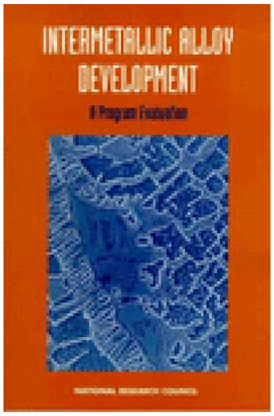

Intermetallic Alloy Development: A Program Evaluation

Panel on Intermetallic Alloy Development, Commission on Engineering and Technical Systems, National Research Council

ISBN: 0-309-52438-5, 68 pages, 6 x 9, (1997)

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INTERMETALLIC ALLOY DEVELOPMENT

A Program Evaluation

Panel on Intermetallic Alloy Development
Committee on Industrial Technology Assessments
National Materials Advisory Board
Commission on Engineering and Technical Systems
National Research Council

Publication NMAB-487-1
NATIONAL ACADEMY PRESS
Washington, D.C. 1997

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This report has been reviewed by a group other than the authors according to procedures approved by a Report Review Committee consisting of members of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine.

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This study by the National Materials Advisory Board was conducted under Grant No.DE-FG41-95R110859 with the U.S. Department of Energy. Any opinions, findings, conclusions, or recommendations expressed in this publication are those of the author(s) and do not necessarily reflect the view of the organizations or agencies that provided support for the project.

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Cover: Scanning electron micrograph of a grain boundary in a weld of Ni_3Al alloy. The two-phased, $\gamma+\gamma'$, microstructure of the matrix is apparent. A particle of Ni-Ni_5Zr eutectic is located on the grain boundary. Courtesy of Oak Ridge National Laboratory.

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Acknowledgments

The hospitality of the employees of Martin Marietta Energy Systems at Oak Ridge National Laboratories during the panel's site visit and their time and effort in meetings and presentations are greatly appreciated. Individuals who prepared presentations or conducted laboratory tours include Bill Appleton, Jim Stiegler, Linda Horton, C. T. Liu, Vinod Sikka, Mike Santella, Rod Judkins, Peter Angelini, and Larry Dickens, Mike Miller, Kathi Alexander, Joe Horton, and Cam Hubbard.

The panel on Intermetallic Alloy Development acknowledges Gary Hudson of United Defense LP/Steel Products Division, Jim Farago of General Motors Delphi Saginaw Steering Systems, and John Rogers of Sandusky International for providing an industrial perspective of the commercial potential of intermetallic alloys.

The panel is particularly grateful to Charles Sorrel and James Quinn of the Department of Energy Office of Industrial Technology and Peter Angelini of the Oak Ridge National Laboratory for assistance in conducting the meeting at Oak Ridge, Tennessee.

Finally, the panel gratefully acknowledges the support of Thomas E. Munns, National Materials Advisory Board (NMAB) senior program officer, Aida C. Neel, NMAB senior project assistant, and Bonnie Scarborough, NMAB research associate.

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Preface

The Department of Energy Office of Industrial Technology (OIT) requested that the National Research Council, through the National Materials Advisory Board (NMAB), conduct a study to evaluate the OIT program strategy, to provide guidance during the transition to the new Industries of the Future strategy, and to assess the effects of the change on crosscutting technology programs. The Committee on Industrial Technology Assessments (CITA) was established to review and evaluate the program and plans of the overall OIT program, to review the plans and progress of selected OIT-sponsored research programs, and to conduct site visits and laboratory evaluations, when appropriate, to supplement program assessments. In the future, the committee will establish and oversee topical panels to review selected aspects of the program, conduct the site visits, and bring in additional members with expertise in the topical areas to be evaluated.

The purpose of the panel on Intermetallic Alloy Development, the first topical panel established under CITA, was to document and evaluate the progress of the Oak Ridge National Laboratory (ORNL) toward the development and commercialization of high temperature intermetallic alloys, to identify industrial applications and barriers to commercialization, and to recommend criteria for selecting and prioritizing future research projects. This topic was selected because the intermetallic alloy program is a mature program focused on crosscutting research and development projects.

The ORNL intermetallic alloy development program is a long-term, collaborative R&D program involving various Department of Energy program offices, including Basic Energy Sciences (BES), which sponsors fundamental research, and Fossil Energy (FE) and Energy Efficiency (EE), which sponsor applied

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research and development programs. The objective of the ORNL intermetallics program has been to develop high strength, ductile, intermetallic alloys that can be processed and utilized for high-temperature structural applications.

The panel met with key ORNL researchers, program managers, and industrial participants on June 6 and 7, 1996, at Oak Ridge, Tennessee, to discuss progress and plans, review program strategies and accomplishments, and tour the laboratory facilities. This report reviews and assesses the intermetallic alloy development program and offers recommendations for the focus of the program in the future, as well as assessing the implications of the lessons learned for the entire OIT program strategy.

The chair thanks the panel members for their efforts, dedication, and patience during the preparation of the report and the staff of the NMAB for their assistance in the publication of the panel's report. The diligence and goodwill of all who were involved made for an unusually effective team effort.

Comments and suggestions can be sent via Internet electronic mail to nmab@nas.edu or by FAX to the NMAB (202) 334-3718.

Norman A. Gjostein, *chair*
Panel on Intermetallic Alloy Development

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Acronyms

AECC	Alloy Engineering and Casting Company
AIM	Advanced Industrial Materials
BES	Basic Energy Sciences
CITA	Committee on Industrial Technology Assessments
CRADA	cooperative research and development agreement
DOE	Department of Energy
ECUT	Energy Conversion and Utilization
EE	Energy Efficiency
FE	Fossil Energy
IOF	Industries of the Future
NRC	National Research Council
NMAB	National Materials Advisory Board
OD	outer diameter
OIT	Office of Industrial Technology
ORNL	Oak Ridge National Laboratory
UDLP	United Defense LP/Steel Products Division

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Executive Summary

Intermetallic compounds are a unique class of materials consisting of ordered alloy phases formed between two or more metallic elements where the different atomic species occupy specific sites in the crystal lattice. Intermetallic alloys with high aluminum content have been considered for use in demanding structural applications because of their inherent oxidation resistance and strength retention at high temperatures. However, they can be extremely brittle at ambient temperatures, are difficult to process, and are prone to environmental degradation.

The development program described in this report was undertaken by the Oak Ridge National Laboratory (ORNL) to increase the understanding and improve the properties of intermetallic compounds so that they could be processed and utilized as structural materials in a number of demanding high temperature environments in a number of industries. This program, which was begun in 1981, is one of the longest continuously funded materials development programs ever undertaken at ORNL. The U.S. Department of Energy Office of Industrial Technology (OIT), through the Energy Conversion and Utilization (ECUT) and Advanced Industrial Materials (AIM) programs, has provided roughly one-third of the funding to ORNL for the development and commercialization of intermetallic alloys.

In 1995, OIT's program management strategy was revised to reflect a new commitment to increasing and documenting the commercial impact of OIT programs (provided the products still met OIT goals of improving energy efficiency and reducing adverse environmental impact). OIT's research and development management strategy was changed from a "technology push" strategy to a "market pull" strategy. Seven industries—steel, forest products, glass, metal casting,

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aluminum, chemicals, and petroleum refining—were found to consume more than 80 percent of the energy consumed by the manufacturing sector of the economy and to produce more than 90 percent of the hazardous waste products generated in this same sector. These seven industries, designated Industries of the Future (IOF), became the focus of OIT programs. OIT research projects are now selected and prioritized to meet the business and technological needs of the IOF.

The National Research Council Intermetallic Alloy Development Panel was established to review the progress and accomplishments of the intermetallic alloy research and development program; to describe program management strategies, including selection criteria, commercialization plans, and industry involvement; to describe successful and unsuccessful efforts to develop commercial applications for intermetallic alloys; to suggest potential applications in the OIT target industries; and to recommend criteria for selecting and prioritizing future projects for the research and development of intermetallic materials and processes.

This study is part of the National Research Council Committee on Industrial Technology Assessments (CITA), which was established to evaluate the OIT program strategy, to provide guidance during the transition to the new IOF strategy, and to assess the effects of the change in program strategy on crosscutting technology programs, that is, programs to develop technology applicable to several industries.

Intermetallic alloy development was selected as the first panel topic under CITA because the intermetallic alloy program is a mature program already focused on crosscutting research and development. The emphasis of this report is on lessons that can be derived from the development of Ni_3Al alloys and processes, which have been the focus of the OIT intermetallics research program at ORNL. These lessons may be of benefit to OIT in the implementation of the IOF strategy throughout the OIT program.

The panel's findings include a review and assessment of the intermetallic alloy development program and recommendations for the future focus of the program as well as an assessment of the implications for the entire OIT program and the transition to the IOF strategy. The major recommendations are included in this summary. Additional recommendations can be found in Chapter 4 of the report.

PROGRAM ASSESSMENT

Overall, the ORNL intermetallic alloy development program has been successful in terms of the technical goals and objectives established by the program, i.e., to develop high strength, ductile intermetallic alloys that can be processed and utilized for high-temperature structural applications. The program has been well managed, with effective integration of program elements—from basic research through production-scale demonstrations—and effective coordination of program goals and responsibilities among participating funding and research organizations.

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Program Management

In the panel's judgment, the ORNL intermetallics program has been a successful science and technology development program for a number of reasons. These include consistent and continuous funding (since 1982); effective integration of basic and applied research and development by universities, other national laboratories, and industry; the flexibility to reorient and refocus research efforts in response to promising results or identified needs; and the establishment of partnerships and collaborations with industry to identify industry needs and establish practical goals for technology development.

Technical Program

The ORNL intermetallic alloy development program has made significant technical advances since its inception—from basic exploratory research and characterization through process development and scaling. The early decision to focus on Ni_3Al alloys and to concentrate on optimizing alloy composition, characterizing material behavior, and developing production-scale processing methods has been critical to the success of the program.

Technical accomplishments in the characterization and development of Ni_3Al alloy compositions include:

- the identification of brittle grain-boundary fracture mechanisms at ambient temperatures and the substantial loss of ductility at intermediate temperatures as major material deficits
- the determination of causes for brittle ambient-temperature fracture (moisture-induced embrittlement) and intermediate-temperature ductility loss (dynamic oxygen-induced degradation)
- the improvement of ductility by microalloying with boron and chromium
- the improvement of elevated temperature strength and processibility using standard alloying techniques, including solid-solution strengthening, dispersion strengthening, and improving strength, weldability, and castability

In the panel's judgment, some of the most significant accomplishments of the intermetallic alloy research program have been in the development of manufacturing processes. Developments in this area include:

- a production-volume melting process that maintains aluminum concentration while melting higher-temperature-melting constituents (Exo-melt® process)
- methods and alloy modifications for low-cost casting processes
- materials (e.g., weld wire) and processes for making structural welds and weld repairs

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Commercialization

The results of successful use of Ni_3Al alloys in a variety of trial production applications, as well as recent commercial orders for furnace transfer rolls in steel mills and heat-treat furnace fixtures, indicate that the commercial application of these alloys is likely to expand in the next several years. However, although Ni_3Al alloys have performed well in production-scale trials, it is unclear at this time if the level of successful commercial application will repay the research investment. Criteria that need to be considered in the full commercialization of a new material include:

- The availability of alternative materials. To replace an established material, factors other than performance must be considered. These include the cost and supply of raw materials; production capability; cost of materials, fabrication processes, tooling, and facilities; demonstrated reliability; and supplier infrastructure.
- Industrial participation. Successful commercialization requires a strong, committed, and, in some instances, lucky industrial proponent who understands the real hurdles and motivation for industrial acceptance.
- Technology Readiness. The technology, especially the processing technology, must be substantially developed prior to commercialization.

These criteria have been a part of the commercialization strategy for the ORNL intermetallics program, but ultimately ORNL depends on industry to commercialize new technologies.

