Laboratory cleanup effort developed for risk analysis.[39] We link R&D to risk analysis by representing R&D as a means to reduce the cost of accomplishing activities in one of the three major activity groups into which we have categorized specific management actions—storage, treatment, and disposal. This cost reduction permits either a larger volume of at least some activities or the same activities to be carried out at lesser cost, though in general the model rearranges activities in response to relative cost shifts. As a proxy for program outputs, we use reductions in total risks in storage and disposal at the end of our analysis period, which we refer to as terminal-period risk. For instance, if R&D were to reduce the unit cost of maintaining waste in storage, some of the cost formerly used for storage could be transferred to treatment, and more waste could be treated and moved into disposal, resulting in the reduction of terminal period risk.

Briefly, our model prioritizes cleanup tasks using three different criteria: (1) terminal risk reduction, (2) total risk reduction, and (3) life-cycle cost reduction. We then examine the impacts of three different R&D outcomes. The model considers three waste types, transuranics, mixed wastes, and low level wastes, and three operations, storage, treatment, and disposal, over a ten year planning horizon. A $200 million budget was assigned to each year. Because we have not estimated the cost of conducting the R&D to achieve the cost reductions we posit, we do not calculate "return on investment." We employ a "sensitivity analysis approach," examining different (uniform) levels of cost reduction across each cost category.

It should be noted that using this model as a vehicle for analysis illustrates one of the major issues raised above, namely that without an integrated system for project sequencing, individual projects could make different contributions to the overall cleanup goal. In this analysis, we take terminal risk reduction as the program goal,

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[39] D. J. Bjornstad, D. W. Jones, M. Russell, K. S. Redus, and C. L. Dümmer, *Outcome-Oriented Risk Planning for DOE's Clean Up*, JIEE 98-01, October 1998; and D. W. Jones, K. S. Redus, and D. J. Bjornstad, (2000). The consequences of alternative environmental management goals: A non-linear programming analysis of nuclear weapons legacy clean-up at Oak Ridge National Laboratory, *Environmental Modeling and Assessment*, *5*: 1-17.

insert cost reductions due to R&D and examine how terminal risk reduction changes when project sequencing is optimized for terminal risk reduction, and (separately) for two other criteria. For each criterion, the model chooses project sequences in an optimal manner and (because we assume projects can be undertaken incrementally) each cleanup action contributes equally to the overall cleanup goal at the margin. Thus, when the model employs terminal risk reduction as a goal, and we insert R&D-driven cost reductions and measure their impacts on terminal risk, we measure the impact of R&D on a fully integrated program. When the cleanup activities are optimized around a common goal, as in our model, each cleanup task makes a roughly equal contribution to the goal at the margin. When this is true, the value of an incremental cost reduction for each individual cleanup activity is also equal. This leaves R&D managers in the unique position of pursuing innovations that yield the greatest payoff; however, they still the need to justify why a particular cleanup activity was targeted. For cases in which sequencing is carried out by one of the other two criteria, the impact of the same R&D-driven cost reductions on terminal risk is much less.

We thus illustrate that the contribution of cost-reducing R&D can be quite different when viewed programmatically and in pursuit of different goals. For instance, when the reduction of terminal period risk is the goal that guides cleanup task prioritization, cost-cutting R&D is quite effective in reducing terminal risks. However, if life-cycle cost reduction is used to prioritize cleanup tasks, the same R&D will lower costs, but be much less effective in reducing terminal risk. We thus demonstrate that choosing R&D targets within the context of program goals leads to a much more effective overall cleanup than choosing them separately.

Tables A-1, A-2, and A-3 report the sensitivity of terminal risk to ten percent, thirty-five percent, and fifty percent reductions in the unit cost of activities in storage, treatment, and disposal following each of the three sequencing criteria. The specification of these cost reductions, for purposes of the analysis, has the entire array of activities within each of these categories fall by the specified percentage, i.e., for each of the three waste types. While clearly R&D can be more carefully targeted, this specification is compatible with a specific R&D result that reduces the cost of an entire category of cleanup actions. We calculate the sensitivity of terminal risk in the form of elasticities, which is the percent reduction in terminal risk divided by the percent change in cost. When the cost change is a cost reduction, the elasticity will be negative for a reduction in terminal risk. These calculations are most fruitfully interpreted relative to one another. We do not assert that they forecast specific cleanup outcomes for Oak Ridge.

