A Decision Framework for Prioritizing Industrial Materials Research and Development

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PREFACE

Federal research and development sponsors, managers, and other decisionmakers are faced with increasingly difficult choices on how to best allocate shrinking resources among various R&D programs. As part of a study performed for the National Renewable Energy Laboratory, this report describes a structured method, in the form of a decision framework developed by RAND, for identifying priorities in materials R&D. The study's objective is to define research priorities for the Industrial Materials for the Future program of the U.S. Department of Energy Office of Industrial Technologies.

A RAND documented briefing published earlier on the initial results of the study (DB-364-NREL) identified research challenges in meeting industry-defined performance targets for energy savings, waste reduction, and productivity improvement across multiple industries. The decision framework described in this report provides a structured method for ranking research activities that address those multiple-industry research challenges.

This report should be of interest to research and development sponsors, managers, and those who perform research, and individuals or organizations that develop or use new technologies.

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SUMMARY

As government research and development (R&D) budgets continue to decrease in real dollars,[1] and marketplace forces require industry to focus its R&D on incremental improvement of existing technologies and processes,[2] federal R&D sponsors, managers, and other decisionmakers are faced with increasingly difficult choices on how to most effectively use shrinking R&D budgets. In light of these increasing budgetary constraints, R&D program managers at the U.S. Department of Energy (DOE) Office of Industrial Technologies (OIT) seek to maximize the benefits that can be achieved through available R&D resources by using three closely related strategies:

1. Conducting only R&D that targets improved performance goals in industrial processes
2. Concentrating resources on R&D with multiple-industry impact
3. Conducting R&D that bridges the gap between basic research and commercialization of the product of that research.

The OIT implements the first strategy through its Industries of the Future (IOF) initiative, in which teams from the nine most energy-intensive industries define visions of future technology that will be used to reduce energy use, reduce waste production, and improve productivity and develop technical road maps to achieve performance targets. The OIT implements the second and third strategies through "cross-cutting" (multiple-industry) R&D programs in three technological areas—materials, sensors and controls, and combustion.

This report focuses on the OIT Industrial Materials for the Future (IMF) program, which sponsors materials R&D.[3] The program addresses high-priority, multiple-industry materials research needs or challenges (referred to as MIRCs) that must be met to achieve IOF objectives. In this report, we describe a structured method (i.e., a decision framework) for identifying priorities in materials R&D. The framework is based upon technical data and expert judgments on the potential benefits of a par-

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[1]See *Science and Engineering Indicators 2000*, National Science Foundation, Washington, D.C., www.nsf.gov/sbe/srs/seind00/start.htm.

[2]See *Smart Prosperity: An Agenda for Enhancing Productivity Growth,* National Coalition for Advanced Manufacturing, Washington, D.C., 2001.

[3]While the decision framework discussed here is applicable to sensors and controls and to combustion, a discussion of R&D programs for those areas is beyond the scope of this report.

ticular R&D program or R&D in a particular area and the probability of success in achieving those benefits. This method was developed for and is applied to the IMF program.

Like many decisions that must be made in industry and government, allocating scarce IMF R&D funds rarely involves obvious choices. First, a choice may need to be made from among several candidate R&D projects or initiatives, each of which may have significant potential benefits and/or excellent candidate materials,[4] and the best choice may not be so clear-cut. Second, there are no guarantees that after the R&D is conducted the desired materials properties (e.g., yield strength, ductility, or oxidation resistance) will be achieved and the anticipated benefits will result. Therefore, these decisions are made with some degree of uncertainty.

Conducting this decisionmaking process in a manner that truly optimizes the available resources and that is both transparent (i.e., it follows a clear and logical process) and auditable (i.e., it has a well-documented audit trail) requires a structured method that is capable of the following:

1. Managing the complex task of having to evaluate a large number of candidate materials and R&D options
2. Taking into account the inherent uncertainty in the eventual outcomes
3. Identifying the options that will produce the maximum benefits from available R&D resources.

The quantitative R&D decision framework described in this report explicitly incorporates estimates of the uncertainties associated with a technology (for instance, how feasible it is for a material to achieve a certain property level) and with the R&D process itself (for example, uncertainty surrounding development of the material, production of the material, and fabrication of parts with the material). The decision framework uses these estimates and the anticipated benefits in energy and waste savings and increased productivity to compute an *expected value* for each R&D option. That expected value is the product of the anticipated benefits, the potential of candidate materials to achieve needed properties, and the probability of success of the R&D process. The framework, therefore, provides a measure of the value of conducting an R&D project or program given the inherent uncertainties in the outcome, and accordingly provides a useful basis for comparing and ranking R&D activities aimed at addressing multiple-industry research challenges.

The principal benefit of this method of analysis is not so much a precise ranking of various R&D projects, but rather a procedure for setting R&D priorities that is transparent, well documented, and incorporates expert judgment. It may be useful to periodically revisit and monitor the values that are assigned to R&D programs as new findings are reported in the literature and as a greater understanding of materials and industrial processes is achieved. For example, rankings may change when new

[4]"Candidate materials" refers to a specific type of material (e.g., stainless steel, intermetallics, glass ceramics) upon which research will be performed to obtain the desired suite of properties.

research results extend the region of applicability of a material or better define desired materials properties.

We recommend that this decision framework be used to evaluate proposed R&D when a project portfolio is being developed, and that it be used to identify and evaluate data that are necessary to both address the various MIRCs and identify the R&D needed to acquire those data. We recommend extending the framework to incorporate probability distributions to reflect the decreasing likelihood of a particular outcome (for example, if experts do not agree on the probability of success of an activity, the distribution would reflect this difference of opinion). We also recommend extending its application to other OIT programs and using it to reevaluate programs at a later date as the R&D activities progress.

Finally, we propose that the framework be applied to other R&D programs by quantifying benefits using similar units of measure based on achieving desired technological characteristics. Using anchored scales similar to those shown in Chapter Three, the framework can be employed to estimate the potential of candidate technologies and the probability of success of proposed R&D. Expected values computed from these estimates can then be used to determine program priorities.

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ACRONYMS

Btu	British thermal unit
CBR	Cost-benefit ratio
CMR	Core materials research
DOE	Department of Energy
EV	Expected value
GPRA	Government Performance and Results Act
IMF	Industrial Materials for the Future
IOF	Industries of the Future
IRR	Internal rate of return
MIRC	Multiple-industry research challenge
MPa	Megapascals (1,000,000 pascals [Pa])
MPR	Materials properties research
NPV	Net present value
NREL	National Renewable Energy Laboratory
NSF	National Science Foundation
OIT	Office of Industrial Technologies
R&D	Research and development
SEU	Subjective expected utility
TIM	Technological Innovation Matrix

Chapter One

INTRODUCTION

As government research and development (R&D) budgets continue to decrease in real dollars,[1] and marketplace forces require industry to focus its R&D on incremental improvement of existing technologies and processes,[2] federal R&D sponsors, managers, and other decisionmakers are faced with increasingly difficult choices on how to most effectively use shrinking R&D budgets. In light of these increasing budgetary constraints, R&D program managers at the U.S. Department of Energy (DOE) Office of Industrial Technologies (OIT) seek to maximize the benefits that can be achieved through available R&D resources by using three closely related strategies:

1. Conducting only R&D that targets improved performance goals in industrial processes

2. Concentrating resources on R&D with multiple-industry impact

3. Conducting R&D that bridges the gap between basic research and commercialization of the product of that research.[3]

The OIT implements the first strategy through its Industries of the Future (IOF) initiative, through which teams from the nine most energy- and waste-intensive U.S. industries define visions of future technology and develop technical road maps to achieve performance targets. The OIT implements the second and third strategies through "cross-cutting" programs to coordinate and sponsor R&D in three technological areas common to all nine IOF industries—materials, sensors and controls, and combustion.

This report presents a structured method (i.e., a decision framework) for identifying materials R&D priorities.[4] Specifically, we describe a decision framework that uses

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[1]See *Science and Engineering Indicators 2000*, National Science Foundation, Washington, D.C., www.nsf.gov/sbe/srs/seind00/start.htm.

[2]See *Smart Prosperity: An Agenda for Enhancing Productivity Growth,* National Coalition for Advanced Manufacturing, Washington, D.C., 2001.

[3]*Basic research* is "curiosity-driven" research (i.e., intended solely to answer questions of interest to the researcher) that leads to materials with new suites of properties. *Commercialization* is the use of these materials in a process, component, or product. Applied research is necessary to link these two activities by refining the properties to meet application needs and by providing the needed materials production and fabrication capabilities.

[4]While the decision framework discussed here is applicable to sensors and controls and to combustion, a discussion of R&D programs for those areas is beyond the scope of this report.

measures of the potential benefits from an R&D program and the probability that the R&D will be successful in providing materials with the desired properties to compute an expected value for each research project. We further describe how the potential benefits and probability of success are assessed and documented for both industrial process R&D and R&D for developing, producing, and fabricating materials with enhanced properties.

In the following sections, we give an overview of the three strategies the OIT uses to maximize the benefits from R&D, and a brief description of the nature of the Industrial Materials for the Future (IMF) program and the methodology for our decision framework.

R&D STRATEGIES USED BY THE OFFICE OF INDUSTRIAL TECHNOLOGIES

In the following sections, we summarize the three strategies used by R&D program managers in the OIT to maximize the benefits that can be achieved through available resources.

Goal-Driven R&D

The first approach used by the OIT to increase the impact of finite R&D funding is to focus R&D on "market pull" rather than "technology push." For example, a *technology push strategy* would select and prioritize R&D programs primarily for their potential to reduce energy consumption and waste generation without specific industrial performance goals. In comparison, the OIT's *market pull strategy* prioritizes R&D programs based on their ability to address industrial process goals for the nine most energy- and waste-intensive U.S. industries (known collectively as the Industries of the Future).

The OIT, in collaboration with industry partners, has identified the highest-priority technologies that are needed to meet the performance targets for reducing energy consumption and waste generation and increasing output productivity in each of the IOF industries. These technologies and performance targets are the basis for prioritizing R&D programs for funding.[5]

Multiple-Industry R&D

The second approach used by the OIT to increase the benefits resulting from its R&D funding is to seek opportunities to conduct R&D that applies to more than one of the Industries of the Future. This strategy not only increases the impact of the R&D but also eliminates duplication of R&D efforts within each industry. Multiple-industry

[5] For more information on the IOF, the industries' visions of future operations, and their "technology road maps" and how they were created, see www.oit.doe.gov. It should be noted that curiosity-driven basic research that underpins the OIT's R&D is funded by the DOE Office of Science, the National Science Foundation (NSF), several other federal agencies, and the private sector.

R&D focuses on higher-risk technologies (those that are less likely to succeed, are costly to develop, or take longer to come to fruition) that no single industry would pursue on its own, and enables industry-specific follow-on R&D that is ultimately transferred to research and development teams within each IOF industry.

The OIT created separate programs to manage the R&D for each of three areas that "cross-cut" the IOF: a program for R&D on materials, a program for R&D on sensors and controls, and a program for R&D on combustion. The OIT Industrial Materials for the Future (IMF) program coordinates materials R&D for all nine IOF industries and prioritizes each R&D project based on its application to more than one industry. A documented briefing published earlier by RAND, *Industrial Materials for the Future (IMF) R&D Priorities* (2001),[6] identifies the high-priority, multiple-industry materials research needs that must be met to achieve the IOF objectives (in this report, we refer to those needs as *multiple-industry research challenges* [MIRCs]). That briefing also describes a structured approach for identifying R&D objectives from the vision statements and technical road maps developed by several IOF industries.[7]

R&D to Bridge the Gap Between Basic Research and Commercialization

The third strategy used by the OIT to increase the impact of R&D funding is to conduct R&D and engineering activities to ensure, and accelerate, the transition from basic research to commercialization. Without funding these types of activities and facilitating partnerships between basic research scientists and industrial applications engineers, research results—even those with high potential—will fail to be used beyond the concept or demonstration phase of a project.