FUTURE PROGRAM FOCUS

Throughout the ORNL intermetallic alloy development program, interaction with industrial participants has been critical to identifying needs and priorities. Interactions with industry have helped ORNL focus on optimizing alloy compositions and developing process technologies to meet industrial needs. In addition to the collaboration mechanisms previously used by ORNL (cooperative research and development agreements, cofunded research projects, license agreements), IOF industry "vision documents" and road maps would also be helpful for identifying industry needs and priorities that can be met through the application of intermetallic alloys. Examples of potential applications include expanding the use of Ni_3Al for hot metalworking (dies, fixtures, furnace components), developing nickel and iron aluminides for processing equipment used in high temperature and corrosive environments in the chemical and refining industries, and using Ni_3Al in transfer and processing rolls for the steel and paper industries.

In addition to characterizing the physical and mechanical properties of Ni_3Al, which has been emphasized in previous work, the focus should now shift to

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modeling solidification (casting and welding) processes and to establishing production processing standards and methods for machining and welding nickel and iron aluminides. This shift would extend the industrial applications and improve the potential for commercialization of intermetallic alloys.

The panel believes that reliance on industry needs alone, even with an effective identification strategy, has inherent drawbacks. For example, important crosscutting or exploratory research programs might not be supported if they are not identified as high-priority industry needs by any one group.

Recommendation. ORNL should focus research on optimizing alloys and developing process technologies for a select number of alloy families for which ORNL has unique expertise and capability. In addition to the Ni_3Al-based alloys emphasized in previous programs, ORNL has particular experience with iron aluminides (Fe_3Al, FeAl).

Recommendation. ORNL should continue to emphasize the development of manufacturing process technology for selected alloys to maximize opportunities for commercialization and technology transfer to industry.

Recommendation. ORNL should emphasize low-cost processes in the development and optimization of intermetallic alloys.

Recommendation. OIT and the ORNL intermetallic alloy development program should use the following approach to identify and prioritize research programs:

- Identify IOF needs and priorities that can be met through the application of intermetallic alloys.
- Establish, with input from IOF teams interested in the commercial uses of intermetallic alloys, a target level of support for crosscutting research and development programs.
- Identify projects with the potential to meet identified industry needs and develop material and process technology goals based on these potential applications.
- Emphasize crosscutting projects that could lead to commercial application in more than one industrial sector.

IMPLICATIONS FOR THE OFFICE OF INDUSTRIAL TECHNOLOGY PROGRAM

The lessons learned from the development of Ni_3Al alloys and processes can provide OIT with general guidelines for coordinating and managing several funding and research organizations and for establishing effective industrial

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collaborations. These guidelines can be used in the implementation of the IOF strategy throughout the OIT program.

Even though the ORNL intermetallic alloy development program has relied on industrial participants to establish needs and priorities, the "profit-based" metrics used in industry for measuring the efficacy of research and development may not be appropriate for government-funded long-term research. IOF guidance is useful for ensuring that the program is relevant, but the panel suggests that short-term (i.e., one to three years) commercial potential should not be the primary "compass" directing the selection of OIT projects. In the panel's judgment, metrics compatible with Department of Energy and OIT organizational objectives for comparing and selecting programs for the IOF program should include the potential for conserving energy, the potential for reducing waste, consistency with IOF business objectives and technology road maps, commercial potential/market value, and potential use in more than one industrial sector (crosscutting technologies).

Because OIT is part of the federal research and development establishment, it cannot participate fully and actively in the commercialization process, especially in the later stages when the product is brought to market. Rather, the technologies developed by OIT must be commercialized by industry.

Recommendation. OIT should emphasize the early involvement of key industrial participants, including the suppliers, producers, and users of particular materials or process technologies. OIT should adopt collaboration mechanisms, such as cooperative research and development agreements, cofunded research programs, exchanges of personnel, and the use of laboratory user centers (e.g., the ORNL Metals Processing User Center).

Recommendation. OIT should support joint projects with potential suppliers and users of a specific technology to demonstrate and debut the technology.

Recommendation. When licensing technology developed by an OIT research and development program, OIT should specify the relationship between the research and development program and the licensee's business strategy. OIT should not enter into exclusive licensing arrangements that rely on unrealistic technology development for commercialization (i.e., licensing too early) or that unnecessarily restrict or preclude use of the technology by other industries.

Recommendation. OIT should develop a mechanism for the orderly termination of (1) projects that have met OIT objectives and have progressed to the final stage of commercialization (market introduction) and (2) projects that do not have sufficient industrial interest to support demonstration, process development, and scale-up.

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Introduction

The Department of Energy (DOE) Office of Industrial Technology (OIT) sponsors research and development programs to improve energy efficiency and resource utilization in energy- and waste-intensive U.S. industries. The programs focus on materials processing 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.

Since 1993, the OIT has been changing from a "technology push" program strategy, in which projects are selected and prioritized primarily for their potential for reducing energy consumption or waste generation, to a "market pull" strategy, in which industry needs and priorities are the primary criteria. The OIT program has focused on seven energy- and waste-intensive materials processing industries—steel, forest products, glass, metal casting, aluminum, chemicals, and petroleum refining. These industries, designated as "Industries of the Future" (IOF), use about 80 percent of the energy (Figure 1-1) and produce more than 90 percent of the manufacturing waste in the entire industrial sector.

As Table 1-1 shows, each industrial segment has (or will) develop a technology "vision" that identifies high priority needs, including the strategic goals and research priorities for each industry. Based on these visions, the industry groups will develop research agendas, devise implementation strategies to meet their high priority needs, and commit the resources to conduct and manage the research projects. OIT facilitates the IOF process by assisting with planning, coordinating participants and catalyzing industry interactions, providing access to the national laboratories, and sharing the cost of selected projects.

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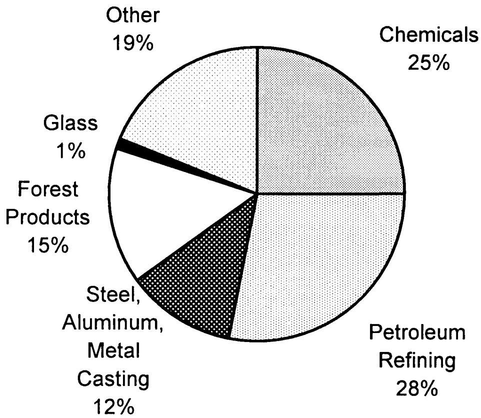

FIGURE 1-1 Manufacturing energy use (1991). Total energy use is 20.3 Quads (quadrillion BTUs). Source: OIT.

COMMITTEE ON INDUSTRIAL TECHNOLOGY ASSESSMENTS

The OIT asked the National Research Council (NRC), through the National Materials Advisory Board, to conduct a study to evaluate their program strategy and to provide guidance during the transition to the new IOF strategy and assess the effects of the change on crosscutting technology programs, that is, programs to develop technologies applicable to several industries. The Committee on Industrial Technology Assessments (CITA) was established to review and evaluate the program and plans of the overall OIT program, review the plans and progress of selected OIT-sponsored research programs, and to conduct site visits and laboratory evaluations, when appropriate, to supplement program assessments. The committee will suggest improvements to the technical programs, methods of coordinating research with other agencies, and mechanisms for transferring technology to industry. To help the committee review the overall OIT program, CITA will establish and oversee topical panels to review selected aspects of the program, conduct the site visits, and bring in additional members with expertise in the topical areas to be evaluated.

PANEL ON INTERMETALLIC ALLOY DEVELOPMENT

The first topical panel established under CITA was the Panel on Intermetallic Alloy Development. This topic was selected because the intermetallic alloy program, which has been active at Oak Ridge National Laboratory (ORNL) since 1981, is a mature program focused on crosscutting research and development projects. OIT, through the Energy Conversion and Utilization (ECUT) and Advanced Industrial Materials (AIM) programs, has provided significant funding

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TABLE 1-1 Status of IOF Vision Documents

Industry Sector	Vision Document	Date Released
Forest Products	Agenda 2020: A Technology Vision and Research Agenda for America's Forest, Wood, and Paper Industry	November 1994
Metal Casting	Beyond 2000: A Vision for the American Metalcasting Industry	September 1995
Steel	Steel: A National Resource for the Future	May 1995
Aluminum	Partnerships for the Future	March 1996
Glass	Glass: A Clear Vision for a Bright Future	January 1996
Chemicals	Technology Vision 2020: The U.S. Chemical Industry	December 1996
Petroleum Refining	TBD	Not Available

(roughly one third of the total) to ORNL for alloy development and commercialization. The purpose of this report is to document and evaluate the progress of ORNL toward the development and commercialization of high temperature intermetallic alloys, to identify industrial applications and barriers to commercialization, and to recommend criteria for the selection and prioritization of future research projects. The panel was charged with the following tasks:

- to review the progress and accomplishments of the intermetallic alloy research and development program
- to describe program management strategies, including selection criteria, commercialization plans, and industry involvement
- to describe successful and unsuccessful efforts to develop commercial applications for intermetallic alloys
- to suggest potential applications in the OIT target industries, including steel, forest products, glass, metal casting, aluminum, chemicals, and petroleum refining
- to recommend criteria for selecting and prioritizing future projects for the research and development of intermetallic materials and processes

The panel's evaluation included a site visit to ORNL on June 6 and 7, 1996, when panel members met with key ORNL researchers, program managers, and industrial participants to discuss progress and plans, review program strategies and accomplishments, and tour the laboratory facilities. The agenda for the evaluation meeting and a list of participants appears in Appendix A.

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Oak Ridge National Laboratory Intermetallics Program

Intermetallic compounds are a unique class of materials, consisting of ordered alloy phases formed between two or more metallic elements where the different atomic species occupy specific sites in the crystal lattice (NRC, 1984; Anton et al., 1989). Intermetallics differ from conventional alloys in that they generally possess long-range-ordered crystal structures at ambient and intermediate temperatures. Intermetallic compounds form in composition ranges close to stoichiometric ratios. Thus, although the laws of chemical valency are usually not followed, the compounds often have relatively simple chemical names like TiAl, Ti_3Al, NiAl, Ni_3Al, CuZn, Cu_3Au, and Nb_5Si_3 .

Intermetallics have characteristics of both metals and ceramics, and their mechanical properties are intermediate between metals (which are generally softer and more ductile) and ceramics (which are generally harder and more brittle). The predominant bonding in ceramics is covalent and ionic, as opposed to metallic bonding. Intermetallics contain both metallic and covalent bonds, depending on the constituent metals. Because of their intermediate position, the properties of intermetallics can be strongly influenced by small changes in the system (i.e., variations in the microstructure can result in changes in strength and ductility over a considerable range).

A great deal of work has been done in the last 10 to 15 years to develop and characterize intermetallics and to develop processing technologies. In response to the need for low density, high performance alloys for use in the components of airframes and turbine engines (NRC, 1993, 1996), for example, concerted efforts have been made in recent years to improve the properties of intermetallic alloys, especially alloys based on aluminides (e.g., TiAl, Ti_3Al, NiAl, Ni_3Al, FeAl,

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Fe_3Al). Their inherent oxidation resistance and retention of strength at high, homologous temperatures make them prime candidates for use at intermediate temperature ranges, where creep resistant alloys are required. The major problem with many intermetallics is that they can have extremely low ductility at ambient temperatures. Therefore, before they can be used as structural materials, intermetallics must be modified to improve their ductility and strength and to make them more resistant to oxidation and corrosion. In addition, processes must be developed for preparing and processing these materials into usable shapes.

The development program described in this report was undertaken by ORNL to increase the understanding of, and to improve the properties of, Ni_3Al and other intermetallic compounds so that they could be processed and utilized as structural materials in demanding, high temperature environments in a number of applications by a number of industries.

In this chapter, the ORNL program for developing intermetallic alloy materials and processes is described; program management and interactions among the sponsoring groups within DOE are outlined; significant technical accomplishments and collaborations with industrial partners and licensees are reviewed; and conclusions and suggestions concerning the technical program are presented. The emphasis of this report is on lessons that can be derived from the development of Ni_3Al alloys and processes, which have been the focus of the OIT intermetallics research program at ORNL. These lessons may be of benefit to OIT in implementing the IOF strategy throughout the OIT program.