Table A-1. Sensitivity of Terminal Risk to Changes in Specific Cost Components of Clean-up Activities, Objective Function: Minimize Terminal-Period Risk

% reduction in storage cost	% reduction in treatment cost	% reduction in disposal cost	beginning risk, R(0)	terminal risk, R(T)	Elasticity of terminal risk with respect to cost change
			216,100	99,034	[base case; no change in cost]
A. Technological change reduces treatment costs across all waste types					
0%	-10%	0%	216,100	94,029	**-0.518**
0%	-35%	0%	216,100	86,712	**-0.379**
0%	-50%	0%	216,100	82,424	**-0.366**
B. Technological change reduces storage costs across all waste types					
-10%	0%	0%	216,100	96,500	**-0.259**
-35%	0%	0%	216,100	94,748	**-0.126**
-50%	0%	0%	216,100	93,916	**-0.106**
C. Technological change reduces disposal costs across all waste types					
0%	0%	-10%	216,100	97,348	**-0.172**
0%	0%	-35%	216,100	96,508	**-0.074**
0%	0%	-50%	216,100	96,017	**-0.062**

2. The Effect of R&D under Terminal Risk Minimization

Table A-1 shows the elasticities of terminal risk to the cost reductions when the managerial objective is to reduce terminal period risk (last column of the table). The first panel of the table contains the results for R&D innovations that affect treatment costs, the second panel reports the corresponding results when R&D results affect storage costs, and in the third panel, the R&D operates on disposal costs. Within each panel, there are three rows, reporting larger percentage cost reductions following from the R&D. Note first that the elasticities are negative, indicating that R&D which reduces costs also reduces terminal risk. Savings due to innovation are passed along as greater levels of cleanup. Next, observe that the sensitivity falls substantially between the ten-percent and the thirty-five-percent cost reductions, then levels out considerably between the thirty-five- and fifty-percent reductions. This declining marginal effectiveness of cost reduction reflects declining marginal productivity in each of the activity groups, one of the model's non-linearities. This means that continued improvement of storage technology, without improvement in treatment and disposal technologies, eventually delivers smaller improvements in terminal risk reduction.

For the managerial goal of terminal risk minimization, the biggest R&D "bang for the buck" appears to be in treatment technology, for all three levels of cost reduction. Storage offers the second most attractive R&D target, followed by disposal. The reduction in effectiveness is smallest for the continuing improvements in storage technology and is greatest in disposal technology.

3. The Effect of R&D under Life-cycle Cost Minimization

When R&D results are put into action within a management plan to minimize life-cycle costs, savings are reflected as lower spending rates, rather than increases in reducing terminal risk (Table A-2). Improvements in treatment technology actually increase terminal risk slightly, and the effect gets larger for larger percent reductions in cost. (We discuss impacts on costs below.) What happens in this case is that slightly more waste is treated simply because it is cheaper to treat. R&D reducing storage costs has a nearly imperceptible effect on terminal risk, although it does reduce it by a very small amount. The smallest cost reduction has no effect at all on terminal risk. Disposal R&D has the greatest effect on terminal risk, because to take advantage of this cost reduction, waste must be treated, which reduces its terminal risk.

4. The Effect of R&D under All-risk Minimization

All-risk minimization adds treatment risk to terminal risk and seeks to minimize the total (Table A-3). Treatment risk is typically much higher than storage or disposal risk and in this case the model would prefer to treat as little waste as possible, a fact we compensate for by inserting an identical "site treatment plan" in each model run which forces a minimum level of treatment to occur. R&D that reduces operating costs in each of the three areas—storage, treatment, and disposal—increases terminal-period risk, in some cases quite strongly. For example, a 10 percent reduction in unit costs of storage would increase terminal risk by 4.6 percent, not quite a one-for-one increase, but certainly a substantial one. In each operational area, this effect is decreasing in the size of the cost reduction: that is, as the cost reduction gets larger, the increase in terminal risk gets smaller—a kind of diminishing marginal loss. Thus, while a 10 percent reduction in treatment cost would increase terminal risk from the base-case level of 143,402 to 150,112 a 35 percent reduction in storage costs would increase terminal risk to 152,223—a higher level than the 10 percent increase, but far less than 3.5 times higher. Similarly, a 50

Table A-2. Sensitivity of Terminal Risk to Changes in Specific Cost Components of Clean-up Activities, Objective Function: Minimize Life-Cycle Costs

