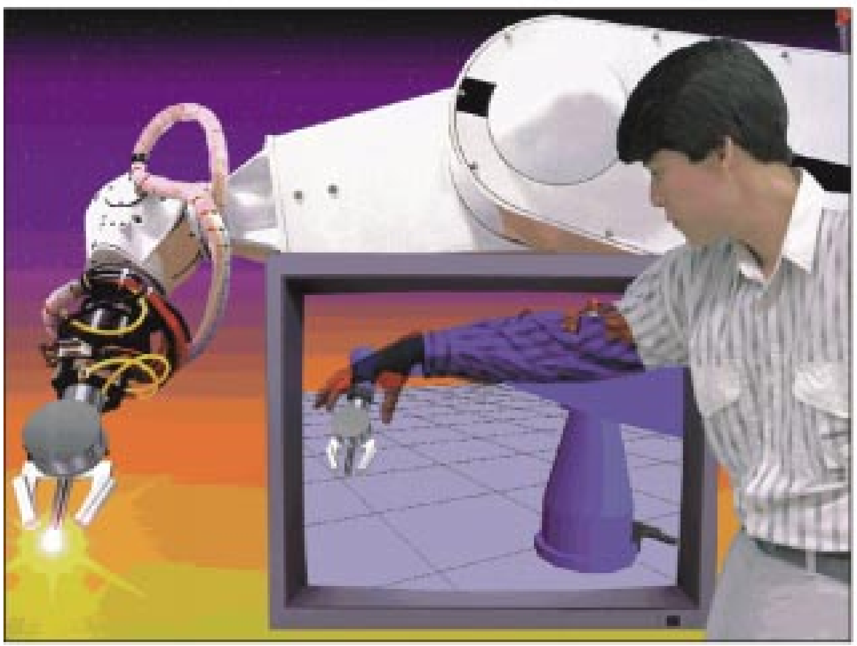
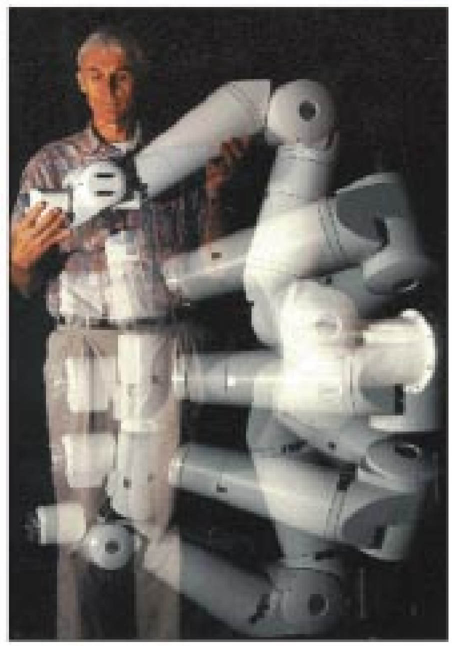




ROBOTICS AND INTELLIGENT MACHINES
IN THE U.S. DEPARTMENT OF ENERGY

A CRITICAL TECHNOLOGY ROADMAP

OCTOBER 1998

THE ROBOTICS AND INTELLIGENT MACHINES ROADMAP DEVELOPMENT TEAM

DOE Representatives
Core Group
Chair: Charles Stuart (DP)

DP: Charles Stuart
Duane Lindner

EE: Marie-Louise (Mal) Caravatti
Lou Divone

EH: Myrna Steele
Murari Sharma

EM: Lin Yarbrough
John DeGregory
Ed Rizkalla

ER: Bob Price
Sam Berk

FE: Marvin Singer
Roy Long

MD: Andre Cygelman
Martha Shields

NE: Jack Wheeler
Anne Phillips
Dan Giessing
Frank Goldner

NN: Terry Donaldson

LABORATORY Representatives
Support Group
Chair: Patrick Eicker (SNL)

SNL: Patrick Eicker
Al Jones
Randy McKee
Ray Harrigan
Leslie Rettinger
Bob Watson
Kwan Kwok
Marie Garcia
Warren Klein
Olin Bray

ORNL: Joe Herndon
Jacob Barhen
Bill Hamel
Reid Kress
Mark Noakes
Lynne Parker
Francois Pin
Nageswara Rao
Thomas Zacharia
John Blair

INEEL: Ron Lujan
Art Denison
Marty Sorenson

LANL: Mark Dinehart
Ken Franklin

LLNL: Maynard Holliday

SITE Representatives
Support Group

Pantex: Jerry Harbour

Allied Signal FM&T:
Dennis Stittsworth
Jim Dycus
Bill Sprague

Lockheed Martin-Y-12:
Dave Post

Savannah River Site:
Jim Wong

OTHER Federal Agencies

NSF: Bruce Kramer

DARPA: Eric Krotkov

ON THE COVER

Upper left: Shown here is a robotic system, currently being developed to serve as a remote inspector for use in materials monitoring operations. Its design will allow for a near-human presence without subjecting personnel to hazardous materials or environments.

Lower left: Integration of perception, action and reasoning capabilities enable this welder to operate a robotic cutting tool from a safe distance. In the future, such technology will offer human-machine interfaces that are as easy to operate as the current personal computer.