HISTORY OF PROGRAM MANAGEMENT

The ORNL intermetallics program is a long-term, collaborative, research and development program involving various DOE program offices. The program was initiated with ORNL "seed" funds and was subsequently funded by Basic Energy Sciences (BES), which sponsors fundamental research, and by two program offices, Fossil Energy (FE) and Energy Efficiency (EE). The intermetallics program, one of the largest, continuously-funded development programs undertaken at ORNL, has received more than $21 million since 1982. The funding profile for the DOE portion of the program is shown in Figure 2-1. In addition to the involvement of DOE organizations, the program has been supplemented by collaborations and partnerships with industry as well as by collaborative efforts with the Office of Naval Research (approximately $100,000 in both 1983 and 1984), universities, and other national laboratories. Figure 2-2 presents a time line of these interactions. Industrial interactions are described later in this chapter.

ORNL has been the lead laboratory for intermetallics research and development funded by the three DOE program offices, in collaboration with universities, industry, and other national laboratories. Figure 2-3 shows the integration of research projects and the development of mechanisms of technology transfer.

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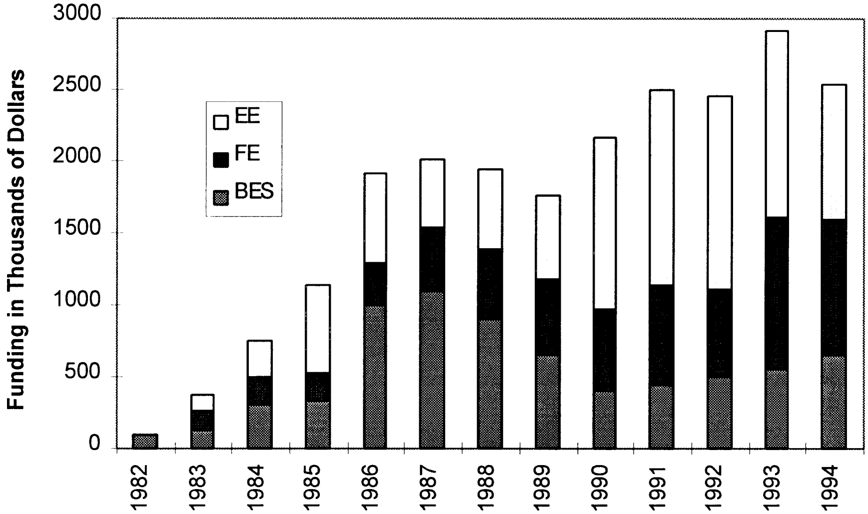

FIGURE 2-1 Profile of funding (in then-year dollars) by Basic Energy Sciences (BES), Energy Efficiency (EE), and Fossil Energy (FE) offices of DOE. Source: ORNL.

Oak Ridge National Laboratory Exploratory Studies Program

The original "seed" funding for intermetallic alloy research was provided in June 1981 through an ORNL-sponsored exploratory study. The objective was to develop a new class of structural materials for advanced energy conversion systems by developing ductile intermetallics using microalloying processes. Thus, from the beginning, the purpose of this program was not just to investigate interesting questions of materials science, but also to identify and facilitate industrial applications for the new materials.

Basic Energy Sciences

Based on the promising scientific results of the ORNL exploratory program, a nickel aluminide development program was initiated by the Division of Material Science of BES. This new program was initiated to advance the principles for alloy design and to use this knowledge to develop improved materials for high temperature structural applications (e.g., turbine and internal-combustion engine components, process tooling). Aluminides were chosen because of their potential for excellent oxidation and corrosion resistance at high temperatures. In addition, using ductile aluminides as structural materials could reduce the nation's dependence on strategic materials like chromium. Since 1982, the focus of the BES-funded program has been expanded. For example, in 1985, the research was divided into four categories, (1) boron segregation and intergranular fractures, (2) microstructures and grain boundary properties, (3) physical properties and

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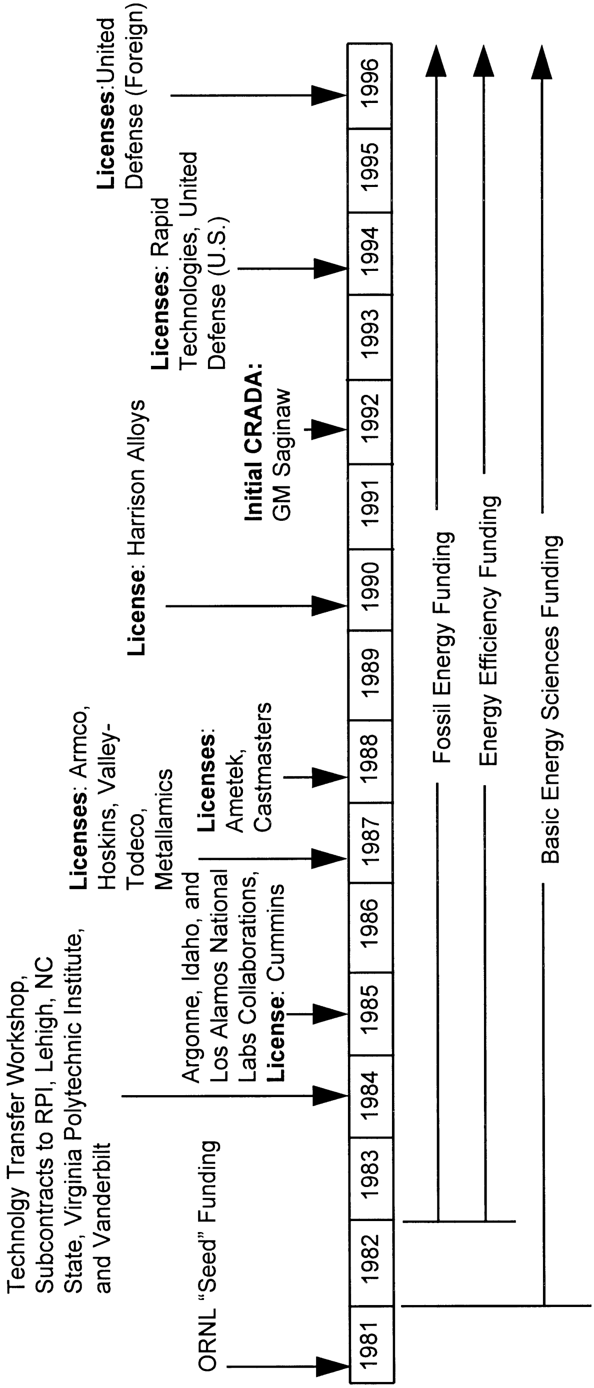

FIGURE 2-2 Time line of program management and interactions.

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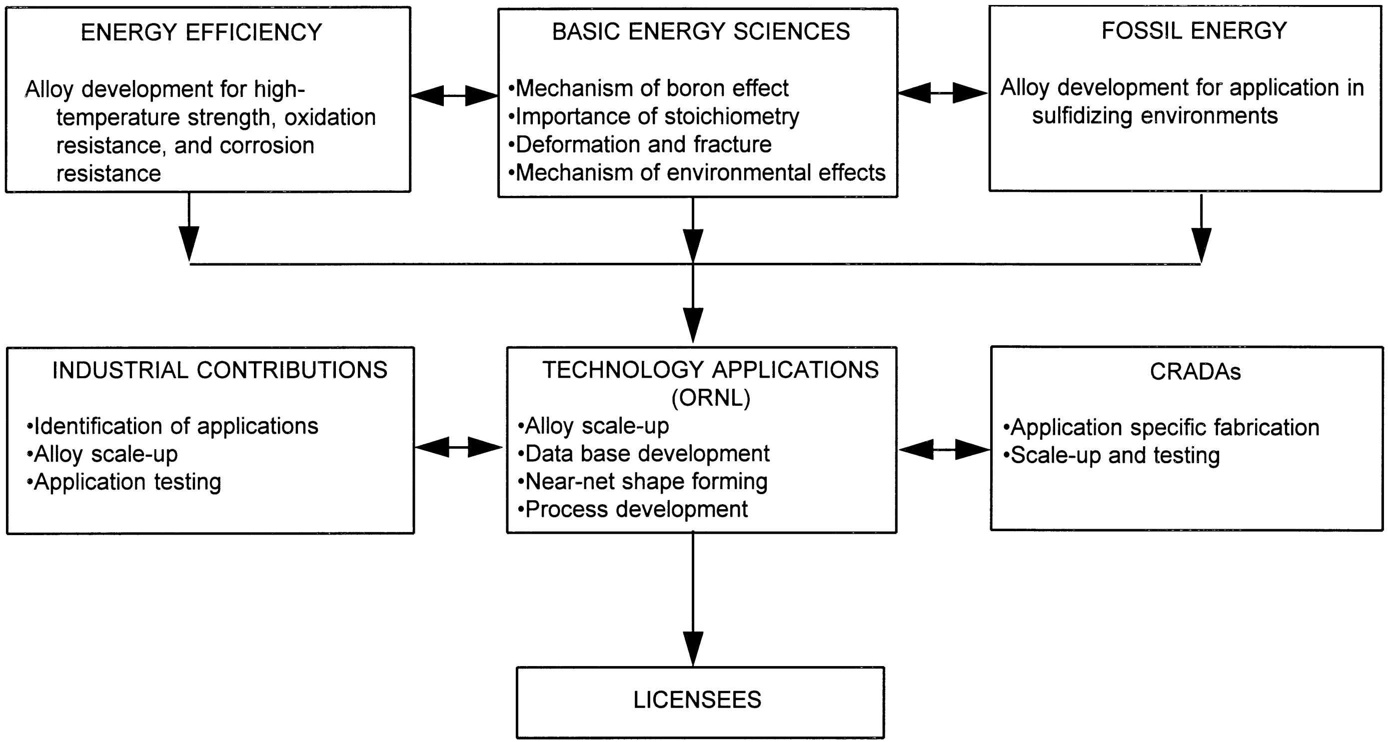

FIGURE 2-3 Integration of research projects and mechanisms for technology transfer. Source: ORNL.

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defect structures, and (4) coordination of an interlaboratory program. Participants in the interlaboratory program, coordinated by ORNL, include the Argonne National Laboratory, the Idaho National Engineering Laboratory, the Los Alamos National Laboratory, and the National Institute for Standards and Technology of the U.S. Department of Commerce.

Program Offices

Starting in 1983, two DOE "mission-oriented" program offices began to fund intermetallic materials and processing technology development programs at ORNL. The sponsoring programs included:

- the Energy Conversion and Utilization Technologies (ECUT) program, renamed Advanced Industrial Materials (AIM), of EE. The AIM program is now part of the OIT research program
- the FE Advanced Research and Technology Development Materials Program

From 1984 to 1989, much of the research and development was funded jointly by EE and FE. The program was expanded, within the funding levels shown in Figure 2-1, to include subcontract work at several universities, including Rensselaer Polytechnic Institute (mechanical properties of hydrogen-charged materials), Vanderbilt University (wear), Lehigh University (diffusion studies), North Carolina State University (mechanical alloying), and Virginia Polytechnic Institute (grain boundary modeling). In 1985, EE and FE made substantial efforts to inform industry about the program and encourage their participation. These included a workshop at ORNL and a market study funded by Martin Marietta Energy Systems. The study, performed by SRI International, looked at the near term (one to five years) and intermediate term (five to ten years) applications of Ni_3Al alloys. Piston engine exhaust valves and aircraft gas turbine components were identified as having the best market potential.