Two kinds of R&D are required to bridge the gap between research and the commercialization of the product of that research. The first type *defines the specific objectives of the research*, starting with R&D on energy- and waste-intensive industrial processes to better understand which process phenomena lead to high energy use, waste, or costly failures. For example, the IMF program sponsors R&D to define how materials behave in the industrial process and how that behavior may lead to inefficiencies in the process (e.g., corrosion or cracking of process components or equipment) or problems with the end product. Because the primary output of this type of R&D is a set of desired materials properties that will improve process efficiencies, enabling IOF performance targets to be met, we refer to this type of R&D as Materials Properties Research (MPR).

Once the desired materials properties have been defined, the second type of R&D must be conducted. This type of R&D develops new technologies, develops processes and techniques to produce the new technologies, and develops processes and tech-

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[6]Silberglitt, Richard, and Jonathan Mitchell, *Industrial Materials for the Future (IMF) R&D Priorities*, Santa Monica, Calif.: RAND, DB-364-NREL, 2001.

[7]*Vision statements* define the characteristics of a particular industry in the future, while *technology road maps* outline research needs, performance targets, and time frames for achieving those characteristics. For details, go to www.oit.gov, click on any menu item under "Industries of the Future," and then click on "Vision and Road Maps."

niques to fabricate replacement components for the industrial process. For example, in the case of materials research, once the desired materials properties are determined, the IMF program sponsors research to develop new materials or improved existing materials (e.g., new microstructures or composite materials) with the desirable properties. The program also sponsors R&D to develop techniques, procedures, and processes to produce new materials in sufficient volume and quality and to fabricate (e.g., cast, sinter, forge, extrude, or join) the new material into components that will be used in the industrial process. The primary output of this R&D is commercialization of the technology for the IOF and other industries. Because this R&D forms the core of the IMF program, we refer to it as Core Materials Research (CMR).

COMPARING THE IMF PROGRAM AND DECISION FRAMEWORK WITH OTHER PROGRAMS AND PRIORITIZATION METHODS

While the IMF program and the decision framework created for this study differ from other R&D programs and project-selection methods, they nevertheless have a number of similarities to other such programs and methods. The goal-oriented nature of the IMF program is similar to that of the federal Small Business Innovation Research and Small Business Technology Transfer Research programs and the Defense Advanced Research Projects Agency research program. The IMF program's focus on industry-defined MIRCs is similar to the approach of certain industry-led consortia, such as the National Center for Manufacturing Sciences and the international Intelligent Manufacturing Systems initiative.

Furthermore, our decision framework uses the technical judgment of domain experts, as do programs that rely on peer review by either individuals, panels, or both—such as the Small Business Innovation Research program and the Small Business Technology Transfer Research program—and basic research programs sponsored by the National Science Foundation (NSF), the DOE's Office of Science, the Department of Defense, and other federal agencies. However, the RAND method is unique in that it asks experts to use ranking scales explicitly based on available technical data and literature rather than a ranking system based merely on expert judgment.

USE OF EXPECTED VALUE TO RANK PROJECTS

An important feature of the decision framework we describe in this report is the calculation of an expected value based upon estimated benefits rather than the customary sum of weighted criteria values. The expected value incorporates the judgments of domain experts into a structure that is both transparent and based upon explicit normalized scales. This feature of the framework provides a basis for detailed discussions of the differences among expert judgments in terms of the technical literature, and it provides a means for revisiting the rankings in the future as additional data become available.

The principal benefit from our method of analysis is not so much the precise ranking of various R&D projects that it provides, but rather a procedure for setting R&D priorities that is transparent (i.e., follows a clear and logical process), is well documented, and incorporates expert judgment.

ORGANIZATION OF THIS REPORT

In Chapter Two, we describe how the IMF program of the OIT identifies materials science and engineering research activities and describe two successful IMF project case studies. Chapter Three describes how the decision framework is used in prioritizing materials R&D. Chapter Four compares the framework with traditional economic and utility prioritization methods and discusses applications and extensions of the decisionmaking framework. In Chapter Five, we present our conclusions and recommendations for use of the decision framework.

Chapter Two

INDUSTRIAL MATERIALS FOR THE FUTURE PROGRAM R&D PROCESS

The U.S. Department of Energy Office of Industrial Technologies sponsors R&D programs to improve energy efficiency and resource utilization in the IOF—a group of nine energy-intensive and waste-intensive U.S. industries (see Figure 2.1). These industries use almost 70 percent of the total energy consumed by U.S. industries and produce almost 90 percent of the waste generated by the entire U.S. industrial sector. The OIT R&D programs focus on these nine materials-and-process industries and are aimed at developing technologies that reduce the use of raw materials and energy, reduce the generation of waste, and increase industrial productivity.

Nine teams, each of which was led by a representative from one of the IOF industries and included engineers, scientists, and program managers from government, academia, and national laboratories, have defined technology visions for each industry

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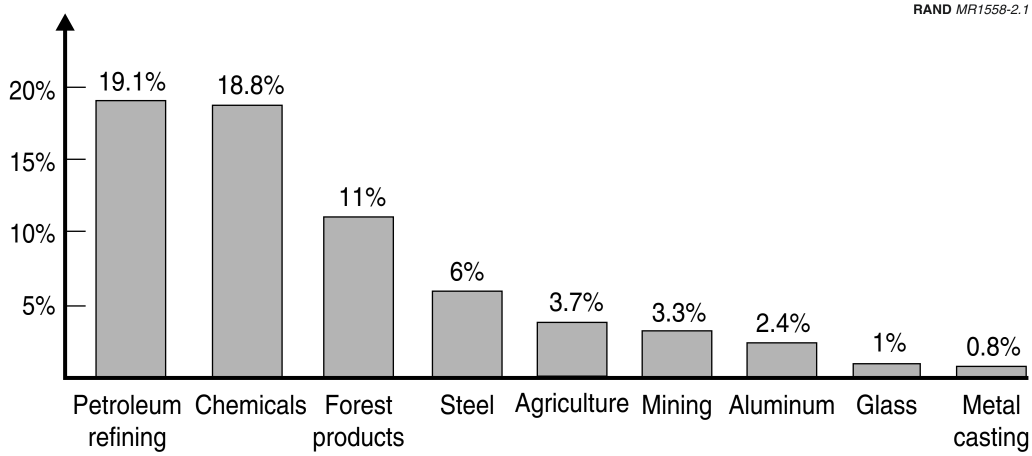

SOURCE: *Vision: Results for Today, Leadership for Tomorrow*, Office of Industrial Technologies, Office of Energy Efficiency and Renewable Energy, U.S. Department of Energy, Washington, D.C., DOE/GO-102001-1164, February 2001.

Figure 2.1—Percentage of Total Industrial Energy Use by Nine Energy-Intensive U.S. Industries

(see Chapter One). Based on these visions of the future, the nine industry teams have developed research agendas, R&D road maps, and implementation plans to meet high-priority needs for technology. The OIT facilitates the process by which the IOF industries achieve their goals by assisting with R&D planning and meeting coordination, facilitating interaction among the different industries, and providing access to national laboratory facilities. The OIT also shares the cost of conducting selected projects.

As we noted in Chapter One, in addition to assembling and managing the nine "vision teams," the OIT also established three "cross-cutting" programs to coordinate and sponsor R&D in three technological areas common to all nine IOF industries: sensors and controls, combustion, and materials. The materials R&D is coordinated by the IMF program, which we discuss in the next section (as noted earlier, discussion of the other two technological areas is beyond the scope of this report).

BACKGROUND ON THE INDUSTRIAL MATERIALS FOR THE FUTURE PROGRAM

The mission of the IMF program is to research, design, develop, engineer, and test new and improved materials, and to explore more-profitable uses of existing materials.[1] The IMF program seeks to maximize the benefits that can be achieved through available funding by sponsoring materials R&D (1) to meet the performance targets of the IOF; (2) to yield the largest impact across industries of the IOF; and (3) to ensure the transition from research concept to commercialization of the product of the research within the IOF and in other industries.

R&D activities funded by the IMF program are conducted according to the sequence illustrated in Figure 2.2. (As we stated in Chapter One, the IMF program uses existing materials or develops new ones to achieve the materials properties that are required to yield improvements in the industrial processes.) The IMF program pursues its mission by addressing multiple-industry research challenges. As indicated by the arrows in the figure, MIRCs are research goals intended to improve industrial processes that are defined by industry teams through the IOF visioning and road-mapping process. The industry teams review each process, focusing on those processes that are energy- and waste-intensive or are subject to high maintenance costs, and identify research goals to reduce energy use and minimize waste and environmental impact. Some of the most important MIRCs that involve materials research are summarized in Table 2.1. Each of the MIRCs (except number 2) is defined by a quantitative set of *desirable materials properties* (e.g., yield strength, ductility, or oxidation resistance).

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[1]U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, Office of Industrial Technologies, *Program Plan for Fiscal Years 2000 Through 2004, Industrial Materials for the Future (IMF)*, Washington, D.C., July 2000, p. i.

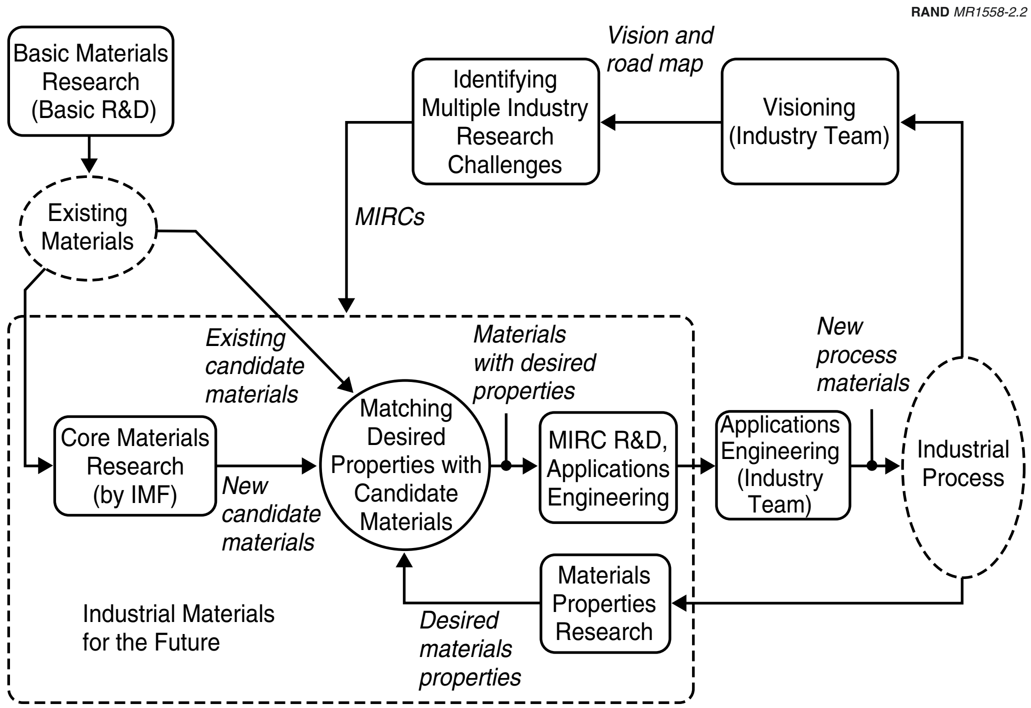

Figure 2.2—Sequence of R&D Activities Funded by the IMF Program

Table 2.1

Multiple-Industry Research Challenges by Industry

MIRC	Applicable Industries
1. Corrosion-, erosion-, and wear-resistant materials for process equipment (specific suite of properties depends on the environment of the specific industrial process)	Agriculture, aluminum, chemicals, forest products, glass, metal casting, mining, petroleum, steel
2. Databases and modeling of materials properties	Aluminum, chemicals, forest products, glass, metal casting, mining, petroleum, steel,
3. High-temperature materials and refractories	Aluminum, chemicals, forest products, glass, metal casting, steel
4. Membranes and physical-separation methods and materials	Agriculture, chemicals, forest products, mining, petroleum
5. Materials that are easily joined and welded without the need for special preparation	Aluminum, chemicals, forest products, metal casting, steel
6. Coatings for process materials, equipment, and products	Chemicals, forest products, glass, metal casting, petroleum, steel

SOURCE: Silberglitt, Richard, and Jonathan Mitchell, *Industrial Materials for the Future (IMF) R&D Priorities*, Santa Monica, Calif.: RAND, DB-364-NREL, 2001.