% reduction in storage cost	% reduction in treatment cost	% reduction in disposal cost	beginning risk, R(0)	terminal risk, R(T)	Elasticity of terminal risk with respect to cost change
			216,100	151,089	[base case; no change in cost]
A. Technological change reduces treatment costs across all waste types					
0%	-10%	0%	216,100	152,064	**+0.06**
0%	-35%	0%	216,100	154,967	**+0.07**
0%	-50%	0%	216,100	157,001	**+0.08**
B. Technological change reduces storage costs across all waste types					
-10%	0%	0%	216,100	151,089	**0.00**
-35%	0%	0%	216,100	150,481	**-0.01**
-50%	0%	0%	216,100	150,481	**-0.01**
C. Technological change reduces disposal costs across all waste types					
0%	0%	-10%	216,100	150,123	**-0.06**
0%	0%	-35%	216,100	147,396	**-0.07**
0%	0%	-50%	216,100	144,344	**-0.09**

percent decrease in treatment cost still would increase terminal risk, but only to 154,333. These diminishing effects of cost reductions on terminal risk are reflected in smaller absolute values of the elasticity of terminal risk with respect to cost change as the percent cost reduction gets larger.

Just as the terminal risk elasticities get smaller with larger cost reductions, each set of three elasticities gets smaller as we move across the operational areas: the elasticities are largest for treatment cost reductions, next largest for storage cost reductions, and smallest for disposal cost reductions. We reiterate that, within each of these operational areas, the elasticity gets smaller as the cost reduction gets larger.

Table A-3. Sensitivity of Terminal Risk to Changes in Specific Cost Components of Clean-up Activities, Objective Function: Minimize All Risks in All Periods

% reduction in storage cost	% reduction in treatment cost	% reduction in disposal cost	beginning risk, R(0)	terminal risk, R(T)	Elasticity of terminal risk with respect to cost change
0%	0%	0%	216,100	143,402	[base case; no change in cost]
A. Technological change reduces treatment costs across all waste types					
0%	-10%	0%	216,100	155,608	**+0.82**
0%	-35%	0%	216,100	157,105	**+0.26**
0%	-50%	0%	216,100	158,322	**+0.16**
B. Technological change reduces storage costs across all waste types					
-10%	0%	0%	216,100	150,112	**+0.46**
-35%	0%	0%	216,100	152,223	**+0.13**
-50%	0%	0%	216,100	154,333	**+0.09**
C. Technological change reduces disposal costs across all waste types					
0%	0%	-10%	216,100	146,013	**+0.18**
0%	0%	-35%	216,100	146,013	**+0.05**
0%	0%	-50%	216,100	146,013	**+0.03**

5. The Influence of Cost Reductions on the Levels of Goal Attainment

The salient finding of this analysis could be described thus: when terminal risk reduction is the overall programmatic goal, operational cost reductions achieved through the implementation of R&D results will be quite effective in reducing terminal risk (Table A-4); but when other goals guide programmatic choices, the effect of cost reductions on the level of terminal risk attained is erratic and small. This finding leaves open the question of whether these cost reductions actually help in reaching higher levels of those other programmatic goals. We examined this question for the case of the life-cycle cost minimization goal and found the cost reductions to be quite effective in achieving that goal, as shown in Table A-2. In contrast to the pattern of sensitivities of terminal risk to cost changes, the sensitivity

Table A-4. Sensitivity of Life-Cycle Cost Minimization to Changes in Specific Cost Components of Clean-up Activities

% reduction in storage cost	% reduction in treatment cost	% reduction in disposal cost	Elasticity of life-cycle cost with respect to cost change
			[base case; no change in cost]
A. Technological change reduces treatment costs across all waste types			
0%	-10%	0%	**-0.273**
0%	-35%	0%	**-0.292**
0%	-50%	0%	**-0.307**
B. Technological change reduces storage costs across all waste types			
-10%	0%	0%	**-0.171**
-35%	0%	0%	**-0.195**
-50%	0%	0%	**-0.197**
C. Technological change reduces disposal costs across all waste types			
0%	0%	-10%	**-0.584**
0%	0%	-35%	**-0.730**
0%	0%	-50%	**-0.780**

of the value of the objective function to cost changes is highest for disposal cost reductions and lowest for treatment cost reductions; and within each operational category of cost reductions, the degree of sensitivity increases somewhat (but at a decreasing rate) as the cost reduction gets larger. (In fact, the increase in sensitivity to disposal cost reductions is quite substantial between the 10 percent and 35 percent cost reductions.) These results highlight the need to align R&D goals with overall programmatic goals, in other words, to operate in the right-hand column of Pasteur's Quadrant.