Also in 1985, a licensing agreement was executed with Cummins Engine Company for the use of Ni_3Al alloys in diesel engine turbochargers. Based on the Cummins license and the results of the workshop, efforts were made beginning in 1986 to support industrial applications focused on material processing technologies, including isothermal forging and rolling, near-net-shape casting and rolling, injection molding of powder into shapes, and extrusion, rolling, and forging. For the first three years, the alloy development efforts were primarily devoted to improving the durability and fabricability of wrought alloys. However, based on the results of industrial collaborations, the focus of the program was changed in 1988 to the development of castable alloys. (Industrial interactions and collaborations are described in more detail later in this chapter.)

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In 1989, FE terminated work on iron-modified nickel aluminides and focused all of its funding on Fe_3Al-type alloys because these had better sulfidation resistance. FE is interested in developing new structural materials for fossil energy conversion systems like coal gasifiers and fluidized-bed combustors. The FE iron aluminides program included corrosion tests, welding tests, and other development and scale-up projects to support potential industrial applications. The EE (ECUT/AIM) program has focused on the castability, weldability, and scale-up of nickel aluminides since 1989.

TECHNICAL PROGRESS AND ACCOMPLISHMENTS

From the beginning, the research and development on intermetallics has been multidisciplinary and has included basic research to increase the understanding of alloy properties, improve alloy design and properties, develop first principles theory, investigate advanced analytical techniques for characterization, and research processing and fabrication in areas such as casting and welding. These efforts have been widely recognized in the scientific and technical community (three R&D 100 Awards; the E.O. Lawrence Award; the Humboldt Award [Germany]; and several best paper of the year citations).

Development of Nickel Aluminide (Ni_3Al)

In the early 1980s, ORNL initiated a program to increase the understanding of the generally brittle behavior of intermetallic compounds and to modify that behavior by alloying and processing changes so that intermetallic alloys would be useful as structural (load bearing) materials. The focus of the initial program was on Ni_3Al, one of the few materials known to exhibit a significant increase in yield strength with increasing temperature (from ambient conditions to about 800°C). The remarkable properties of nickel-based superalloys used in aircraft turbine engines result from the presence of Ni_3Al. These attractive attributes provided the impetus for the development of Ni_3Al alloys as structural materials for commercial applications.

Alloy Development

The initial results of the ORNL studies confirmed (as was known from the literature) that at room temperature single crystals of Ni_3Al were quite ductile. The results also showed, however, that polycrystalline samples were brittle, with the failure being almost completely intergranular. In addition, polycrystalline samples exhibited a severe loss of ductility at intermediate temperatures when exposed to oxidizing atmospheres (Liu and Sikka, 1986). Reduced ductility was apparent at about 300°C, with a ductility minimum at about 750°C.

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The next step in the research process (in the mid 1980s) was to develop and validate ways to improve the room- and intermediate-temperature ductility of Ni_3Al (Liu, 1993). It had been previously reported that the presence of a small amount of boron (500 to 1000 ppm, by weight) in the alloy made the polycrystalline material fully ductile at room temperature (Aoki and Izumi, 1979). The ORNL team investigated this phenomenon extensively and was able to show that the ductilization effect was most pronounced in a slightly substoichiometric composition (23 to 24 atomic percent aluminum) and did not occur in a stoichiometric or a superstoichiometric composition (Liu et al., 1985). They also found that the boron was strongly partitioned to the grain boundaries, from which they inferred that the strong segregation of the boron lowered the interfacial free energy of the boundaries. In addition, they showed that the addition of chromium (about 8 percent) to Ni_3Al strongly ameliorated intermediate-temperature oxygen embrittlement, presumably by encouraging the formation of an impenetrable surface oxide layer (Liu and Sikka, 1986).

Following these discoveries, the Ni_3Al intermetallic alloys were strengthened using conventional alloying techniques to produce alloys with sufficient strength to be considered as replacements for currently used materials (e.g., Fe-Ni-Cr steel alloys). The Ni_3Al alloy was solid-solution strengthened by the addition of molybdenum, zirconium, and/or hafnium. Zirconium and hafnium were also found to improve castability and weldability. Finally, either carbon or additional boron was added to provide strengthening through the presence of carbide or boride dispersions.

ORNL scientists developed a number of Ni_3Al-based alloys that exhibited a good balance of properties in the wrought condition. As is described later in this chapter, some of these alloys were modified to make them more amenable to casting (Sikka, 1996). Precision-, sand-, and ingot-casting processes are considered the best methods for fabricating components from nickel aluminides.

Two Ni_3Al alloys now receiving focused attention in the ORNL program are IC-221M and IC-396M. The alloy compositions for these alloys are shown in Table 2-1. Figure 2-4 shows mechanical properties, including yield strength, ultimate strength, and elongation, and their variation with temperature compared with an Fe-Ni-Cr steel alloy (alloy HU) that is currently used in high temperature industrial applications. The Ni_3Al alloys have superior strength and high temperature property retention compared with the current material. Both Ni_3Al alloys have similar yield strength values from room temperature (590 to 620 Mpa [85 to 90 ksi]) to 926°C (565 to 590 Mpa [82 to 85 ksi]). Both have room temperature ultimate strengths in the range 830 to 900 Mpa (120 to 130 ksi). However, IC-221M exhibits an increase in strength to 930 Mpa (135 ksi) at 704°C; the strength of IC-396M decreases slowly with temperature to 810 Mpa (118 ksi) at 704°C. Above 704°C, the strength of IC-221M decreases more rapidly with temperature than IC-396M (e.g., at 926°C, the ultimate strengths of IC-221M and IC-396M are 655 Mpa (95 ksi) and 600 Mpa (87 ksi), respectively). Both alloys

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TABLE 2-1 Ni_3Al Alloy Compositions

Alloy Number	Composition (weight percent) Ni	Al	Cr	Mo	Zr	B	Remarks
IC-50	88.08	11.3	–	–	0.6	0.02	wrought
IC-218	83.1	8.7	8.1	–	0.2	0.02	wrought
IC-221M	81.1	8.0	7.7	1.4	1.7	0.008	cast
IC-221W	79.80	8.00	7.70	1.50	3.00	0.003	weld filler wire
IC-396M	80.42	7.98	7.72	3.02	0.85	0.005	cast
Fe-Ni-Cr (HU)	39.0	–	18.0	–	–	–	wrought, contains 0.55% C, balance Fe

Source: Sikka, 1993.

show adequate ductility at room temperature (14 to 18 percent), although IC-221M exhibits a rather serious minimum in ductility (5 to 6 percent) at 871°C to 926°C. IC-396M exhibits a less serious minimum in ductility (9 percent) at 760°C to 815°C. Impact resistance values as measured by a Charpy impact test for both alloys are above 40J (30 ft-lb) from room temperature to about 593°C. The testing that has been completed was performed to provide a basic understanding of materials response in potential industrial applications, such as hot metalworking tooling, forging dies, and furnace fixtures (Sikka, 1993). Additional testing is needed to provide engineering properties, like creep, fatigue behavior, and fracture toughness, that would enable expanded use of Ni_3Al alloys in more critical structural applications.

Recent alloy development at ORNL (in the late 1980s and early 1990s) has been focused on a more complete understanding of the causes of low room-temperature and intermediate-temperature ductility. Previously, it had been widely assumed that the brittle behavior of intermetallics was a result of their covalent bonding. However, some stoichiometric compounds, such as Fe_3Al and single-crystal Ni_3Al, are ductile at room temperature. In a series of recent experiments, ORNL researchers have shown that low room-temperature ductility was caused by the presence of ambient moisture and that specimens tested in dry gases or high vacuum were fully ductile (Liu, 1992). They later showed that moisture in the air reacted with aluminum in the alloy to produce atomic hydrogen, which diffused rapidly through the grain boundaries and caused the materials to become brittle at room temperature (Takeyama and Liu, 1992). In addition, intermediate-temperature embrittlement was shown to be a dynamic, oxygen-induced ductility loss caused by the presence of oxygen in the environment. These experiments, which were designed and performed by ORNL scientists, have resulted in a more complete understanding of the embrittlement phenomena in Ni_3Al. Additional fundamental research is needed to determine the mechanisms of ductility enhancement provided by alloying elements so that alloy composition can be further optimized.

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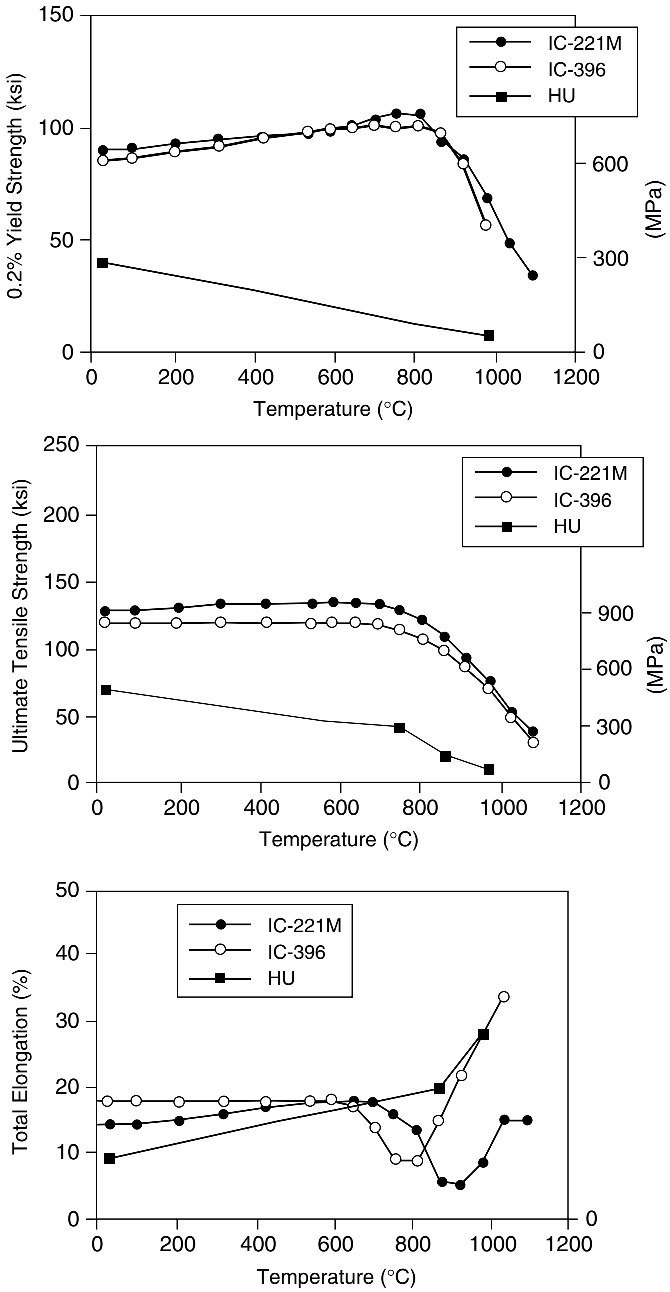

FIGURE 2-4 Mechanical properties of cast Ni_3Al based alloys (IC-221M and IC-396M) and Fe-Ni-Cr steel alloy as a function of test temperature. Source: ORNL.

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Process Development

In addition to the alloy development described in the previous section, significant progress has been made toward the development of manufacturing process technologies for intermetallics. The ORNL process development program includes melting, casting and casting modeling, investment casting (including mold development and alloy modifications for better casting), mechanical working, rolling, and welding. Although the ORNL investigations began as a development program for wrought alloys, the investigators shifted the emphasis of the program toward the development of casting alloys and processes in response to the desire by Cummins Engine Company, an early licensee, to produce cast components. The study of the interactions between Ni_3Al alloys and various casting mold media was required for the development of a compatible mold-metal system. Alloy compositions were subsequently modified to make them more castable. As a result, alloys that can be sand and investment cast are now available (Sikka, 1996). The resulting castings show considerable promise as forging dies and as hardware for heat treatment furnaces.