The IMF program addresses each MIRC by matching candidate materials[2] with the desired materials properties. This activity of matching desired properties with candidate materials within the sequence of R&D activities funded by the program is illus-

[2]"Candidate materials" refers to a specific type of material (e.g., stainless steel, intermetallics, glass ceramics) upon which research will be performed to obtain the desired suite of properties.

trated by the circular shape in Figure 2.2. However, some MIRCs are not described in the industry road maps in sufficient detail to define the desired materials properties. In this case, MPR is required to determine the desired materials properties that are needed to address that particular MIRC (as indicated in the bottom portion of Figure 2.2).

The objective of MPR is to determine the role of each material in a particular process and to define how making certain changes in materials properties can contribute to reducing energy use, waste, and environmental impact. The behavior of a material is quantified through an examination of the material before, during, and after its use in a process. In some cases, samples of the material are also examined in the laboratory. The materials and industrial process may also be modeled for purposes of simulating materials behavior and its consequences.

Special emphasis is given to materials failure, degradation of materials properties, and materials properties that contribute directly to energy utilization, waste, or decreased productivity. For example, special emphasis would be placed on a capital-intensive piece of equipment that a vision team has identified as a source of costly materials failures and frequent production stoppages. In such a case, the introduction of new materials could increase the average time between failures significantly and may even yield increases in productivity. The result of this MPR is a set of desirable materials properties that can be used to identify candidate materials.

After the desired materials properties are identified, a match with existing materials is sought, as indicated by the diagonal arrow in Figure 2.2. If no satisfactory match can be found with existing materials, then the IMF program sponsors CMR, which builds on the latest results that have emerged from basic materials research sponsored by other entities, to improve the properties of existing materials or develop new materials. This activity is indicated in the figure by the left-hand path from "Existing Materials" to "Matching Desired Properties with Candidate Materials." Basic research in materials science and engineering sponsored by the DOE Office of Science, the NSF, other federal agencies, and the private sector provides the source materials and techniques for CMR sponsored by the IMF program.

CMR to improve the match between materials and desired properties is at the heart of the process illustrated in Figure 2.2. The IMF program, accordingly, devotes approximately one-third of its budget to research in areas such as

- database development
- properties of materials at high temperatures
- determinants of wear-, erosion-, and corrosion-resistance
- relationships between processing and materials properties
- modeling of materials processing, forming, and deposition
- methods for separating industrially important materials
- sensor materials

- materials chemistry
- surfaces of, interfaces among, and joining of materials.

After a satisfactory match between desired materials properties and candidate materials has been established, the applications engineering process is conducted to provide components made of the appropriate new material or materials, which will then be used in specific industrial processes, as indicated in Figure 2.2 by the arrows extending from the right of the circle and ending at "Industrial Process." The first part of this applications engineering process is sponsored by IMF. It consists of R&D to produce the new material in sufficient quantities and with high enough quality to meet the needs of the industrial application. In addition, IMF sponsors research and development in the fabrication (e.g., casting or welding) of substitute process components that use the new material.

Multiple-industry research demonstrations are then pursued, followed by near-term demonstrations held within industrial facilities, which could be cosponsored by the IMF program and OIT industry teams or directly sponsored by the industry teams. Ultimately, the applications engineering process demonstrates that the new or improved existing material can be produced and fabricated into a useful product that will demonstrate the desired properties in a realistic industrial-service environment. However, this process requires a long-term commitment from both the IMF program and its partners in the end-user and materials industries.

It is important to note that the research activities just described are not necessarily sequential. Furthermore, the process is a highly iterative one that includes MPR to define the desired materials properties and CMR to develop new materials to achieve the desired properties. A critical feature, and indeed a strength, of the process is that new candidate materials can emerge at any time as increased knowledge of composition-processing-properties relationships or fabrication methods is gained from basic materials research.

We conclude this chapter with brief descriptions of two successful IMF projects. The first—involving intermetallic alloys for high-temperature processing—is a case in which the desired materials properties were already known and core research was required to improve the properties of a candidate class of materials to match those desired properties. The second—involving materials for kraft recovery boilers—is a case in which MPR to define the relationship between the service environment and materials longevity was necessary before candidate materials that were a good match with the desired properties could be identified.

CASE STUDY 1: INTERMETALLIC ALLOYS FOR HIGH-TEMPERATURE PROCESSING

This case study relates to a CMR project by the IMF to develop a new candidate material that demonstrates desired properties identified by all the IOF teams. In this case, knowledge of the desired materials properties was extensive enough that CMR could be initiated immediately.

Identifying Opportunities for Improvement

All the IOF teams identified opportunities for substantial energy savings, increased productivity, and reduced environmental impact by introducing materials into the industrial process that have significantly improved oxidation resistance *or* high-temperature strength. The steel, chemicals, and petroleum IOF industries, and their supporting industries—heat-treating and forging—identified the need for materials with *both* improved oxidation resistance and improved high-temperature strength.

Matching the Candidate Material with the Desired Properties

No existing materials exhibited properties capable of meeting the desired materials properties. In particular, steel alloys showed greatly reduced strength at temperatures above 400°C, whereas industrial performance targets called for strength retention at temperatures up to 600°C.

Core Materials Research

Intermetallic alloys are materials composed of more than one metallic element—for example, iron and aluminum or nickel and aluminum—that have a long-range-ordered crystal structure and properties that fall somewhere between those of metallic and ceramic materials. The iron and nickel aluminides were long recognized as strong candidate materials with high-temperature strength and oxidation resistance properties that matched the properties desired by the steel, chemicals, and petroleum industries and their supporting industries, such as heat-treating and forging. However, problems with embrittlement, leading to fabrication difficulties, and low ductility and creep[3] in service environments presented significant technical barriers to using these aluminides in applications in these industries.

A major CMR program performed over the past 20 years, which was initiated by the Oak Ridge National Laboratory and continued with the support of the DOE's Office of Basic Energy Sciences, Office of Fossil Energy, and IMF (and its predecessor programs), overcame significant technical barriers to improve the match between desired and candidate materials properties. This CMR resulted in the production of industrially useful intermetallic alloys. A comprehensive review and evaluation of this program was carried out and reported on by the National Materials Advisory Board of the National Academy of Sciences.[4]

This CMR provided an understanding of the mechanisms causing embrittlement and reduced ductility in the presence of moisture and oxygen. Armed with this knowledge, the core research team then focused on improving ductility through microalloying of the candidate materials with boron and chromium and avoiding embrittlement by using standard alloying techniques such as solid-solution strengthening

[3]Time-dependent strain under stress.

[4]*Intermetallic Alloy Development: A Program Evaluation*, Washington, D.C.: National Research Council, National Academy Press Publication NMAB-487-1, 1997.

and dispersion strengthening. The improved match of the candidate materials properties with the desired properties (e.g., 15 percent elongation at 600°C) then provided the basis for work on alloy production methods to allow fabrication of products for testing in industrial processes. (This work addressed the third MIRC listed in Table 2.1.)

The production method development work led to an innovative production-volume melting-and-alloying technique, low-cost casting processes, and materials and processes for making structural welds and weld repairs.[5] These developments were critical to the IMF program being able to attract materials production companies that licensed the processes and cast products for testing by end-user industries.

Benefits

Products that are currently undergoing testing include nickel aluminide trays and assemblies for heat-treating furnaces that are used to carburize steel for the automotive industry, nickel aluminide furnace rolls used to transfer steel in reheat furnaces that are used by the steel industry, iron aluminide–stainless steel composite tubes for petrochemical processing that are used by the chemical and petroleum industry, and aluminide forging dies and radiant burner tubes.

The benefit of the IMF research is that, in these applications, the aluminide products are providing energy savings and productivity improvements well beyond those possible with incremental improvements in the properties of current materials. For example, General Motors' Delphi Saginaw Steering Systems has estimated that it can meet its steel heat-treating needs with an expansion of just two furnaces instead of three because the higher strength-to-weight ratio of the aluminide trays and fixtures allows greater loading of steel, and the longer-lasting aluminide trays substantially reduce maintenance and downtime.[6] The IMF program estimates that the use of these trays and fixtures will generate annual energy savings of 30 trillion Btu and an annual energy cost reduction of $100 million by 2020.[7] The estimated cost of the R&D leading to these savings is approximately $40 million over a period of more than 20 years, approximately half of which was provided by IMF and its predecessor programs and the balance by the DOE Office of Science and Office of Fossil Energy. Moreover, this R&D on intermetallic alloys has led to other applications, including steel transfer rolls and furnace coils for ethylene production, which have estimated annual energy savings and energy cost reductions that are comparable to or greater than those for the heat-treating trays and fixtures applications.

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[5]*Intermetallic Alloy Development: A Program Evaluation,* 1997, p. 20. For details, see Sikka, V. K., "Processing of Aluminides," pp. 561–604, and David, S. A., and M. L. Santella, "Joining," pp. 655–676, in N. S. Stoloff and V. K. Sikka, eds., *Physical Metallurgy and Processing of Intermetallic Compounds*, New York: Chapman and Hall, 1996.

[6]"Delphi Adopts Ni_3Al for Heat Treat Fixtures," *Advanced Materials and Processes*, ASM International, Vol. 159, No. 6, June 2001, p. 9.

[7]Sorrell, C., P. Angelini, and R. Silberglitt, "Industrial Materials for the Future (IMF) Program Intermetallic Alloy Development Activities," OIT Case Study, Office of Industrial Technologies, unpublished.

CASE STUDY 2: MATERIALS FOR KRAFT RECOVERY BOILERS

This case study concerns an IMF project on MPR to better understand the operating environment and the causes of materials failures in kraft recovery boilers. In this case, candidate materials capable of achieving the desirable materials properties already existed; therefore, no CMR was required.

Background

The kraft recovery boiler is an essential piece of equipment in U.S. paper mills. The kraft chemical pulping process is the process most commonly used by U.S. paper mills to separate the cellulose fibers used to make paper from other wood components. The process uses sodium hydroxide and sodium sulfide and produces a concentrated liquid waste product called "black liquor," which is burned in a boiler to recover the chemicals, which are then reused for pulping. This "recovery boiler" also produces steam that is used in plant processes and to generate electricity for the plant.

Identifying Opportunities for Materials Improvement

Approximately 50 percent of U.S. paper mills have only one boiler. Therefore, a boiler shutdown can result in a plant shutdown and subsequent loss of revenue. The material currently used for the boiler tubes is a composite with an inner layer of carbon steel and an outer layer of stainless steel. The forest products industry team identified cracking of the boiler tubes at and near the boiler floor, where molten sodium carbonate and sodium sulfide (smelt) collects, as an important materials research problem that needed to be addressed.[8] The team recognized that its knowledge of the failure mechanism was insufficient to define desired materials properties and identify candidate materials; therefore, MPR was required.

Materials Properties Research

A coordinated MPR program was sponsored by the IMF program and its predecessor program, Advanced Industrial Materials, and was led by Oak Ridge National Laboratory, the Pulp and Paper Research Institute of Canada, and the Institute of Paper Science and Technology. This research team included 17 paper companies, 5 boiler manufacturers, and 2 tube fabricators, with more than 50 percent of the cost-sharing covered by the industry partners. Through its MPR, the research team identified the cracking mechanism of the boiler tubes through detailed on-site examinations, nondestructive and microscopic evaluation of a large number of failed tubes, and thermal and mechanical modeling of tube stresses using finite element methods.

[8]"Materials Needs and Opportunities in the Pulp and Paper Industry," prepared for the U.S. Department of Energy, Office of Industrial Technologies, Advanced Industrial Materials Program, P. Angelini, compiler, Oak Ridge National Laboratory, Oak Ridge, Tenn., ORNL/TM-12865, August 1995.

The research team concluded that the poor match between the thermal expansion coefficients of the 304L stainless steel used for the outer layer of the composite tube and the carbon steel used for the inner layer was a principal factor contributing to the cracking of the tubes.[9] The team also concluded that tube temperature excursions and the water-based washing and drying process that was used when the boilers were shut down for maintenance further contributed to the cracking.