Two process developments are particularly noteworthy—an exothermic melting (Exo-melt®) process and welding processes. Melting Ni_3Al-based alloys is difficult because of their high aluminum content and because of the great difference between the melting temperatures of the two main alloy constituents (Ni and Al). The result is that it is difficult to avoid the loss of aluminum at the temperature required to melt the nickel, zirconium, and molybdenum. ORNL scientists developed the Exo-melt process to address this problem (Sikka, 1996). The Exo-melt process uses the heat generated in the exothermic intermetallic formation reaction to melt the remaining alloy constituents and achieve good mixing of the components in a very short time. This process requires less heat than conventional melting processes, resulting in a savings of about 50 percent in both time and energy.

The second significant process development program concerned welding and weld repair processes. Many castings have surface defects that have to be repaired before the castings are ready for service. Also, it is often necessary to fabricate large, more complicated structures from smaller components. Welding is generally used for the structural and cosmetic repair of castings and is often used for the cost-effective fabrication of complex structures from smaller components. ORNL has conducted a comprehensive, 10-year program to develop knowledge and expertise in welding technologies including a basic understanding of melting and solidification processes for Ni_3Al alloys along with the development of production-scale welding process methods (David and Santella, 1996).

Other Intermetallics

Based on the progress of ORNL investigators with Ni_3Al alloys, the program was expanded to include the study of other intermetallic materials, including NiAl,

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Fe_3Al, FeAl, TiAl, Ni_3Si, and Cr-Cr_2Nb. Not surprisingly, each of these intermetallics was found to have unique characteristics. Applying lessons learned from work on Ni_3Al was not generally useful for other compounds because they did not have comparable characteristics. For example, the addition of a small amount of boron strengthened FeAl but did not improve ductility as it had for Ni_3Al.

Iron aluminide alloys are remarkably oxidation and sulfidation resistant and are therefore of great interest to the chemical and fossil fuel industries. The investigation of Fe_3Al materials and process technology has been part of the ORNL intermetallics program since 1988. In that time, a family of Fe_3Al alloys has been developed that includes alloy formulations optimized for room temperature ductility (5 percent chromium), sulfidation resistance (2 percent chromium), and fabricability (low aluminum content) (Liu, 1993; Sikka et al., 1993a). Although the mechanical properties of Fe_3Al alloys are significantly inferior to Ni_3Al, they are competitive with the ferritic and austenitic steels they are intended to replace.

In addition to alloy development, ORNL investigations of degradation mechanisms have shown that Fe_3Al alloys exhibit the same kind of moisture-induced embrittlement at room temperature as the Ni_3Al materials (Liu et al., 1990; McKamey et al., 1991; McKamey, 1996; Sikka et al., 1993b). Although progress has been made in the development and characterization of Fe_3Al alloys, optimizing alloy composition and developing manufacturing process technology must still be done before these materials can be considered for production applications.

The ORNL investigators have also studied TiAl materials, which are of great interest within the research community because of their relatively low density and their potential for high strength. Previous work by other laboratories had shown that substoichiometric aluminum compositions were much stronger than near-stoichiometric compositions (Huang and Hall, 1991), that they were strengthened by the addition of a small amount of tungsten (Martin et al, 1983), and that adding silicon was likely to strengthen them and enhance oxidation resistance (Tsuyama et al., 1992; Kasahara et al., 1990). The most significant development by the ORNL program in the investigation of TiAl alloys resulted from a processing scheme that yields a unique microstructure with a refined colony size and ultrafine lamellar spacing. The resultant material is a TiAl-based alloy with a 1000 Mpa (145 ksi) yield strength and good creep/stress rupture properties. However, the long-term stability of this microstructure under applied load has not yet been established.

INTERACTIONS WITH INDUSTRY

ORNL has facilitated interactions with industry in the following ways:

- collaborating with industrial researchers
- encouraging personnel assignments and exchanges

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- making ORNL's unique research and development facilities available
- conducting workshops
- establishing cooperative research and development agreements (CRADAs)
- licensing
- subcontracting research and development

Since the program's inception in 1982, ORNL has established more than 200 research and development collaborations with academia, industry (more than 100), and other national laboratories; organized almost 40 symposia and meetings; and sponsored ORNL research involving 15 postdoctoral fellows and 25 graduate students. CRADAs and licenses have motivated efforts to further the commercialization of Ni_3Al alloys. Companies that enter into CRADAs feel that they benefit from the expertise of ORNL researchers, leverage their investments (which makes them more likely to participate), and to some extent protect intellectual property and proprietary information. Carrying out application-specific development under the terms of a CRADA before manufacturing and/or licensing is attractive to industry. An example is the GM Delphi Saginaw project described later in this chapter, which began with a CRADA.

The licensing strategy now being followed by ORNL has evolved since 1985. The first license agreement, signed in 1985 with Cummins Engine Company, was for the use of Ni_3Al alloys in diesel engine components. The focus was on lower temperature (760°C to 982°C) diesel engines rather than on turbine engines. The protection was exclusively for that specific use and allowed for sublicensing to material suppliers. Other licenses issued by ORNL related to Ni_3Al alloys included:

- Hoskins Manufacturing Company for heating elements (1987)
- Metallamics, Inc., for molds and dies (1988)
- Armco, Inc., for mill products (1988)
- Valley-Todeco for aircraft fasteners (1988)
- Harrison Alloys for heating element wire (1991)

The emphasis of ORNL's current licensing strategy is different in that the current strategy maintains the protection of intellectual property, allows for the termination of inactive licenses, is nonexclusive as much as possible (exclusive only when necessary as an incentive to commercialization), tries to cultivate new licensees and nurture markets for advanced materials, and helps market the technology by using CRADAs and supporting research and development to assist licensees and potential licensees in developing Ni_3Al products.

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Cummins Engine Company

An early, exclusive license for a specific application with Cummins Engine Company was finalized in 1985 for the use of nickel aluminide alloys for turbochargers in diesel engines. However, the license has not led to the commercialization of nickel aluminides for this application, apparently because the license was formalized before the necessary processing technology had been developed. The data indicating that nickel aluminide was a good candidate for this application was developed on wrought alloys. However, the components under investigation were best produced by investment casting, and the nickel aluminide components had to be joined to a dissimilar material by welding. Because the technologies for casting and welding were not sufficiently developed, ORNL refocused on the development of cast alloys and processing rather than on wrought materials.

Casting development at PCC Airfoils, Incorporated, (along with ORNL) under the Cummin's license resolved many of the casting issues and contributed to the development of the IC-221M alloy in 1991. Further development has led to the addition of hafnium as an alloying element to improve castability, but no production applications had been realized by the time the Cummins license expired in 1992. Nickel aluminide turbochargers had been produced for testing, but problems with weight and performance have shifted the focus of the program from nickel aluminides to titanium aluminides.

Sandusky International

Another application of nickel aluminides being evaluated is for centrifugal cast furnace rolls. In a partnership with Metallamics, ORNL, and Bethlehem Steel, Sandusky International has produced nickel aluminide furnace rolls for Bethlehem Steel with a diameter of 36.2 cm (14.25 in.) and length of 685 cm (270 in.) (Figure 2-5). This is the largest nickel aluminide centrifugal casting that has ever been made. The improved oxidation resistance of the nickel aluminide alloys can reduce the incidence of surface blemishes introduced onto furnace rolls during service and thus improve the surface quality of the steel slabs being transported by the rolls. Another potential benefit could be to reduce the furnace down time required to maintain the rolls. Nickel aluminide centrifugal casting offers Sandusky an opportunity not only to diversify its product mix and take advantage of a potential market, but also to use existing equipment more efficiently.

Two furnace rolls were cast in the summer of 1993 from IC-396M alloy. ORNL funded the production of these components for evaluation at Bethlehem Steel. The rolls were connected to sand-cast nickel aluminide trunnions and introduced into a reheat furnace in 1994. Both have been used since that time in an environment of about 900°C to 925°C, the hottest zone of the furnace.

Sandusky identified several factors that affect the success of this application. One is the surface smoothness of the furnace roll. The outer diameter (OD)

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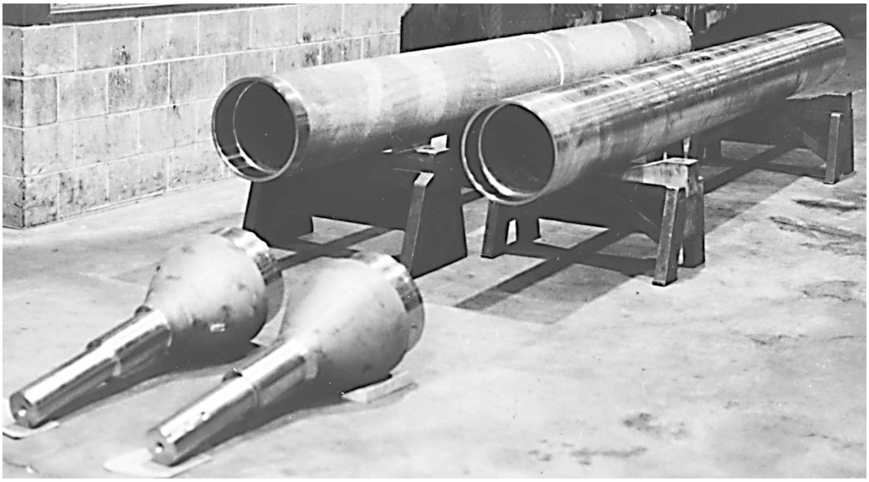

FIGURE 2-5 Cast and welded Ni_3Al transfer roll (for installation at Bethlehem Steel, Chesterton, Indiana). The roll was cast by Sandusky International (Sandusky, Ohio), and the trunnions were cast by Alloy Engineering and Casting Company (Champaign, Illinois). Source: ORNL

surface of the nickel aluminide casting is not as smooth as the OD of a machined surface. However, using the roll in the as-cast condition is preferable to investing the time and expense of machining. One of the rolls now in service has an as-cast OD surface, while the other has a machined OD surface, so both conditions can be evaluated. So far, both rolls have performed satisfactorily.

Sandusky has also focused attention on the weldability of nickel aluminide alloys and the long-term performance of the welds. In this application, attaching the trunnions to each end of the furnace-roll casting was problematic. Cost considerations led to a preference for welding rather than using mechanical means of attachment. Both welding and mechanical attachments were investigated with the two rolls in service; one roll was welded to the trunnions, while the other roll was mechanically attached. Both joining approaches presented some difficulties. The welded roll had to be removed from service when cracks were found in the welds. The roll and the trunnions were secured mechanically with pins, and the roll was put back into service. The second roll had to be removed from the furnace when the pins used to attach the roll to the trunnions failed. The mechanical attachment was redesigned, and the repaired roll was subsequently returned to service.

ORNL has made significant progress in welding nickel aluminide components. For this application, Sandusky supplied parts of a centrifugally cast roll of alloy IC-221M to ORNL for the development of girth welding procedures. Industrial welding capability for nickel aluminide alloys will enhance the commercial viability of furnace rolls and be important for many other applications.

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Nickel aluminide furnace rolls cost about twice as much as rolls made from steel. However, experience so far indicates that they will greatly extend the service life of the rolls. Based on the successful trials, Bethlehem Steel has ordered 32 transfer roll assemblies for delivery during 1997 to their Burns Harbor Plant.

GM Delphi Saginaw Steering Systems

Delphi Saginaw Steering Systems is investigating the use of nickel aluminides for trays and assemblies in carburizing heat-treating furnaces. The furnace assemblies (Figure 2-6) include base trays, upper fixtures, lower fixtures, and support posts. Each assembly carries about 340 kg (750 lbs) through the furnace. In comparison with the steel alloys now being used, nickel aluminides offer potential advantages of superior carburization and oxidation resistance, higher elevated temperature strength, and higher creep strength, which would reduce scheduled and unscheduled down time in heat-treating furnaces. If these advantages can be realized, an additional payoff could be savings in energy because assemblies produced with less mass require less energy to heat.

This project began in 1992 with a CRADA between Delphi Saginaw Steering Systems and ORNL. The program is being carried out in three phases. The first phase, beginning in 1992, consisted of the development of casting and molding techniques at Alloy Engineering and Casting Company (AECC), mold filling and solidification modeling at ORNL, coupon tests in a pusher-type carburizing furnace at Delphi, and the development of welding at ORNL.