Matching the Candidate Material with the Desired Properties

This successful MPR program defined the desired materials properties for the outer layer of the composite tube: (1) a thermal expansion coefficient to match that of the carbon steel layer of the tube (to minimize the mechanical stress that leads to stress-corrosion cracking), and (2) increased yield strength to prevent the occurrence of damaging tensile stresses. It was then possible to match these properties with two different existing materials—Inconel 625 and Incoloy 825—that could be used in place of the 304L stainless steel for the outer layer of the composite tube. For these two candidate materials, the properties match was good enough that the project moved directly to testing in the paper mills.

Oak Ridge National Laboratory estimated that tube lifetime doubled with the new materials and energy costs were reduced by 5 percent. The new composite tube materials are now routinely being installed whenever recovery boiler tube replacements are made. The annual benefit due to gains in productivity using the new composite tubes is projected by IMF to reach $130 million by 2020. The R&D investment that produced this benefit totaled approximately $6 million.

The R&D program also demonstrated that conditions leading to the tube-cracking do not occur during normal operation of the recovery boiler. The combination of tensile stresses and liquid corrosive material, which together lead to the cracking, occur during the washing and drying of the tubes when maintenance is performed. The R&D team recommended changes in the maintenance procedure that can significantly reduce or eliminate the cracking problem, thereby extending the lifetime of the existing tubes.

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[9]Keiser, James R., et al., “Why Do Kraft Recovery Boiler Composite Floor Tubes Crack?” *TAPPI Journal,* Vol. 84, No. 8, August 2001, p. 48, available from Technical Association of the Pulp and Paper Industry, 15 Technology Parkway South, Norcross, GA 30092.

Chapter Three

IDENTIFYING RESEARCH PRIORITIES USING THE DECISION FRAMEWORK

In the previous chapter, we described how the IMF program addresses MIRCs identified by the OIT industry teams by improving existing materials, developing new materials, and engineering and fabricating replacement components for industrial processes. However, R&D on every MIRC that the OIT identifies cannot be funded in a single R&D budget cycle. In this chapter, we present the framework for ranking MIRCs according to their potential benefits and the probabilities for success in achieving those benefits through either MPR or CMR. We also describe methods for estimating the potential benefits and probabilities of success.

CHOOSING BETWEEN THE TWO TYPES OF FUNDED R&D ACTIVITIES

For each MIRC defined by the OIT industry teams, two types of R&D activities may be funded:

1. **Materials Properties Research.** With MPR, R&D is performed on the industrial process to identify opportunities in which materials with improved properties can yield significant energy and waste reductions and/or increased productivity. The R&D defines desired properties that can be used to identify appropriate candidate materials, and it serves to more clearly focus CMR activities.
2. **Core Materials Research**. With CMR, R&D is performed on existing or new materials to develop a greater understanding of their properties and to improve those properties. CMR is also done to develop techniques and processes to produce materials and fabricate components that meet the challenges of a particular application.

CMR is conducted only when there is enough information about the environment in which the material will be applied that the materials researchers have a strong probability of achieving the desired goals for the materials properties. Otherwise, conducting additional MPR on the operating environment to further refine the desired materials properties is prudent.

The two case studies presented in Chapter Two demonstrate the importance of determining early in the R&D process which option (CMR or MPR) is the most appropriate for the application. For example, in Case Study 2 (on recovery boilers), the MPR identified the source of failure as the cracking that resulted from a mismatch in the thermal expansion coefficients of two adjacent materials in a composite tube. No CMR was required because suitable materials already existed that were capable of satisfying the desired materials properties.

Case Study 1 (on intermetallic alloys), by comparison, illustrates a scenario in which the desired materials properties had been established but could not be satisfied with existing materials. The potential existed, however, to achieve the desired materials properties by performing CMR to develop a new class of materials (intermetallic alloys) capable of meeting the desired materials properties.

DECIDING HOW TO ALLOCATE SCARCE FUNDS

Like many decisions that must be made in industry and government, how to best allocate scarce IMF R&D funds rarely has an obvious solution. The decisionmaking process is complicated by a number of factors and a measure of uncertainty. First, there may be several candidate R&D opportunities, each of which may have significant potential benefits and/or include excellent candidate materials. Second, there are no guarantees that after the R&D is conducted the desired materials properties will be achieved and the anticipated benefits will result.

Conducting this decisionmaking process in a way that truly optimizes available resources, and that is both transparent and auditable (i.e., follows a clear and logical process and has a documented audit trail), requires a structured method. That method encompasses three principal tasks:

1. Managing the complex task of having to evaluate a large number of candidate materials and R&D options
2. Taking into account the inherent uncertainty in the eventual outcomes
3. Identifying the options that will produce the maximum benefits from available R&D resources.

The next section briefly discusses how existing R&D valuation methods and decisionmaking frameworks approach these tasks, setting the stage for a discussion of the decision framework for IMF that follows.

EXISTING QUANTITATIVE DECISION FRAMEWORKS

Forecasting the value of and likelihood of success of any R&D program or initiative is largely about managing uncertainty. No method exists to model all the decision contingencies, no matter how objective the modeling may be. Therefore, practitioners of R&D planning and prioritization must resort to quantitative methods that use aggregate measures of uncertainty.[1]

[1]Akerlof, G. A., “The Market for Lemons: Qualitative Uncertainty and the Market Mechanism,” *Quarterly Journal of Economics*, No. 84, pp. 488–500.

Numerous well-established methodologies exist for quantitatively selecting R&D options that will produce optimal outcomes. These methodologies fall within two broad categories: those that focus on the properties of a technology and those that focus on the risks inherent in the process of developing that technology.[2] Both of these categories of methodologies assign values normalized by *anchored scales*[3] to enable generation of a cumulative value of an R&D option for comparison with other options.

The first category analyzes risk in terms of technological properties. Values of risk (or probability of success) are assigned using anchored scales for defined elements of the technology.[4] For example, values can be assigned to the maturity of the technology of each component, the availability of certain materials or components, the mean time between each component failure, or other relevant factors. By using anchored scales, the values of the properties are normalized and can be summed and grouped to generate an overall measure.

The second category analyzes risk in terms of the R&D process. A statistical approach is used to assign risks (or probabilities of success) to the outcomes of each stage in the R&D "value chain" (the stages of R&D from basic research to commercialization).[5] These risks are accumulated to generate an overall measure of risk using an anchored scale. When the processes are connected within a model, Monte Carlo simulations can be run to develop an overall probability distribution of outcomes. The apparent rigor of this approach is subverted by the extreme subjectivity of all the probability distributions assigned to the processes. Furthermore, constructing the model and running the simulations often require several months of labor.[6]

ALTERNATIVE QUANTITATIVE DECISION FRAMEWORK FOR IMF R&D

As an alternative to the quantitative decision framework discussed in the previous section, here we put forward a quantitative decision framework that is more trans-

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[2]Roussel, P. A., K. N. Saad, and T. J. Erickson, *Third-Generation R&D*, Boston: Harvard Business School Press, 1991; and Jarret, E. L., *Effect of Technical Elements of Business Risk on Decision Making*, Industrial Research Institute, Washington, D.C., 2000.

[3]By "anchored scales," we mean numerical scales with defined upper and lower limits and threshold values. (See, for example, Davis, John, Alan Fusfeld, Eric Scriven, and Gary Tritle, "Determining a Project's Probability of Success," *Research and Technology Management,* Industrial Research Institute, Washington, D.C., May–June 2001, p. 51.) The values are normalized by using the same scales when assigning the values for different factors or options.

[4]See Hartmann, George C., and Andras I. Lakatos, "Assessing Technology Risk: A Case Study," *Journal of Research Technology Management*, April–May 1998, p. 32; and Levin, R., A. Klevorick, R. Nelson, and S. Winter, "Appropriating the Returns from Industrial Research and Development," *Brookings Papers on Economic Activity,* No. 3, pp. 783–831.

[5]Hartmann, George C., and Mark B. Myers, "Technical Risk, Product Specifications, and Market Risk," in *Managing Technical Risk: Understanding Private Sector Decision Making on Early Stage Technology-Based Projects*, NIST GCR 00-787, National Institute of Standards and Technology, Gaithersburg, Md., April 2000, p. 64.

[6]These quantitative approaches have been widely applied to maximizing trade-offs among several objectives when deciding on which materials to employ in a process or in developing a product. (Field, F. R., and R. de Neuville, "Materials Selection—Maximizing Overall Utility," *Metals Matter,* Vol. 4, No. 6, 1998; and Roth, R., F. Field, and J. Clark, "Materials Selection and Multi-Attribute Utility Analysis," *Journal of Computer-Aided Matter Design,* ESCOM Science Publishers, Leiden, The Netherlands, Vol. 1., No. 3, October 1994, p. 325.)

parent and not nearly as labor intensive. It explicitly incorporates estimates of the uncertainties associated with both a technology (e.g., the uncertainty associated with the feasibility of a material achieving a certain property level) and the R&D process (e.g., the uncertainty of success in converting a candidate material into a desired product). This decision framework uses normalized expected values based on expert judgments in a straightforward process that avoids extensive computation.

When a MIRC identifies an opportunity for application of advanced materials in an energy- or waste-intensive industrial process, two questions must be answered about MPR to assess the value of the R&D:

1. **What is the industrial process benefit?** That is, what is the potential benefit in energy and waste savings and/or increased productivity that can be generated by improving the materials used in the process?
2. **What is the probability of successfully identifying the needed materials improvements through MPR?** That is, what is the likelihood of identifying the materials properties in the industrial process that result in the current behaviors and defining the desired materials properties that will achieve the desired process performance for a particular benefit or benefits?

When the MIRC already includes a definition of the desired materials properties and CMR can be conducted, three questions must be answered about the CMR to assess the value of the R&D:

1. **What is the industrial process benefit?** That is, what is the potential benefit in energy and waste savings and/or increased productivity that can be generated by improving the materials used in the process?
2. **What is the potential of the candidate material?** That is, what is the candidate material's potential of achieving the desired property levels that would result in energy or waste savings and productivity improvements? (Achieving materials properties that are a fraction [e.g., 50 percent] of the desired materials properties may yield sufficient benefit to warrant conducting the R&D.)
3. **What is the probability of achieving improved process materials through CMR?** That is, what is the likelihood of the R&D process enabling a candidate material to achieve the desired materials properties and then retain those properties throughout the process of materials production and fabrication of a replacement component?

Our decision framework uses the anticipated benefits in energy savings, waste savings, and increased productivity and resulting probabilities to compute an *expected value* for each R&D option. The expected value represents a normalized measure of the benefits of each MIRC and can be used to compare R&D opportunities for each MIRC.

ILLUSTRATING HOW THE IMF R&D DECISION FRAMEWORK IS USED

Figure 3.1 illustrates an IMF R&D "decision tree." All numbers are purely hypothetical and do not reflect actual MIRCs, MPR, or CMR. The dollar figures under the Benefit column are the dollar amounts that addressing each MIRC would generate if the full suite of desired materials properties is achieved. The numbers under the Potential column are estimates of the potential of the candidate material upon which the CMR will be performed to achieve the desired materials properties (i.e., property limits of the material). The numbers under the Probability of Success column are estimates of the probabilities of success for MPR on a specific MIRC or CMR on a specific candidate material. (Note that MIRC 1 and MIRC *n* require MPR, whereas MIRC 2 can be addressed with CMR. Potential does not apply to MIRCs that require MPR. Note also that the MIRC 2 CMR for Candidate Material A and Candidate Material B have different potentials and probabilities of success, reflecting their differing likelihoods of reaching the desired suite of properties yielding the $50 million annual benefit.)

An expected value is computed for each MIRC from the numbers in the decision tree using the procedure described in the next section. The MIRCs with the highest expected values identify those R&D opportunities that have the greatest likelihood of leading to significant benefits. In Figure 3.1, for example, of the R&D done on the three MIRCs, the MPR on MIRC 1 has the highest expected value. Note that of the two CMR expected value paths for MIRC 2, only the path with the highest expected value—CMR on Material B—is ranked.