The longer, second phase was an effort to evaluate trays under production conditions. A cast batch-furnace tray was successfully produced at AECC using the IC-221M alloy. This tray was used for 18 months in 1993 and 1994 in a carburizing batch-furnace, and its performance was evaluated against the performance of a conventional tray of the normally-used HU steel alloy. Both trays were exposed to approximately 1,300 furnace cycles, after which the HU tray had

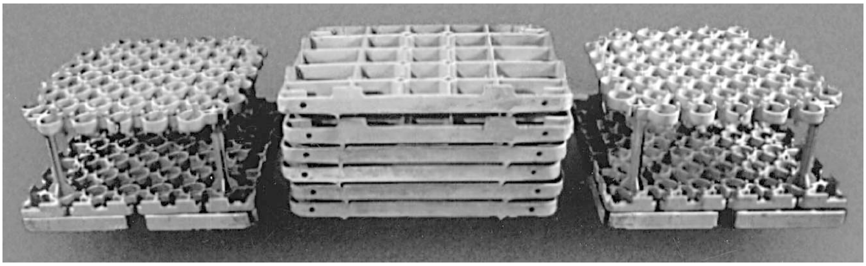

FIGURE 2-6 Ni_3Al carburizing grids (cast at Alloy Engineering and Casting Company, Champaign, Illinois, for Delphi Saginaw Steering Systems, Saginaw, Michigan). Source: ORNL.

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degraded to the point of failure and was removed from service. The nickel aluminide tray was in much better shape. Analyses of the tray and test coupons revealed that the nickel aluminide components were much less susceptible to carburization than the HU alloy. Also, the hardness of the nickel aluminide material was not affected, while the hardness of the HU samples increased significantly. The nickel aluminide tray will be returned to use in the furnace for additional evaluation.

In the third phase of the program, two cast nickel aluminide assemblies (IC-221M pusher trays) have been produced at AECC to be used in a carburizing furnace and compared to the current assemblies, which are made with HU material. One assembly is as-cast; the other is preoxidized. Both assemblies have been in service since January 1996 in a carburizing furnace. Six more batch-furnace trays, three as-cast and three preoxidized, have been produced by AECC for further evaluation in a batch-furnace line.

Delphi believes there is a risk in the large-scale use of nickel aluminides in production carburizing furnaces because of an incomplete understanding of the mode(s) of failure. Data from trial applications will help, but this is an area that requires further study. Based on the earlier success, Delphi has ordered 63 pusher-furnace assemblies for delivery in 1997. Although the use of Ni_3Al in heat-treating furnaces looks promising, currently-used alloys are adequate, and procedures have been developed for processors to deal with weaknesses. Consequently, the rate of introduction of nickel aluminides into production applications may be slow.

United Defense LP

United Defense LP/Steel Products Division (UDLP) is committed to the commercialization of nickel aluminides (and intermetallics in general). At this time, UDLP is the only foundry licensed to melt and pour nickel aluminide-based alloys. UDLP has entered into three Ni_3Al license agreements with ORNL including (1) a domestic general producer license, (2) an exclusive domestic field of use license for tooling and dies, and (3) a foreign combined general and field of use license. Both UDLP and ORNL believe that exclusive licensing to protect the licensee's initial investment from competitors is an essential incentive for commercialization. UDLP has rationalized its investment by having some exclusivity and an opportunity for a head start. In anticipation of future earnings, they have invested significantly in process development, hired scientists to focus on intermetallics, and as of May 1996, melted more than 22,690 kg (50,000 lbs) of nickel aluminide alloys. UDLP sees the role of ORNL, the licenser, as developing technology and promoting and supporting commercialization; they see their role, the licensee, as investing in the technology and producing, marketing, and profiting from products industry wants.

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UDLP has received more than 250 inquiries, both domestic and foreign, and is working to develop products for many industries, including metal casting, steel, chemical, petrochemical, glass, and others. Their efforts so far have been focused on Ni_3Al alloys, but there is also a good deal of interest in FeAl, Fe_3Al, NiAl, and composite materials. They have identified a need for material data (for process modeling, product characterization, etc.), developing welding capability, and developing new alloys.

UDLP appears to be an effective licensee because it is a potential producer, fabricator, and end user of nickel aluminides. The company not only has melting and casting capabilities, but also mechanical presses for forging. UDLP has potential in-house applications for nickel aluminides in its heat treating and forging operations, and its parent company, FMC, may be able to use nickel aluminides in a broad range of manufacturing processes. As a producer, fabricator, and end user, UDLP has the infrastructure for integrated product development and testing.

Other Industrial Interactions

ORNL identified a number of other industrial interactions related to Ni_3Al alloys that are under way. These include:

- processing technology for sand and centrifugal castings (AECC)
- evaluation of Ni_3Al alloys for walking-beam furnace components, such as rails, support bars, and pins (Rapid Technologies, Incorporated)
- development of walking-beam furnace parts and other components (BIMAC, an investment casting foundry, and Castmasters, a sand and investment casting foundry)
- exploratory research in the powder metallurgy of Ni_3Al alloys and possible uses, such as the production of powder-cored weld wire (Ametek Specialty Metal Products Division)
- evaluation of Ni_3Al alloys for use in heat-treating trays and fixtures and for forging tooling (Wyman-Gordon Company)

Other companies working with ORNL include:

- A. Finkl and Sons (furnace bucks and hot ingot cutting tools)
- The Timken Company (carburizing furnace fixtures)
- Lukens Steel (transfer rolls in steel heat-treating furnaces)
- Chevron Corporation (tube hangers in heat recovery boilers)
- PCC Airfoils, Incorporated (trays for ceramic mold sintering furnaces)
- Canmet Canada (permanent molds for casting brass parts)
- SPS Technologies, Incorporated, and Valley-Todeco, Incorporated (fastener fabrication)

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- Hoskins Manufacturing Company and Harrison Alloys (heating element wire)
- Armco Research and Technology (supplier of cast and wrought Ni_3Al alloys)

User Facility

OIT has recently established a DOE user facility at ORNL for metals processing. The facility is called the Metals-Processing Laboratory User Center. The purpose of this center is to provide industry and universities with access to technical expertise and equipment related to metals processing, joining, characterization, and process modeling. The laboratory user center provides ORNL an opportunity to work with researchers and industrial representatives to identify issues and concerns related to the industrial uses of advanced alloys.

CONCLUSIONS

This remainder of this chapter presents the panel's evaluation of the progress and accomplishments of the ORNL program to develop intermetallic alloys. The evaluation includes conclusions pertaining to program management, the conduct of the technical program, and industrial interactions. Recommendations are contained in Chapter 4.

Overall, the ORNL intermetallic alloy development program has been successful in terms of the technical goals and objectives established by the program, i.e., to develop high strength, ductile intermetallic alloys that can be processed and utilized for high-temperature structural applications. The program has been well managed, with effective integration of program elements—from basic research through production-scale demonstrations—and coordination of program goals and responsibilities among participating funding and research organizations. The program has contributed significantly to the fundamental understanding of intermetallics, the development of alloy compositions with useful ranges of properties and performance characteristics, and the development of manufacturing processes for commercial applications. The alloys have performed well in production-scale trials, but full commercialization of Ni_3Al alloys has been slow. However, commercialization is the ultimate goal of the new OIT program.

Program Management

In the panel's judgment, the ORNL intermetallics program has been a successful science and technology development program for a number of reasons. These include:

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- *Consistent commitment of resources*. Consistent and continuous funding (since 1982) has allowed ORNL to assemble a team of outstanding researchers and to establish an international reputation in alloy and process development and characterization.

- *Effective program integration*. The effective organization and management of this multidisciplinary program and the effective coordination among DOE program offices and ORNL have made the technical success of the program possible. As a lead laboratory, ORNL has coordinated the efforts of universities, other laboratories, and industry and has facilitated interactive and iterative activities between basic and applied research and development.

- *Flexibility*. Throughout the history of the program, research efforts have been reoriented and refocused in response to promising results or identified needs, without compromising scientific excellence.

- *Industry involvement*. Partnerships and collaborations with industry have helped the program identify industry needs and establish practical goals for technology development.

Technical Program

The ORNL intermetallic alloy development program has made significant technical advances since its inception—from basic exploratory research and characterization through process development and scaling. The early decision to focus on Ni_3Al and to concentrate on optimizing alloy composition, characterizing material behavior, and developing production-scale processing methods has been critical to the success of the program.

Technical accomplishments in material characterization and in the development of Ni_3Al alloy compositions include:

- the identification of brittle grain-boundary fracture mechanisms at ambient temperatures and the substantial loss of ductility at intermediate temperatures as major material deficits
- the determination of causes for brittle ambient-temperature fracture (moisture-induced embrittlement) and intermediate-temperature ductility loss (dynamic oxygen-induced degradation)
- the improvement of ductility by microalloying with boron and chromium
- the improvement of elevated temperature strength and processibility using standard alloying techniques, including solid-solution strengthening (Mo), dispersion strengthening with carbides and borides (C, B), and improving strength, weldability, and castability (Zr, Hf)

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ORNL researchers have attempted to apply lessons-learned to other intermetallic compounds but with limited success.

In the panel's judgment, some of the most significant accomplishments of the intermetallic alloy research program have been in the development of manufacturing processes. Developments in this area include:

- development of production-volume melting process that maintains aluminum concentration while melting higher-temperature-melting constituents (Exo-melt process)
- development and testing of methods and alloy modifications for low-cost casting processes
- development of materials (e.g. weld wire) and processes for structural welds and weld repairs

Interaction with industrial participants throughout the program have been critical to identifying the needs and priorities for process development.

Although considerable progress has been made, significant work must still be done to enable Ni_3Al alloys to be used for commercial production, including:

- fundamental research to determine the mechanisms of ductility enhancement provided by alloying elements so that alloy composition can be further optimized
- characterization testing to provide engineering properties, for example creep, fatigue behavior, and fracture toughness
- development of data to model solidification (casting and welding) processes and to establish production processing standards and the development of methods for machining and welding nickel and iron aluminides

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3

Program Strategies

The progress and accomplishments of the DOE/ORNL intermetallic alloy development programs have demonstrated how breakthroughs in exploratory and basic research can be developed into commercially promising technologies. This chapter describes the lessons from the ONRL program and their influence on the overall OIT program strategy and commercial applications. The experience from the ORNL intermetallics alloy program can provide guidelines to OIT on how to effect the transition of their research program to the industry-led IOF (Industries of the Future) strategy.

IDENTIFYING AND PRIORITIZING PROJECTS

Until 1995, research and development management of the overall OIT program was driven by a "technology push" strategy. This approach led to documentable technological successes—the development of new materials, properties, and processes—but their commercial impact was more difficult to document. In 1995, OIT's program management strategy was revised to reflect a new commitment to increasing and documenting the commercial impact of OIT programs, provided they still met the overall goals of improving energy efficiency and reducing adverse environmental impact. OIT's research and development management strategy was changed from a "technology push" strategy to a "market pull" strategy. However, two key issues still had to be resolved:

- Which markets should be served?
- Who, within these markets, should do the "pulling"?

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To answer the first question, OIT ranked industries according to their level of energy consumption and waste production. Seven industries—steel, forest products, glass, metal casting, aluminum, chemicals, and petroleum refining—were found to consume more than 80 percent of the energy and to produce more than 90 percent of the hazardous waste products generated in the manufacturing sector of the economy. These seven industries, designated IOF, became the focus of OIT's programs. OIT's research projects are now selected and prioritized to meet the business and technological needs of the IOF.

In the past, technologists and research and development directors from the targeted industries were asked to provide direction for OIT research. In the IOF strategy, the desire to develop industry commitments to research partnerships has led OIT to seek additional guidance on research priorities. Although the industry technical staff still provides a significant voice in setting industry priorities, OIT industry groups also derive input and support from the chief executive level for direction in the form of consensus-based, industry-wide "vision documents" that will ultimately lead to technology-development plans or "road maps." With OIT's assistance, the IOF industries have developed, or are developing, these vision documents.