The computation of the expected value for each MIRC is based on the type of R&D required. Computation of expected value is based upon MPR for MIRCs that identify opportunities for improving energy- and/or waste-intensive industrial processes. This expected value is based on the probability of successfully understanding the behavior of the materials in a process well enough to define the desired materials properties and the potential benefit that would result. Computation of expected value is based upon CMR for MIRCs with desired materials properties. This expected value is based on the probability of successfully developing, producing, and fabricating a new or improved existing material and the potential benefit that would result. Computation of expected values is described in more detail in the next section.

Computing Expected Values for MPR

The computation of the expected value of a MIRC that requires MPR is based on the potential benefit from energy savings, waste reduction, and productivity improvement, and the probability of success of conducting MPR with worthwhile outcomes:

Expected value (MPR) = Benefit *x* Probability of success in conducting MPR

where *Benefit* is defined as the sum of the energy savings, waste reduction, and productivity improvement in an industrial process, and *Probability of success in conducting MPR* is a value between 0 and 1, where zero reflects no probability of success and

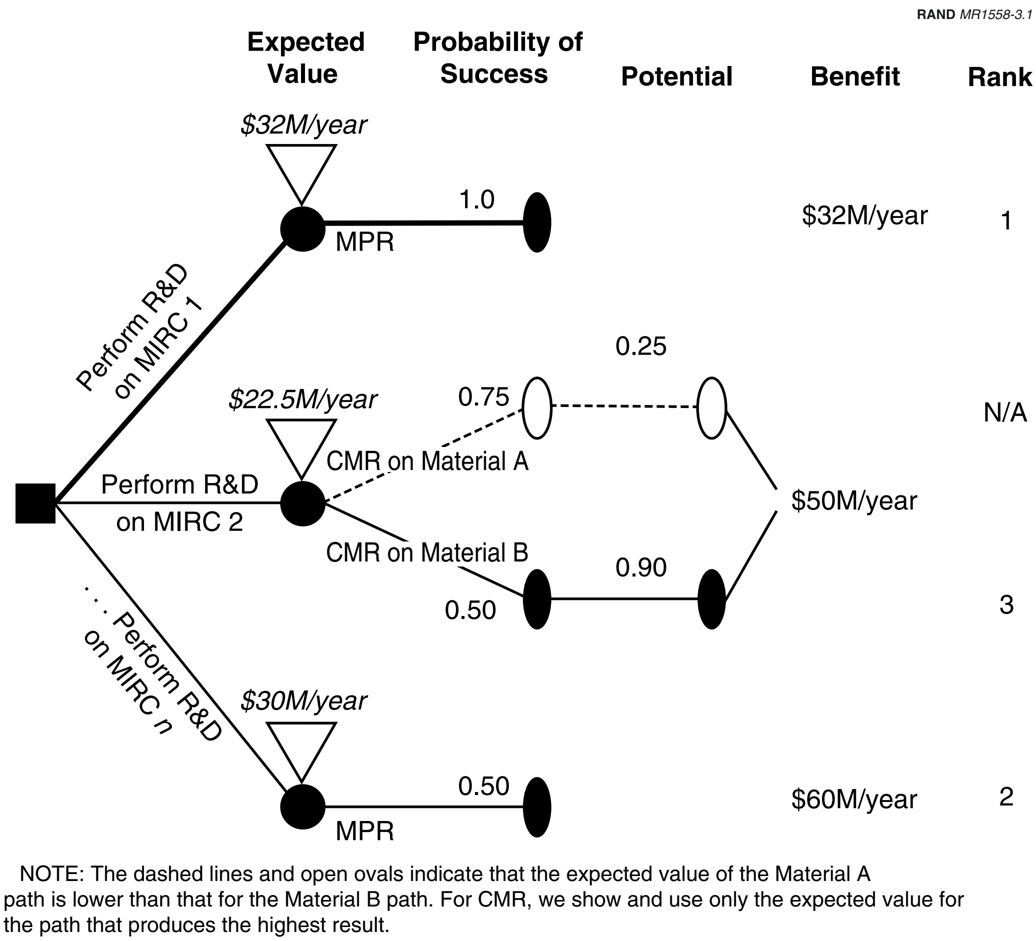

Figure 3.1—IMF Decision Tree

one reflects certainty of success in defining desired materials properties to achieve the benefit.

No estimate of the availability of candidate materials is included in this equation. Based on our experience and the technical literature, the probability of the existence of a candidate material that is producible and that can be fabricated is very high (i.e., approaching 1.0). If this is not the case in a specific application of this framework, the expected value should be multiplied by an additional factor between zero and one to reflect a less-than-certain likelihood of finding a candidate material upon which CMR can be performed to achieve the estimated benefits.

Determining the MPR Benefit. The benefit for each MIRC requiring MPR is determined from estimates of the energy savings, waste reductions, and productivity improvements that are achievable by using materials with improved properties in IOF applications. These estimates are updated annually by the OIT for a selected group of

MIRCs as part of its compliance with the Government Performance and Results Act (GPRA) of 1993.[7]

The OIT uses a formal process that was designed around a standardized spreadsheet to compute the impact of its research projects and programs.[8] Inputs to the spreadsheet include the definition of an industrial unit and estimates of the per-unit energy use and levels of environmental emissions with and without the new technology (in this case, the materials with improved properties). Modeling the market penetration of the new technology is based on a projected year of introduction and selection of one of several penetration-rate curves. Ultimately, the spreadsheet provides annual and cumulative energy savings, waste reductions, and productivity improvements resulting from the use of the improved materials. We adopt these OIT estimates done in compliance with the GPRA as the benefits for each MIRC we investigated. These benefits are normalized by using a consistent set of inputs (e.g., FY2003 GPRA inputs) for all IMF expected-value computations. These GPRA estimates may differ from the benefits actually achieved, but they do represent a consistent set of estimates that enables a comparison across similar units of measure (e.g., cumulative British thermal units [Btu] or dollars saved in 2020) of the benefits of alternative IMF R&D activities.

Probability of Success of MPR. The probability of success of MPR is an indicator of the likelihood that the research results will lead to a sufficient understanding of the impact of materials on the industrial process, which in turn will enable the desired materials properties to be defined. For example, techniques may not be available to fully assess the dynamics of the materials in the industrial process, or there may be conclusive literature on a process or material indicating that opportunities for improvement are small or nonexistent.

The probability of understanding the effect of materials properties on the industrial process through MPR is expressed as a number between 0 and 1.0. A probability of 1.0 represents a certainty that the effect of materials properties on the industrial process will be understood well enough to define the desired materials properties, whereas a probability of 0 represents a certainty that the effect will *not* be understood well enough to define the desired materials properties.

Determining the probabilities of the various possible outcomes of MPR is based upon: (1) the availability of the necessary personnel, equipment, and techniques and the likelihood of having sufficient access to the industrial process to assess the service environment and the behavior of the current materials in that environment (e.g., the source and nature of materials degradation or failure); and (2) the availability and accuracy of methods to model or measure the properties of materials that have degraded or failed in the service environment, or the availability and accuracy of methods to model or simulate the effect that changes in materials properties have on

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[7]"GPRA 2002 Quality Metrics Methodology and Results: Office of Industrial Technologies," Energetics Incorporated, Columbia, Md., February 2001.

[8]The spreadsheet tool is available from the OIT (www.oit.doe.gov).

Table 3.1

Probability of Success of MPR Based on Various Outcomes

Outcomes	Probability of Success
Analysis and technical literature *demonstrate conclusively* that the impact of materials on energy savings, waste reduction, and productivity improvement in an industrial process *can be identified* using existing analysis techniques.	1.00
Analysis and technical literature *suggest* that the impact of materials on energy savings, waste reduction, and productivity improvement in an industrial process *can be identified* using existing analysis techniques.	0.75
Analysis and technical literature *are inconclusive* on whether the impact of materials on energy savings, waste reduction, and productivity improvement in an industrial process *can be identified* using existing analysis techniques.	0.50
Analysis and technical literature *suggest* that the impact of materials on energy savings, waste reduction, and productivity improvement in an industrial process *cannot be identified* using existing analysis techniques.	0.25
Analysis and technical literature *demonstrate conclusively* that the impact of materials on energy savings, waste reduction, and productivity improvement in an industrial process *cannot be identified* using existing analysis techniques.	0.00

process efficiency and yields. The assignment of probabilities of MPR being successful given various outcomes (using the anchored scale shown in Table 3.1) is based on data obtained from experts in industry, national laboratories, and other relevant organizations.[9]

Computing Expected Values for CMR

Computing the expected value of CMR to improve the properties of existing materials, or to develop new materials with desirable properties, is based on an estimate of the probability of achieving the desired properties and anticipated benefits, as in the following equation:

Expected value (CMR on Candidate Material) = Benefit *x* Potential of candidate material *x* Probability of success in conducting CMR

where *Benefit* is defined as the sum of the energy savings, waste reduction, and increased productivity in the process using the improved existing material or the new material,[10] *Potential of candidate material* is a measure of the limits of a material to satisfy all of the desired properties, and *Probability of success in conducting CMR* is the probability that CMR will lead to development of a material with the desired

[9] In using the anchored scale for probability of success of MPR, the assignment of 1.0 or 0.0 is not meant to indicate certainty at either end of the spectrum, but rather that according to the best estimates of experts or data in the literature, the necessary personnel, access to industrial facilities, equipment, and methods are or are not available to adequately define the desired materials properties.

[10] As noted previously, we use the IMF GPRA 2003 benefit estimates—specifically, cumulative benefits in the year 2020—with an assumed year of introduction and market penetration curves based on historical data for technologies with similar estimated payback times.

properties that can be produced in sufficient volume and quantities and fabricated into process components.[11]

The method for computing the expected value of CMR on candidate materials is illustrated by the decision tree in Figure 3.2. As with Figure 3.1, the numbers are purely notional. The decision tree includes options for CMR on existing materials and new materials. The industrial process will result in the benefit shown if the MIRC 2 target materials properties are achieved. The potential and probability of success of the two candidate materials to achieve the desired properties are different, leading to different expected values. In this case, only the candidate material with the highest expected value is considered for MIRC 2 R&D.[12]

Determining the Benefit of CMR on a Candidate Material. The benefit of CMR on a candidate material is the benefit derived from addressing the MIRC— i.e., the savings generated by reduced energy use, reduced waste, and improvements in productivity if the desired materials properties are achieved. These values are determined by the GPRA analysis of the industrial process (described earlier in the chapter in the discussion of determining the benefit of MPR).

Potential of Candidate Material to Satisfy Desired Properties. The potential of a candidate material to achieve the desired materials properties is used to scale the benefits that accrue from improving an industrial process. For example, a candidate material that is capable of achieving the desired properties under some well-defined set of conditions that approximate the industrial service environment is of greater

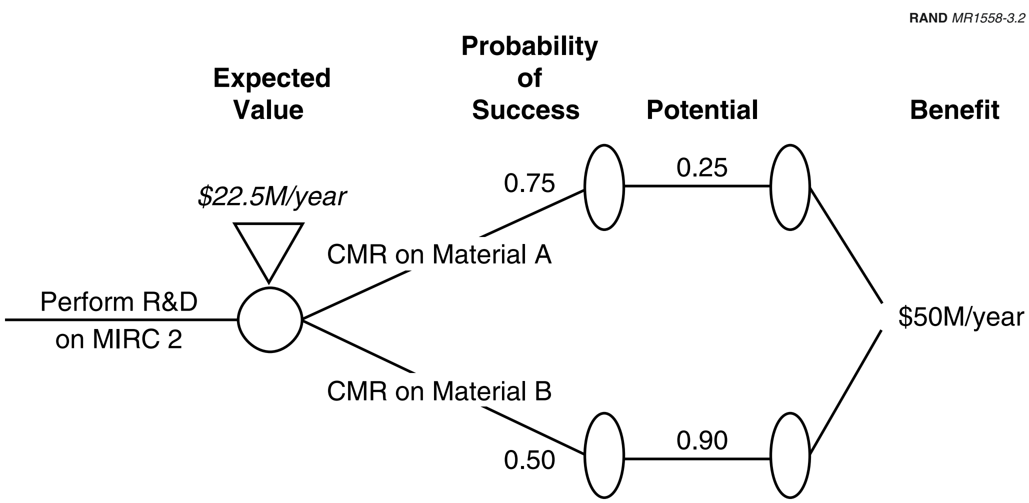

Figure 3.2—CMR Decision Tree

[11]This probability is a value between 0 and 1.0. Zero reflects certainty of failure; 1.0 reflects certainty of success.