Throughout the ORNL intermetallic alloy development program, interaction with industrial participants has been critical to identifying the needs and priorities for developing alloys and processes. Interactions with industry have provided ORNL with a focus on optimizing alloy compositions and developing process technologies to meet industrial needs (see Chapter 2). The experience of the ORNL intermetallic alloy development program in using industrial guidance to establish program goals and objectives may be of use to OIT in implementing the IOF strategy.

ORNL is in the process of assessing their program strategies and research projects with respect to IOF industry needs. For example, an analysis of the needs of the pulp and paper industry *vis a vis* the AIM program goals and ORNL projects has recently been completed (Angelini, 1995). The analysis was based on the industry vision document for the forest products industry (AF&PA, 1994) and on industry workshops with technologists to identify ways that ORNL and the AIM program could address those needs. The intermetallic alloy program would benefit from similar analyses of other industry visions. Examples of potential applications include expanding the use of Ni_3Al for hot metalworking (dies, fixtures, furnace components), developing nickel and iron aluminides for processing equipment used in high temperature and corrosive environments in the chemical and refining industries, and using Ni_3Al in transfer and processing rolls for the steel and paper industries.

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BALANCING INDUSTRY-FOCUSED AND CROSSCUTTING PROGRAMS

Relying exclusively on market pull to define research and development objectives has certain inherent drawbacks. Federally initiated, crosscutting research programs involving technologies that could potentially benefit many industries, but are not the primary concern of any one industry, are not likely to elicit much interest in a market pull strategy. For example, it would be erroneous to assume that a program like the intermetallic alloy development program, which began as an exploratory research project and progressed through the efforts of various DOE program offices and diverse industrial participants, would receive industry support if it had been proposed within the OIT IOF strategy. The panel believes that there is no simple, self-reinforcing mechanism whereby a market pull strategy can be used to identify promising crosscutting programs. Instead, the panel recommends that OIT adopt the following approach:

- Decide, with input from the IOF communities, on an appropriate percentage of overall research and development to be devoted to exploratory research and crosscutting technologies, i.e., develop a consensus that a percentage of research and development funds should be designated for the development of crosscutting technologies.
- Based on analyses of the various IOF road maps, identify common (or related needs) and define and select a list of recommended exploratory research and crosscutting technologies for development. For example, identify potential applications that would benefit from the development of process technologies and the optimization of a particular alloy or alloy family.
- Review these recommendations with the IOF working groups and solicit support and feedback for exploratory and crosscutting projects.

METRICS FOR SELECTING AND PRIORITIZING PROJECTS

Every method of measuring the efficacy of research and development programs has proponents and detractors, and none is universally or even widely accepted. One method, developed for evaluating materials processing innovations, recommends criteria based on (1) potential cost-effectiveness, (2) potential for exploiting new materials technologies, (3) commercial impact, (4) environmental compatibility, and (5) broad applicability (NRC, 1995). The panel recommends consideration of the following metrics, which are compatible with DOE and OIT organizational objectives, as a basis for comparing and selecting programs for the OIT IOF program:

- potential for energy conservation
- potential for waste reduction

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- consistency with IOF business objectives and technology road maps
- commercial potential/market value
- potential crosscutting benefits for multiple applications in more than one industrial sector

The best metrics for measuring OIT's efficacy are likely to be some of the same measures used internally by the IOF. Research and development managers from these industries should be asked to describe their approaches to setting research and development priorities and to measuring research and development effectiveness. However, "profit-based" metrics used in industry (e.g., return on investment) may not be appropriate for measuring the efficacy of government-funded, long-term research. IOF guidance should be sought to ensure that the program is relevant, but the panel suggests that short-term (i.e., one to three years) commercial potential should not be the primary "compass" that directs the selection of OIT programs.

COMMERCIALIZATION

Usually the word "commercialization" implies one of two possibilities. Either the embodiment of a technology must be sold in a way that is both profitable and sustainable, without corporate or government subsidies, or it must be incorporated into a component or system that is similarly sold. In short, to be considered a "commercial" product, normal transactions in the market involving its manufacture and sale must result in someone earning money.

Advanced materials, such as Ni_3Al, are generally developed to meet perceived performance goals set by the user (e.g., high strength and oxidation resistance at elevated temperatures). However, barriers to commercialization may arise if costs, manufacturing processing requirements, and adequate supplier base are not taken into account during the development process. The developers must recognize that alternative materials and solutions may exist, perhaps with lower initial costs. Industries will generally seek the lowest cost alternative compatible with their existing manufacturing knowledge and facilities. Commercialization of Ni_3Al alloys has been relatively slow because there are alternatives to intermetallics for all potential applications. The alternatives now in use may not have the properties (oxidation and carburization resistance, mechanical properties) that nickel aluminides can deliver, but they are well known, perform adequately, are reliable, and usually have lower initial costs.

To replace an established material with an alternate, factors other than performance must also be considered. These include:

- cost and supply of raw materials
- production capability of suppliers and manufacturers
- cost of materials, fabrication processes, and tooling and facilities

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- environmental considerations, including the disposition of wastes
- demonstrated material reliability
- supplier infrastructure
- risk and consequences of material failure

Meeting OIT's commercialization objectives requires early and ongoing interaction with industry/users to ensure that the real hurdles and motivations for acceptance are understood. In addition, developing advanced materials for commercial applications generally requires substantial technology development, especially processing technology. These criteria are part of the ORNL commercialization strategy. For example, ORNL work on nickel aluminide is focused on castability, weldability, formability, scale-up, and mechanical properties, all of which address industrial needs. Work by the ORNL Metals Processing Lab and their technical support of industrial product development have been very important. The AIM program strategy, the IOF focus, the Metals-Processing Laboratory User Center, and changes in the licensing strategy have established a framework for developing technologies that can be commercially successful.

However, commercializing new technologies is a difficult and risky proposition, even for corporations that specialize in, and depend upon, commercialization. Established materials and manufacturing companies worldwide have long lists of failed efforts to commercialize new technologies. In fact, failures greatly outnumber successes. Consequently, in many ways it is unrealistic for ORNL to measure the efficacy of a particular research and development program against the metric of commercialization.

There is no standard way to commercialize new technologies, but there are stages in the commercialization process (NRC, 1993). These stages, shown schematically in Figure 3-1, include the following:

- technology development (research and development)
- product development and demonstration, including trials with selected "key" customers
- early commercialization, including optimization of manufacturing processes and scale-up
- full commercialization to bring the product to market, including market research, developing promotional materials and marketing strategies, and training sales personnel

At every stage of commercialization, the proponents of a new technology must solicit, defend, and secure corporate commitment and funds before advancing to the next step. For new materials technologies, the process generally takes years, often more than a decade, to complete (NRC, 1993).

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ACTIVITY	Develop Knowledge Base	Develop Technology; Examine Concept Feasibility	Large Scale Experimentation and Prototyping/Demonstrate System and Subsystem Feasibility		Develop and Design Advanced Systems	Optimize Processing and Scale-up	Bring to Market
INDUSTRY TERMINOLOGY	Technology Base Development		Product Development and Demonstration		Early Commercialization		Full Commercialization
DOD TERMINOLOGY	6.1 Basic Research	6.2 Exploratory Development	6.3 Advanced Development: 6.3A Component Development	6.3B Feasibility Demonstration	6.4 and 6.5 Engineering Design/Operational Systems Development		Operational Capability

FIGURE 3-1 Phases and activities in the commercialization process. Source: NRC, 1993.

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As part of the federal research and development establishment, it is not possible for OIT to participate fully and actively in the commercialization process, especially in the later stages when the product is brought to market. The technologies developed by OIT must be commercialized by industry. Given the low success rate of the commercialization process, it is difficult to recommend ways to significantly increase the probability of successful commercialization. However, the following actions will improve the probability of production applications of technologies developed under OIT research and development auspices:

- Involve key industrial participants representing suppliers, producers, and users of a material or process technology.
- Avoid making license arrangements that require unrealistic technology development for commercialization (i.e., do not license too early), that unnecessarily restrict application of the technology, or that grant broad field-of-use exclusivity.
- Support projects with potential suppliers and users of the technology to demonstrate and debut the technology.
- Provide a mechanism for the orderly termination of (1) projects that have progressed to the final stage of commercialization (market introduction) or (2) projects that do not have sufficient industrial interest to support demonstration, process development, and scale-up efforts.
- Publicize the technical accomplishments of the program at trade meetings (for instance, the Metallurgical Society, Society of Automotive Engineers, Society of Plastics Engineers, ASM International, and the American Chemical Society). Use these meetings as opportunities for making contacts and establishing networks with technical and business people who may be interested in the technology.
- Establish networks that include not just technical experts, but also sales, marketing, and senior management personnel.
- Expose OIT and laboratory technical personnel to basic business principles associated with commercialization, including cost estimation, value analysis, and market research.
- Recognize that technology development is only a very small link, albeit an important one, in the commercialization chain.

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4

Conclusions and Recommendations

The intermetallic alloy development program at ORNL has contributed significantly to the understanding of intermetallic materials and processing technologies. The program has been characterized by outstanding research and effective coordination between basic and applied research organizations. More important, extensive interactions between ORNL and industrial participants interested in the commercial applications of intermetallic alloys have led to the development of critical alloy compositions and processing methods.

The lessons learned from the development of Ni_3Al alloys and processes can provide general guidelines to OIT in the implementation of the IOF strategy throughout the OIT program. The conclusions and recommendations discussed in this chapter are primarily applicable to OIT-sponsored intermetallic alloy projects and reflect the goals and vision of the OIT/AIM program, i.e., to support development and commercialization of new or improved materials to improve energy efficiency, productivity, and product quality in the major process industries.

Overall, the ORNL intermetallic alloy development program has been successful in terms of the technical goals and objectives established by the program, i.e., to develop high strength, ductile intermetallic alloys that can be processed and utilized for high-temperature structural applications. However, full commercialization of developed technologies, the ultimate objective of OIT's research strategy, has been slow.

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PRIORITIZATION AND METRICS

ORNL's intermetallic alloy program was at first curiosity driven and later technology push driven. Promising applications were identified through interactions with industry and collaborations, workshops, and internally-funded market analyses. Although this approach led to advances in the understanding of materials and process technology for the intermetallic alloys under study, it did not lead to commercialization. Since 1995, the program has been in transition to the OIT IOF (Industries of the Future) strategy; business and technology needs identified by the IOF teams are used to establish program priorities. ORNL has already begun analyzing their priorities with respect to the industry visions, but it is still too soon to predict that the IOF strategy will lead to commercial success or that the level of success will repay the research investment.

The panel believes that relying solely on industry needs, even with an effective identification strategy, has inherent drawbacks. Important crosscutting or exploratory research programs might not be supported if they are not identified as critical industry needs by any one group. The intermetallic alloy development program, for example, which began as an exploratory research project, might not have been supported.

Recommendation. The panel recommends that OIT and the ORNL intermetallic alloy development program use the following approach to identify and prioritize research programs.

- Identify IOF needs and priorities that may be met through the application of intermetallic alloys. Identify possible new projects that are consistent with the IOF vision documents and identified research and business priorities. (The analysis by ORNL of the forest products industry is an important first step in this process.)
- Establish, with input from IOF teams interested in the commercial uses of intermetallic alloys, a target level of support for crosscutting research and development programs.
- Identify projects with the potential to meet identified industry needs. For example, explore the expanded use of Ni_3Al for hot metalworking (dies, fixtures, furnace furniture), the use of nickel and iron aluminides for processing equipment in high temperature and corrosive environments in the chemical and refining industries, and the use of Ni_3Al for transfer and processing rolls for the steel and paper industries and dies for the glassmaking industry. Develop material and process technology goals based on these potential applications.
- Emphasize crosscutting projects that could lead to commercial application in more than one industrial sector.
- Increase the interactions between ORNL and industry through the Metals-Processing Laboratory User Center. Use the center to identify industry

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needs and issues that may require further research in the intermetallic program.