[12]Given equal expected values for CMR on different candidate materials, public-sector R&D funding should be concentrated on candidate materials that have high potential or for which high potential may be demonstrated by R&D. R&D on candidate materials with low potential that leads to incremental advances in technology is properly the responsibility of industry to sponsor.

value than a candidate material that is capable of achieving the desired materials properties under limited or severely restricted conditions. The benefits of CMR on each of the candidate materials are scaled by the potential of the candidate material to exhibit the desired materials properties, using the anchored scale shown in Table 3.2.

Probability of Success of CMR. The probability of success of CMR describes the likelihood of developing an improved material that can be produced in the appropriate form and then fabricated (e.g., cast or forged, heat-treated, or welded) into a component for the target industrial process. For example, although a new material may be developed that demonstrates the ability to meet the desired materials properties, it may be unknown whether the material can be produced in large enough extrusions to facilitate fabrication of a replacement process component.

The probability of achieving the desired materials properties through CMR and eventually manufacturing the component for the target industrial process is designated by a number between 1.0 and 0.0 (see Table 3.3). A probability of 1.0 represents a certainty that the desired component can be achieved with the candidate material, whereas a probability of 0.0 represents certainty that the desired component will *not* be achieved with the candidate material.[13]

Table 3.2

Scaling Candidate Material Expected Benefits by a Measure of the Material's Potential for Achieving Desired Properties

Outcomes	Benefit *x* Potential
Experimental data and technical literature indicate that the desired materials properties *have been achieved* by the candidate material under *all necessary conditions.*	Total benefit *x* 1.00
Experimental data and technical literature indicate that the desired materials properties *have been partially achieved* by the candidate material under *all necessary conditions.*	Total benefit *x* 0.90
Experimental data and technical literature indicate that the desired materials properties *have been partially achieved* by the candidate material under *most conditions.*	Total benefit *x* 0.75
Experimental data and technical literature indicate that the desired materials properties *have been partially achieved* by the candidate material under *some conditions.*	Total benefit *x* 0.50
Experimental data and technical literature indicate that the desired materials properties *have been partially achieved* by the candidate material under *limited conditions.*	Total benefit *x* 0.25
Experimental data and technical literature indicate that the desired materials properties *have been partially achieved* by the candidate material under *severely restricted conditions.*	Total benefit *x* 0.10
Experimental data and technical literature indicate that the desired materials properties *cannot be achieved* under *any conditions.*	Total benefit *x* 0.00

[13]The expert technical judgments required to estimate the outcomes listed in Table 3.3 are made with some degree of uncertainty. Follow-on analysis or other future work may (or may not) eliminate some of this uncertainty. Consequently, in using the anchored scales shown in the table, as stated in Footnote 9, the assignment of 1.0 or 0.0 is not meant to indicate certainty at either end of the spectrum, but rather that according to the best estimates of experts or data in the literature, the capability does or does not exist to achieve the desired materials properties, produce the material, and fabricate the desired components.

Table 3.3

Probability of Success of CMR

Outcomes	Probability of Success
Experimental data and technical literature *demonstrate conclusively* that the desired suite of properties *can be achieved* and that the candidate material *can be produced and fabricated* into the desired components.	1.00
Experimental data and technical literature *suggest* that the desired suite of properties *can be achieved* and that the candidate material *can be produced and fabricated* into the desired components.	0.75
Experimental data and technical literature *are inconclusive* on whether the desired suite of properties *can be achieved* and the candidate material *can be produced and fabricated* into the desired components.	0.50
Experimental data and technical literature *suggest* that the desired suite of properties *cannot be achieved* or that the candidate material *cannot be produced and fabricated* into the desired components.	0.25
Experimental data and technical literature *demonstrate conclusively* that the desired suite of properties *cannot be achieved* or that the candidate material *cannot be produced and fabricated* into the desired components.	0.00

The probabilities of the various possible outcomes of CMR are based on the current body of knowledge and the latest results in the relevant areas of research. Gleaning these probabilities is possible through two fundamentally different approaches:

1. Performing a *detailed and structured review of the research data and literature*, and drawing conclusions from the data and literature concerning which alternative research pathways and activities are most likely to provide candidate materials with the desired properties, or

2. Contacting *a group of experts with enough technical knowledge* to encompass important research areas, and collecting and analyzing their views of the likelihood of the alternative research pathways and activities being successful in achieving the desired properties.[14]

For example, the first approach above was used to define research priorities for solar thermal and photovoltaic energy systems[15] and provides a framework for comparing and evaluating alternative CMR according to the following procedure:

1. Define the candidate materials types.

2. Define the stages of research on each candidate material, beginning with basic research to define specific properties and moving to successively more applied research to improve properties and develop suites of properties closer to the de-

[14]Various methods have been devised to collect and analyze expert opinions, including those in which experts interact with each other to varying degrees (i.e., variations of the Delphi method). For example, see: Linstone, H. A., and M. Turoff, *The Delphi Method: Techniques and Applications*, Reading, Mass.: Addison-Wesley, 1975; and Fitch, K., et al., *The RAND/UCLA Appropriateness User's Method*, Santa Monica, Calif.: RAND: MR-1269-DG-XII/RE, 2001. Note, however, that the use of a Delphi approach in the current context is somewhat unconventional in that the expert judgments are being made with a degree of uncertainty. See Footnote 13.

[15]Herzenberg, S. A., L. K. Hien, and R. Silberglitt, "Active Solar Energy System Materials Research Priorities," Solar Energy Research Institute (now NREL), Golden, Colo., SERI/STR-255-1782, January 1983; Bornstein, J. G., L. K. Hien, and R. Silberglitt, "Photovoltaic Cell Research Priorities," U.S. Department of Energy, Washington, D.C., DOE/ER/30029-T2, December 1983.

sired suite of properties, and then test the properties in the service environment, first in the laboratory, then at the bench scale, and finally in industrial prototypes.

3. Make an array of alternative research activities at each stage of the research for each candidate material. Such an array has the appearance of a matrix that allows the exploration of alternative research paths from basic research to industrial application for each candidate material and was called a Technological Innovation Matrix (TIM) by the authors of both reports cited in Footnote 15.
4. For each element in the TIM, collect data and literature to determine the element's relative importance in achieving the desired suite of properties and the difficulty of the technical challenges that must be overcome. This step allows estimation of the probability of outcomes based on specific technical accomplishments and research pathways, as gleaned from the literature.

In practice, the two R&D assessment approaches listed earlier in this section are used in combination with one another. The OIT industry teams and the national laboratory researchers who work with the OIT program managers effectively form a group of experts. The industry teams provide quantitative, semiquantitative, and qualitative data and analyses of desired properties needs, and the national laboratory researchers provide the same data and analyses concerning the current status and probable improvements of candidate materials properties. The OIT program managers and their supporting contractors essentially provide the structured research reviews using the data provided by the expert group. This process supplies a means for applying the decision framework we describe in this report at a reasonable cost.

Comparing Expected Values of MPR and CMR for Each MIRC

The R&D activity with the highest expected value is identified by using the benefit, potential, and probability of success values for each MIRC (see Tables 3.1 through 3.3).

For MIRCs that require MPR, the expected value of the R&D is the potential benefit multiplied by the likelihood of successfully identifying the impact of the materials on the process and defining the desired materials properties.

For MIRCs that require CMR, the expected value of the R&D is the largest expected value among each of the candidate materials. The expected value for each of the materials is calculated by multiplying the benefit of the improvement in the industrial process that is estimated if materials with the desired properties are available *times* the potential of the candidate material to achieve the desired materials properties *times* the likelihood of developing and producing the new material and eventually being able to fabricate a new component using the candidate material.

EXAMINING A DECISIONMAKING TOOL FOR PRIORITIZING R&D ACTIVITIES

The computation of the expected value of R&D activities, although straightforward, involves the development and manipulation of data for multiple MIRCs, MPR, and

CMR. To enable the decisionmaker to focus on the benefits, potential, and probability of success of R&D activities, a tool was constructed by RAND to serve as a decisionmaking aid that simplifies the computation of the expected value for multiple MIRCs, MPR, and CMR (see Table 3.4). Briefly, the tool can be used as follows: After the appropriate numbers are entered in the cells under the Benefit ($M), Potential, and Probability of Success columns, the Expected Values for MPR and CMR on each MIRC are automatically computed. The ranking of each MIRC, according to its expected value, is also automatically generated. In the remainder of this section, we explain the significance of each entry in Table 3.4 in more depth. For illustrative purposes, we use the actual case study examples from Chapter Two on kraft recovery boilers and intermetallic alloys (MIRC 1 and MIRC 3 from Table 2.1).

Each row in Table 3.4 represents one MIRC. Columns 1 and 2 identify the MIRC number and describe the nature of the MIRC. Column 3 is automatically computed by the tool and identifies the ranking of the MIRC given the Benefit, Potential (if applicable), and Probability of Success.

Column 4 notes whether the type of R&D is MPR or CMR.

Column 5 describes the current process and materials needs that define the MIRC. For a MIRC that does not have a definition of the materials properties and therefore requires MPR, the need is stated as the failure condition or a problem that offers the opportunity for process improvement (see MIRC 1 in Table 3.4). For a MIRC with desired materials properties already defined, the need is stated as the required change in materials properties (see MIRC 3 in the table).

Column 6 describes the cause of the needed change in the process or materials properties and is defined for each of the candidate materials. The needed change may be stated as the failure mechanism for MPR or the reason for the current materials properties.

Column 7 shows the expected values for each MIRC based on the entries for the Benefit (Column 8), Potential (Column 9), and Probability of Success of the R&D (Column 10). In the case of MIRCs that require CMR, expected values are computed for each of the candidate materials.

As shown in the table, the expected dollar value of energy savings and productivity improvements for CMR on high-temperature materials (intermetallic alloys) is $414 million a year, and for MPR on kraft recovery boilers the expected value is $130 million a year. (As noted in Chapter Two, the cost of conducting R&D was approximately $40 million for the CMR on intermetallic alloys and approximately $6 million for the MPR on kraft recovery boilers.)

The following sections describe the rationale for the entries in Table 3.4 that led to the MIRC rankings.

Table 3.4

Decisionmaking Tool for Prioritizing R&D Activities

1. MIRC Number (see Table 2.1)	2. MIRC Description	3. MIRC Ranking	4. R&D Type (MPR or CMR)	5. Process/ Materials Properties Needs	6. Cause of Necessary Change in Process or Materials Properties	7. Expected Value	8. Benefit ($M)	9. Potential	10. Probability of Success
1	Kraft recovery boilers shut down production	2	MPR	Cracking in recovery boilers	Cracking due to poor match in thermal expansion coefficients between inner and outer layers	130	130	N/A[b]	1
3	High-temperature materials	N/A[a]	CMR	Increase yield strength by 600 MPa at 600°C; maintain ductility at 15 percent	Steel alloys: intergranular fracture due to thermally induced embrittlement	115	920	0.25	0.5
3	High-temperature materials	1	CMR	Maintain yield strength above 800 MPa at 600°C; increase ductility to 15 percent	Intermetallic alloys: loss of ductility at intermediate temperatures due to oxygen-induced degradation	414	920	0.9	0.5

[a]CMR on steel alloys is not ranked because it has a lower expected value than CMR on intermetallic alloys and both of them address MIRC 3.
[b]Potential does not apply to MPR.

Rationale for the Data Input for MIRC 3, High-Temperature Materials (CMR R&D)

Benefit ($). The following benefit from application of the intermetallic alloys was estimated by IMF for the OIT FY2003 GPRA analysis (figures are estimated for the year 2020 based on unit savings and market penetration analysis):[16]

- Nickel aluminide heat-treating fixtures: energy savings of 30 trillion Btu per year (dollar savings of $100 million a year) plus productivity improvements adding up to a dollar savings of $450 million a year
- Nickel aluminide transfer rolls for steel furnaces: energy savings of 7 trillion Btu per year (dollar savings of $30 million a year)
- Iron aluminide and other advanced alloy tubes for ethylene production furnaces: energy savings of 80 trillion Btu per year (dollar savings of $60 million a year) plus productivity improvements adding up to a dollar savings of $280 million a year.

The total benefit for these three applications was estimated to be $920 million a year in 2020.

Type of R&D: CMR. Property requirements to achieve the stated benefits were defined as increased yield strength to 800 MPa at 600°C while maintaining ductility at 15 percent elongation.

Candidate Materials. Two candidate materials were investigated. Current steel alloys exhibit a yield strength of 200 MPa with good ductility (i.e., 15 percent elongation) at 600°C. As already noted, the desired materials properties to achieve the benefits are a yield strength of 800 MPa with 15 percent elongation at 600°C. Improvement of steel alloys requires overcoming intergranular fracture due to thermally induced embrittlement.

Another option is to develop new intermetallic materials to achieve the desired properties. Intermetallic alloys exhibit yield strength of 830 MPa at 600°C. However, they also have reduced ductility at 300°C. Research identified moisture-induced embrittlement and dynamic oxygen-induced degradation as the cause of the loss of ductility, and known techniques such as microalloying with boron and carbon and solid-solution strengthening and dispersion strengthening were feasible approaches to raise the observed ductility minimum up to higher temperatures.

Potential. Based upon the properties of existing and developmental steel alloys, it is unlikely that research on this candidate material would produce the Factor 4 increase in high-temperature strength required to match the desired materials properties. However, steel alloys do exist that have the desired properties but they exhibit those properties when used at much lower temperatures; therefore, this option would correspond to the outcome *limited conditions* because high-temperature

[16]Mortensen, John, *Industrial Materials for the Future (IMF) FY2003 GPRA Benefits and Performance Measurement Analysis*, prepared for the IMF Program and National Renewable Energy Laboratory, Washington, D.C., February 2002.

performance is critical to achieving the anticipated benefits. Thus, according to Table 3.2, the benefit is scaled by 0.25 given the steel alloy potential.

The intermetallic alloys achieved the desired high-temperature yield strength or *partially achieved* the desired properties under *all necessary conditions*. Therefore, according to Table 3.2, the benefit is scaled by 0.90 given the intermetallic alloy potential.

Probability of Success of CMR. No data exist that explicitly demonstrate that the desired increase in yield strength cannot be achieved, and a wide variety of steel alloys have been produced and fabricated into components. Thus, the experimental data and technical literature are *inconclusive*. According to Table 3.3, we assigned 0.50 as the probability of success of CMR on this candidate material.

However, knowledge of the mechanism by which the ductility was reduced and the existence of techniques to increase the ductility *suggest* that the ductility at 600°C can be increased. But no manufacturers have experience with producing these alloys or fabricating components from them; therefore, casting and welding methods, for example, need to be developed. Thus, we consider the data on producibility and fabricability to be *inconclusive*. According to Table 3.3, we assign 0.50 as the probability of success of CMR on this candidate material.

Expected Value. The expected value of CMR on the steel alloy was computed to be $115 million a year, roughly 12 percent of the estimated total $920 million a year benefit, reflecting only a 50 percent likelihood of achieving 25 percent of the desired materials properties.

The expected value of CMR on the intermetallic alloys was $414 million a year, 45 percent of the estimated total benefit, reflecting an estimate of achieving 90 percent of the desired materials properties and a 50 percent probability of success.

Comparison of these expected values indicates that R&D on intermetallic alloys is a more attractive option than R&D on steel alloys because it has the potential to yield significant improvements in performance and has a significant likelihood of successfully accomplishing the necessary R&D. The steel alloy R&D would be expected to yield only incremental improvements in yield strength, which is reflected in its limited potential and ultimately its smaller expected value.

Rationale for the Data Input for MIRC 1, Kraft Recovery Boilers (MPR R&D)

Benefit. The IMF FY2003 GPRA analysis, based on input from forest products industry experts, estimated that the productivity improvements resulting from reduced downtime of kraft recovery boilers, if tubes with a longer lifetime were available, would produce 25 trillion Btu per year of energy savings in 2020. These estimates assumed that the recovery boiler tubes would not need to be serviced beyond a scheduled annual maintenance shutdown. The benefit due to productivity improvements, specifically the savings from less-frequent shutdowns and lower tube replacement costs, is $130 million a year.

Type of R&D: MPR. The cause of the boiler tube failures was not known, so the desired materials properties could not be determined. This MIRC is, therefore, a candidate for MPR rather than CMR.

Probability of Success of MPR. Literature reviews and expert analysis determined that the cause of the cracking in the boilers could be identified. The probability of success of MPR for the kraft recovery boilers was very high. Companies within the forest products industry agreed to provide access to the recovery boilers in their plants during shutdowns for routine maintenance or shutdowns due to failures. Materials scientists and engineers at Oak Ridge National Laboratory were available to inspect the failed tubes on site. These scientists and engineers also had access to the necessary facilities to evaluate the tubes off site and had appropriate computational facilities and simulation models to model the properties of the tube materials. The fact that this group had successfully accomplished this type of research many times before added to the probability of success of the R&D. Thus, according to Table 3.1, we assigned a probability of success of 1.0 to this MPR.

Expected Value. The expected value of MPR on the kraft recovery boilers was computed to be $130 million a year, reflecting the high probability of success of achieving the full benefit. The expected value ranks this R&D option below the option for CMR on intermetallic alloys; therefore, MIRC 3 (high-temperature materials R&D) is ranked above MIRC 1 (kraft recovery boilers R&D) in Table 3.4.

PRACTICAL USE OF THE FRAMEWORK

As we noted in Chapter One, the principal benefit of this method of analysis is not so much a precise ranking of various R&D projects, but rather a procedure for setting R&D priorities that is transparent (i.e., follows a clear and logical process) and well documented, and incorporates expert judgment. It may be useful to periodically revisit and monitor the values that are assigned to R&D programs as new findings are reported in the literature and a greater understanding of materials and industrial processes is achieved. For example, rankings may change when new research results extend the region of applicability of a material or new MPR results better define the desired materials properties for a high-benefit MIRC.

Chapter Four

DECISION FRAMEWORK CONTEXT, APPLICATIONS, AND EXTENSIONS

In this chapter, we provide a context for the decision framework by comparing it with traditional economic and utility methods used to assess the value of R&D. We then go on to describe application of the framework and extensions of its use.

COMPARING THE FRAMEWORK WITH OTHER R&D ASSESSMENT APPROACHES

The decision framework we describe in this report derives the expected value of an R&D activity by using quantitative estimates of a benefit together with subjective estimates of the activity's potential (which scales the benefit estimate) and the activity's probability of success. Many traditional economic measures assess the value of activities in terms of their investment costs and expected cash returns, given a value for the cost of capital. Typical cost-benefit measures include net present value (NPV), internal rate of return (IRR), and cost-benefit ratio (CBR), which are defined as:

$$\text{NPV} = \sum_{i=0}^{N} (\text{return}_i - \text{cost}_i) \; / \; (1 + \text{cost of capital})^i$$

$$\text{IRR} = \text{Cost of capital such that } \sum_{i=0}^{N} (\text{return}_i - \text{cost}_i) \; / \; (1 + \text{cost of capital})^i = 0$$

$$\text{CBR} = [\sum_{i=0}^{N} (\text{cost}_i) \; / \; (1 + \text{cost of capital})^i] \; / \; [\sum_{i=0}^{N} (\text{return}_i) \; / \; (1 + \text{cost of capital})^i]$$

NPV reflects the amount one should be willing to pay at the present time for benefits received in the future, discounted by the cost of capital invested now. *IRR*—the value of the cost of capital if the NPV is set to zero—enables comparisons of alternatives by forcing NPV in each investment to be equal to zero. *CBR* reflects the discounted cash outflows divided by the discounted cash inflows. (The typical estimated ten-year return on investment for IMF-funded programs is far in excess of the typical cost of $300,000 per year over five years.)

When the returns of an activity cannot be easily translated into economic terms, multiattribute utility models provide a means for dealing with the situation. In this type of decisionmaking approach, noneconomic costs and returns are transformed into common utility scales, according to the following functional relationship:[1]

$$U(\text{costs, returns}) = U[u(\text{cost}_1), u(\text{cost}_2), \ldots u(\text{cost}_n), u(\text{return}_1), u(\text{return}_2), \ldots u(\text{return}_n)]$$

Unfortunately, models based on a utility theory such as this do not accurately reflect human decisionmaking. The most critical problem is that the expectations held by decisionmakers bias the outcomes. Subjective expected utility (SEU) theory was developed to take these biases into account. In this approach, the biases of the stakeholders are incorporated into a group utility model using the following functional relationship:[2]

$$U = U\{U[u(\text{cost}_1, \text{return}_1), u(\text{cost}_2, \text{return}_2), \ldots u(\text{cost}_n, \text{return}_n)]\}$$

Use of SEU theory requires the formulation of mappings of attributes to utilities in order to ensure a standardized comparison, in addition to identifying the attributes and their range of values. Well-developed procedures exist for identifying parameters and forecasting levels of attributes. Sensitivity analysis is also commonly employed to assess the impact of uncertainties.[3]

The R&D decision framework described in this report incorporates aspects of both the economic assessment methods and the utility theory approaches and was designed to use parameters that are specific to its domain of application. The benefit value is derived from the IMF project benefits that are estimated using standard benefit analysis techniques. The introduction of uncertainty associated with the potential of reaching desired materials properties and the probability of success of the R&D is akin to the estimation of the standardized utility in the SEU approach.

We should note that many R&D investment decisions are not simply one-time actions but rather are designed to pursue a particular technology-evaluation path. The expectation is that the project or program, and the decision that is made regarding the pursuit of that project or program, will be reviewed and revisited at a later date as more information concerning the technological characteristics (i.e., the *potential*) and the progress of the research (e.g., as it affects the *probability of success*) becomes available. In this sense, the *expected value* that is computed using the RAND decision framework could more properly be called a *prospective value*, since it is an estimate based on the best current knowledge of what we anticipate the ultimate value of the project will be. Viewed in this manner, the decision to fund a particular project is a decision to "purchase" a real option—that is, an opportunity to gather additional information that will allow a more informed decision at a later date. The benefit of this approach is that it provides a vehicle to identify those options that would not be

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[1]Keeney, Ralph L., and Howard Raiffa, *Decisions with Multiple Objectives: Preferences and Value Tradeoffs,* New York: Cambridge University Press, 1993.

[2]Keeney and Raiffa, 1993.

[3]Keeney and Raiffa, 1993.

pursued based on the current state of the technology, but that may have much greater value after the research to obtain the expected value has been pursued.[4]

APPLYING THE FRAMEWORK: IDENTIFICATION OF PROGRAM PRIORITIES

As we stated earlier, the decision framework described in this report provides a quantifiable and auditable approach to determining priorities for funding IMF R&D. The framework is based on a model of the way in which R&D is typically conducted, while taking into account the different types of R&D under consideration by the IMF program. The stated value for each R&D option is based on estimates of the benefit of the R&D if the desired materials properties are achieved and on estimates of the probabilities of success of achieving those benefits with the candidate materials. The framework, therefore, provides a structured method for determining the relative value of MPR or CMR on each MIRC and provides a relative ranking of MIRCs in terms of the likely benefit that accrues from the R&D aimed at achieving IOF performance targets.

The IMF program identifies new R&D projects through a solicitation process that explicitly requires that proposals include information on the benefits of the proposed R&D. The solicitation process also calls for a description of the current technical status of the area to be researched and the barriers to overcome in accomplishing the research. The response to these proposal requirements provides input that can be used in estimating the parameters needed to compute the expected values that are the basis of the decision framework. Using their expert judgment together with the anchored scales presented in the tables in Chapter Three, the proposal evaluators can then assign values for the potential of the candidate material to achieve the anticipated benefits and the R&D's probability of success. The decisionmaking tool can then be used to rank proposals according to the expected value of the proposed R&D.