- Explore the use of value-based metrics, such as metrics based on methods of market and cost analysis, to evaluate and prioritize research and development projects and goals.

FOCUS FOR THE RESEARCH AND DEVELOPMENT PROGRAM

The ORNL intermetallic alloy development program has made significant technical advances in exploratory research and characterization and process development and scaling. The early decision to focus on Ni_3Al and to concentrate on optimizing alloy composition, characterizing material behavior, and developing production-scale processing methods was critical to the success of the program.

Technical accomplishments in material characterization and in the development of Ni_3Al alloy compositions include the identification of critical material deficiencies, the characterization of important degradation mechanisms, and the optimization of alloying technology to improve structural performance and processibility. ORNL researchers have attempted to apply the lessons learned from these developments to other intermetallic compounds, with limited success.

In the panel's judgment, some of the most significant accomplishments of the intermetallic alloy research program have been in the development of manufacturing processes, including the production-volume melting process (Exo-melt process), methods and alloy modifications for low-cost casting processes, and materials and processing methods for structural welds and weld repairs. Industrial participants have been critical in identifying these needs and priorities. Additional work, including welding and machining process development and the development of solidification models for casting and welding processes, may be needed to accelerate the commercial use of Ni_3Al alloys.

Recommendation. Focus research on alloy optimization and the development of process technologies for a selected number of alloy families for which ORNL has unique expertise and capability. In addition to the Ni_3Al-based alloys emphasized in previous characterization and development programs, ORNL has particular experience with the iron aluminides (Fe_3Al, FeAl).

Recommendation. Continue to emphasize the development of manufacturing process technology for selected alloys to maximize opportunities for commercialization and technology transfer to industry.

Recommendation. Emphasize low-cost processes in the development and optimization of intermetallic alloys.

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Recommendation. Develop data bases of materials properties and processing methods to support industrial application and commercialization. In addition to the physical and mechanical properties that were emphasized in previous work on Ni_3Al, develop data required to model solidification (casting and welding) processes. Establish production processing standards and methods for machining and welding nickel and iron aluminides.

Recommendation. Whenever possible, use alloys and processing in ORNL laboratory equipment to gain experience through operational tests and technology evaluations with developmental materials. For example, use Ni_3Al within ORNL for in-furnace fixtures and metalworking tools and dies.

IMPLICATIONS FOR THE OFFICE OF INDUSTRIAL TECHNOLOGY PROGRAM

The panel believes that the ORNL intermetallics program is an excellent example of a successful scientific and technological program, with effective integration of program elements—from basic research through production-scale demonstrations—and effective coordination of program goals and responsibilities among participating funding and research organizations. Long-term, consistent, collaborative funding by various DOE program offices, effective program integration, flexibility to reorient and refocus research based on promising results or identified needs, and partnerships and collaborations with industry have all contributed to the success of the program. The lessons learned from the development of Ni_3Al alloys and processes can provide OIT with general guidelines for coordinating and managing several research organizations and funding from several sources, and for effective industrial collaborations. These guidelines can assist OIT in the implementation of the IOF strategy throughout the OIT program.

Throughout the ORNL intermetallic alloy development program, interactions with industrial participants have been critical to identifying the needs and priorities for technology development. However, the profit-based metrics used in are not appropriate for measuring the efficacy of government-funded, long-term research. IOF guidance should be sought to ensure that the program remains relevant, but the panel suggests that short-term (i.e., one to three years) commercial potential should not be the primary "compass" directing the selection of OIT projects. In the panel's judgment, metrics compatible with DOE and OIT organizational objectives for comparing and selecting programs for the OIT IOF program should include: potential for energy conservation, potential for waste reduction, consistency with IOF business objectives and technology road maps, commercial potential/market value, and potential benefits for multiple applications in more than one industrial sector (crosscutting technologies).

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The results of successful use of Ni_3Al alloys in a variety of trial production applications, as well as recent commercial orders for furnace transfer rolls in steel mills and heat-treat furnace fixtures, indicate that commercial application of these alloys is likely to expand in the next several years. However, although Ni_3Al alloys have performed well in production-scale trials, it is unclear at this time if the level of successful commercial application will repay the research investment. Full commercialization has been slow for a variety of reasons. First, alternative materials are available for all potential applications. To replace an established material, factors other than performance must be considered. These include the cost and supply of raw materials; production capability; cost of materials, fabrication processes, tooling, and facilities; demonstrated reliability; and supplier infrastructure. Second, successful commercialization requires a strong, committed, and in some instances lucky industrial proponent who understands the real hurdles and motivation for industrial acceptance. Finally, the technology, especially the processing technology, must be substantially developed prior to commercialization. These criteria have been incorporated into the commercialization strategy for the ORNL intermetallics program. However, as part of the federal research and development establishment, it is not possible for OIT to participate fully and actively in the commercialization process, especially in the later stages when the product is brought to market. Technologies developed by OIT must be commercialized by industry.

Recommendation. Emphasize the early involvement of key industrial participants representing suppliers, producers, and users of particular materials or process technologies. Use collaboration mechanisms, such as cooperative research and development agreements, cofunded research programs, exchanges of personnel, and the laboratory user center.

Recommendation. Support projects with potential suppliers and users of the technology to demonstrate and debut the technology.

Recommendation. When licensing technology developed within the OIT research and development program, understand the relationship between the technical program and the licensee's business strategy. Avoid making exclusive license arrangements that rely on unrealistic technology development for commercialization (i.e., do not license too early) or that unnecessarily restrict or preclude application of the technology in other fields of use.

Recommendation. OIT should develop a mechanism for the orderly termination of (1) projects that have met OIT objectives and have progressed to the final stage of commercialization (market introduction) and (2) projects that do not have sufficient industrial interest to support demonstration, process development, and scale-up.

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Appendices

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Appendix A

Meeting Agenda

Panel on Intermetallic Alloy Development

Thursday, June 6 and Friday, June 7, 1996
Oak Ridge National Laboratory
Oak Ridge, Tennessee

Thursday, June 6, 1996

8:15 am	Introduction	Pete Angelini, *ORNL (OIT program)*
8:30	Welcome	Bill Appleton and Jim Stiegler, *ORNL*
8:45	NRC Committee and Panel Objectives	Norman Gjostein, *panel chair*
9:00	Integration of Research and Development Efforts on Ni_3Al and Iron Aluminide	Linda Horton, *ORNL (BES program)*

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Session 1a. Technology Development

9:30	Design of Ni_3Al alloys (History of Ni_3Al alloy development)	C. T. Liu, *ORNL*
10:10	Fabrication Technology of Ni_3Al Alloys (Casting and wrought aspects of fabricating Ni_3Al; other industrial needs; data base; alloy design and materials fabrication)	Vinod Sikka, *ORNL*
11:05	Joining of Ni_3Al (Historical development in the area of welding and joining technology for Ni_3Al; IC-50 alloy, IC-221 alloy, FA alloy; wire and consumables; bulk and weld overlay [weld repair])	Mike Santella, *ORNL*
11:45	Design and Status of Other Intermetallic Alloys/Composites (Applicability of initial alloy design advances to other materials systems, joining, alloy design [structural and weld overlay])	C. T. Liu, *ORNL*

Session 1b. Program Management

9:15	BES Perspective	Linda Horton, *ORNL (BES program)*
9:45	Fossil Energy Perspective	Rod Judkins, *ORNL (FE programs)*
10:30	AIM efforts (ECUT and AIM efforts, objectives, selection criteria, subcontracts, CRADAs)	Pete Angelini, *ORNL (OIT/AIM programs)*
11:30	Commercialization (outline and status of patents, licensing technology)	Larry Dickens, *ORNL*

Session 2. Current and Future Applications and Plans

1:15 pm	Tour of Processing Laboratory (highlighting Ni_3Al components being evaluated by industry)	Vinod Sikka, *ORNL*

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1:45	Industrial Perspective (forging dies, heat treating systems; user/producer)	Gary Hudson, *United Defense*
2:15	Industrial Perspective (heat treating trays for carburizing furnaces; user)	Jim Farago, *General Motors*
2:45	Industrial Perspective (centrifugal casting of Ni_3Al rolls for steel reheat furnaces; producer)	John Rogers, *Sandusky International*
3:30	Additional Industrial Interactions	Vinod Sikka, *ORNL*
4:00	Future Activities and Relationship to IOF	Pete Angelini, *ORNL* (*OIT/AIM programs)*

Friday, June 7, 1996

8:30 am	Panel Executive Session (conclusions and recommendations)	Panel
1:00 pm	Tours of Facilities Important to the Development of Intermetallic Alloys (Alloy Development, Materials Fabrication, Joining and Welding, Atom Probe, Analytical Electron Microscopy)	
2:30	Summary	Peter Angelini, *ORNL* Norman Gjostein, *panel chair*

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Appendix B

Biographical Sketches of Panel Members

Norman A. Gjostein (chair) is a materials engineering consultant. He retired in 1995 as director of Powertrain and Materials Research Laboratory at Ford Motor Company. Dr. Gjostein's directorate included research in automotive materials, engines, computer-aided engineering, and manufacturing systems. His experience has included 35 years at Ford, mostly in the evaluation and application of advanced materials in automotive systems. He has experience in process design and commercialization, as well as in the evaluation of intermetallic alloys for automotive engine applications. Dr. Gjostein is a member of the National Academy of Engineering and is currently serving on the Committee on Industrial Technology Assessments.

John V. Busch is president and founder of IBIS Associates. His professional focus is in economics and business development for technology-based organizations with specialties in business development, cost modeling, and technology assessment. In addition to his business background and experience, Dr. Busch has technical background in materials science and engineering, industrial materials processing, polymers and composites, economic analysis, and cost modeling. He is currently serving on the Committee on Industrial Technology Assessments and is a member of the National Materials Advisory Board.

Timothy E. Howson is director of technology of the Forging Division of Wyman-Gordon Company, a producer of high-performance forgings. Dr. Howson has worked at Wyman-Gordon for over 14 years and has experience in

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thermomechanical processing of nickel and titanium alloys, process modeling, and the development and control of forging and other manufacturing processes.

Lyman A. Johnson is manager for technology implementation at the GE Aircraft Engines Engineering Materials Technologies Laboratories. He has been responsible for the research and development activities on advanced metallic materials and composites, including intermetallic alloys, at both GE Aircraft Engines and GE Corporate Research and Development Center. Dr. Johnson has been at GE for 29 years and has experience in commercialization of intermetallic alloys for jet engine and other applications.

Harry A. Lipsitt is professor emeritus of materials science and engineering in the Department of Materials and Mechanical Engineering at Wright State University. Dr. Lipsitt spent 30 years at the Air Force Wright Laboratories working on the development and evaluation of high-temperature metals and on pioneering research on intermetallic compounds. His research and expertise are in physical and mechanical metallurgy.

Anatoly Nemzer is manager of materials engineering at the Princeton Research and Development Center of the FMC Corporation. Mr. Nemzer was trained as a chemist and chemical engineer. He has been involved in process development chemistry and corrosion engineering within the chemical processing industry for 16 years. He spent 10 years at Rohm and Haas before taking his current position at FMC in 1990. He has been active in the development of new applications for high-temperature, corrosion-resistant materials in chemical processes. Mr. Nemzer is a member of the board of directors of the Materials Technology Institute of the Chemical Process Industries, Inc.

Maxine L. Savitz is general manager of AlliedSignal Ceramic Components. Her experience includes materials development, production, and utilization; technology transfer; energy policy and energy conservation; and aerospace technology. Dr. Savitz has served on research advisory panels concerned with materials and processing and energy programs for several agencies, including the Gas Research Institute, the National Institute of Standards and Technology, DOE, and the Oak Ridge National Laboratories. Dr. Savitz is a member of the National Academy of Engineering and is currently serving on the Committee on Industrial Technology Assessments.

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