However, rather than just ranking the proposals according to their expected value, we recommend also plotting the evaluation data on a graph such as the one shown in Figure 4.1. *Benefit* times *Potential* is plotted along the y axis and *Probability of Success* is plotted along the x axis. The constant expected value (EV) curves in the graph (marked EV_1, EV_2, and EV_3) are hyperbolas with their expected value increasing along the line $y = x$. As shown in the figure, R&D projects can then be classified according to their ratio of risk (as measured by probability of success) to potential return (as measured by the product of benefit and potential), in addition to their expected value. This method provides a means for distinguishing projects that promise only incremental advances (typically those with a high probability of success but only low to moderate benefits) from those with the potential to change the technological baseline (typically those with a low to moderate probability of success but high benefits). As indicated in the figure, the most desirable region is that with a high scaled benefit and high probability of success.

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[4]The authors are indebted to Steven Popper for elucidating the points made in this paragraph.

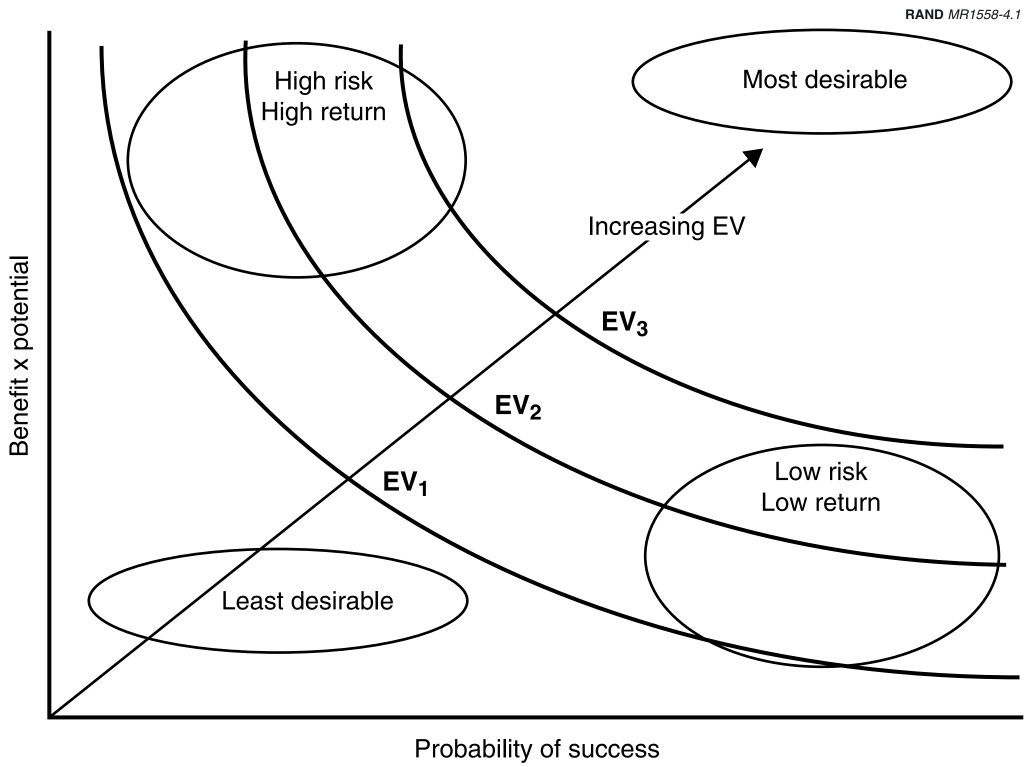

Figure 4.1—Representation of Decision Framework Data: Plotting of Scaled Benefit Versus Probability of Success

APPLYING THE FRAMEWORK: COLLECTION AND ANALYSIS OF DATA

Identification of the data needed to evaluate MIRC expected values is another important application of the decision framework. For many MIRCs with a large potential benefit, the critical tasks in determining the R&D to pursue in order to achieve that large benefit are the collection and analysis of data on industrial processes and on existing and new materials that have the potential for energy and waste reduction and productivity improvements. In some cases, the necessary data may not be available and an R&D activity will be required to obtain those data. An R&D activity such as this may include development or application of theory on, computer simulation of, and/or experiments on materials performance in real or simulated industrial environments. Another R&D activity along these lines is the development of a database on the relationships among microstructure, processing, and properties of candidate materials. Use of the decision framework will identify those situations in which pursuing this type of R&D (see the description of MPR in Chapter Three) has a high expected value.

FURTHER EXTENSIONS OF THE DECISION FRAMEWORK

A number of opportunities exist to extend the decisionmaking framework. For example, in this report we use a scaled measure of uncertainty that reflects only the average (mean) without taking into account the distribution of probability. One way to extend the framework would be to apply probability distributions to reflect the decreasing likelihood of a particular outcome from one to zero. For example, if experts do not agree on the probability of success of a CMR activity, the distribution would reflect this divergent opinion, yet will weight any type of consensus as the average. Figure 4.2 illustrates how Figure 4.1 would look if a group of hypothetical projects were plotted including their probability distributions.

A topic we did not explicitly address in this report is accounting for the costs of conducting the R&D or the costs of producing and fabricating a new material. First, the benefits far outweigh the costs for a given project. Using an example from Chapter Three, MIRC benefits for the intermetallic alloy R&D were estimated at $414 million per year, while the costs of R&D were less than $1 million per year. Second, the estimation of the probability of success includes the anticipated difficulty in overcoming technical barriers to production and fabrication, which can be translated into time and money. Considering the relative size of the IMF budget (slightly greater than $10 million a year) and the anticipated benefits, this approach may turn out to be a reasonable one.

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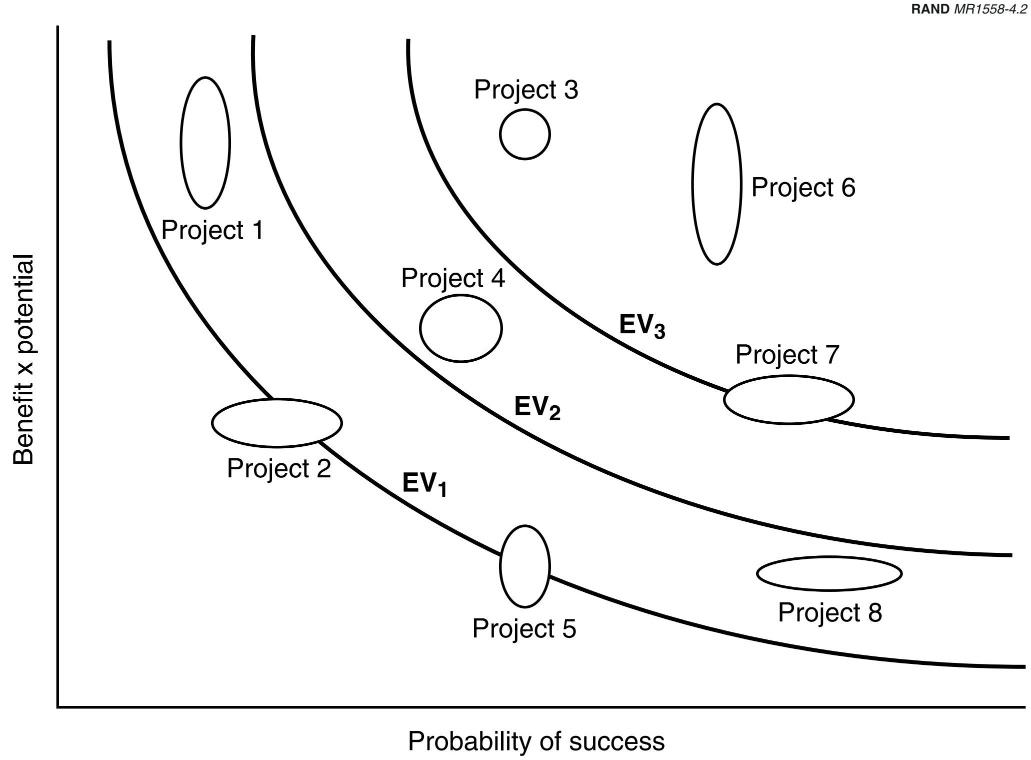

Figure 4.2—Representation of Decision Framework Data: Plotting of Scaled Benefit Versus Probability of Success for a Group of Projects Including Probability Distributions

Incorporating uncertainty is a key element of the decision framework. The R&D probabilities of success are determined on the basis of expert opinion and through evaluation of the technical literature. Traditional decision theory would use historic data to determine these probabilities. One area for future work is the gathering of historic data on similar R&D activities to quantify (or validate) these probabilities of success. Using such data, one might envision application of this framework to the other programs that cross-cut the OIT (see Chapter One) or to support the IOF industry teams.

The Internet offers other potential opportunities for expanded use of the decision framework. Smart search engines could be used to scour the Web to identify research in specific areas. (This search would be limited to journals and other scientific publications.) The Internet also could be used to conduct asynchronous and remote delphi tests (with participants providing input at different times and locations). Input to the delphi process could be submitted over the Web, instead of during a face-to-face meeting, so test participants would not be limited solely to those who are available to participate in person.

Chapter Five

CONCLUSIONS AND RECOMMENDATIONS

This report addresses the problem of allocating scarce R&D resources from the perspective of the DOE's Office of Industrial Technologies. In particular, the report addresses the challenge faced by the Industrial Materials for the Future program in allocating R&D resources to provide benefits across multiple industries. To attack this problem, RAND developed a decision framework that takes into account the special characteristics of the OIT and the IMF, most notably their need to address various multiple-industry research challenges. These MIRCs are identified by industry teams as being key to reducing energy use and waste production and to increasing productivity in the nine energy- and waste-intensive Industries of the Future.

The RAND decision framework uses quantitative estimates of benefits and expert judgments, based upon technical data and the technical literature, to compute an expected value for R&D activities in a manner that is transparent, auditable, and straightforward. That value is the product of three factors: (1) the resulting benefit if desired materials properties are achieved, (2) the potential of candidate materials to achieve those properties, and (3) the probability of success of the R&D achieving the desired properties in a material that can be produced and fabricated into replacement components for an industrial process. We conclude that this expected value provides a useful basis for comparing and ranking R&D activities aimed at addressing multiple-industry research challenges. It provides an alternative to the traditional sum of weighted criteria used to evaluate R&D programs. By multiplying a quantitative estimate of potential benefits by the probability of success of the R&D, managers ensure that opportunities with large benefits are not overlooked in favor of R&D with high probabilities of success but only incremental benefits.

We also conclude that the principal benefit of this method of analysis is not so much a precise ranking of various R&D projects, but rather a procedure for setting R&D priorities that is transparent (i.e., follows a clear and logical process), well documented, and incorporates expert judgment. It may be useful to periodically revisit and monitor the values that are assigned to R&D programs as new findings are reported in the literature and as a greater understanding of materials and industrial processes is achieved. For example, rankings may change when new research results extend the region of applicability of a material or new MPR results better define the desired materials properties for a high-benefit MIRC.

We recommend that this decision framework be used to evaluate proposed R&D when a project portfolio is being developed, and that it be used to identify and evaluate data that are necessary to both address the various MIRCs and identify the R&D needed to acquire those data. We recommend extending the framework to incorporate probability distributions to reflect the decreasing likelihood of a particular outcome (for example, if experts do not agree on the probability of success of an activity, we would indicate this difference of opinion as a distribution). We also recommend extending its application to other OIT programs and using it to reevaluate programs at a later date as the R&D activities progress.

Finally, we propose that the decision framework be applied to other R&D programs by quantifying benefits using similar units of measure based on the achievement of desired technological characteristics. Using anchored scales akin to those in Tables 3.1 through 3.3 of this report, the framework could then be used to estimate the potential of candidate technologies to achieve those desired characteristics and to estimate the probability of success of the proposed R&D. Expected values computed from the benefit, potential, and probability of success estimates could then be used in determining program priorities.