Upper right: By the year 2020, team of intelligent machines will be sent to buried waste sites, and in a few weeks they will sense and map the location of contamination and buried waste, then retrieve, sort, treat, and package the waste, with only orchestration from remote human operators.

Lower right: Future robotic arms will use advanced kinematic configurations that are more dexterous and human-like. This photo is a time-lapse exposure of a redundant kinematic manipulator—a novel robot arm—that can maneuver around objects in confined areas.

SANDIA REPORT
SAND98-2401
Unlimited Release

Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy under Contract DE-AC-4-94AL85000.

Robotics and Intelligent Machines Roadmap

Table of Contents

1.0 INTRODUCTION

1.1 Overview

Today, the U.S. Department of Energy (DOE) faces a number of overarching challenges. It must:

- lower the cost of its operations in the face of inflationary and other pressures on its budget;
- remove its workers from almost all hazardous environments to meet the pressure of rising regulatory standards; and
- find the means to carry-out necessary operations which are too hazardous for humans to perform, but for which no alternatives are currently available.

Many of these challenges will be met most effectively through the use of robotics and intelligent machines (RIM). This document, the *Robotics and Intelligent Machines in the U.S. Department of Energy: A Critical Technology Roadmap,* traces the connection between DOE's multiple mission needs and the future of RIM science and technology (S&T). For the purpose of this document, "RIM" refers to systems composed of machines, sensors, computers and software that can provide DOE with a wide range of capabilities and processes to meet its present and future needs. The Roadmap is the result of a six-month, collaborative effort by a team of DOE representatives and national laboratory scientists, with input from additional DOE plants and sites. It defines, for the first time, a DOE research and development path for RIM, beginning today and continuing through the year 2020, which, if implemented, will support DOE's missions while simultaneously advancing the state-of-the-art of RIM.

Other Federal Agencies have also seen the need for RIM. For example, representatives from the Defense Advanced Research Projects Agency and the National Science Foundation contributed to this roadmapping effort, while NASA, the Department of Defense (DoD), and other Federal Agencies are engaged in RIM development projects jointly with DOE. Concurrently, DOE's national laboratories are playing a leadership role in the national Robotics and Intelligent Machines Cooperative Council (RIMCC), which includes representation from industry, academia, and government. The objective of the RIMCC is to bridge the gap between end-users, suppliers and the research community.

Key legislative and administration leaders also see the potential value of these technologies. In November 1997, Senators Lieberman, Snowe, Bingaman, Domenici, and D'Amato, along with Congressmen Franks and Meehan, sent a letter to the Secretaries of Defense, Energy, and Commerce, the Administrator of NASA, and the Director of the National Science Foundation endorsing an eight point program to advance the state-of-the-art in robotics and intelligent machines. A copy of their letter is provided in Appendix A.

1.2 DOE's Motivations for RIM

Over the next two decades, requirements for facility decontamination and decommissioning; site characterization and remediation; weapons system manufacturing and dismantlement; and materials disposition will change dramatically. To continue meeting DOE's national security and environmental quality goals in an era of declining budgets, DOE programs must focus on increasing efficiency and productivity, and on reducing human and environmental exposure to radioactive, explosive, and toxic materials. Advances in RIM technology will be instrumental in helping DOE meet its goals in the following areas:

Worker Safety. Although DOE employee exposure to hazards has decreased over time, people still work in situations that involve exposure to radioactive and other hazardous materials. Despite the use of personal protective equipment, these hazards remain. In the future, RIM will enable the DOE to remove humans from most such situations.

Process Design and Operation. The availability of low-cost computing is dramatically expanding the use of models and the simulation of complex processes. In the future, product designers will use RIM to test production processes and ensure part manufacturability. Production equipment will rely on process models as real-time references and will take advantage of the increasing number of low-cost, capable sensors emerging from microelectronics laboratories to measure and control processes in operation. "Eyes" on a chip already exist—soon the analytic capabilities of an entire chemistry lab will exist on a chip.

Operations Safety and Productivity. The use of personal protective equipment, necessary for many hazardous operations, greatly decreases worker productivity. In addition, great care must be taken to ensure that the equipment itself does not cause danger. Remotely operated equipment also has significant limitations: it is slow compared to direct human manipulation, and because it requires the constant attention of the human operator, it is fatiguing, requiring operators to be rotated from their positions frequently. Future RIM technology will improve the safety and productivity of remote operations, especially in those situations requiring large-scale or continuous handling of equipment, materials, and wastes.

Waste Remediation. In the future, RIM will use sensor-derived information to make decisions about the fastest, safest way to handle and recover waste or to decontaminate and decommission a facility. RIM will use algorithms to generate the software needed to implement the required operations. Sensor-rich machines will rapidly conduct precision recovery, sorting, and treatment of buried waste while being supervised by human operators located far from the hazardous areas.

Materials Safety and Security. Large quantities of Special Nuclear Materials are being placed in storage as they are recovered from retired nuclear weapons in the U.S. and former Soviet states. Until a decision is made on the means by which to render these materials are unusable, they must be stored in a safe and secure manner. In the future, the coupling of mobile RIM with micro-engineered sensors will result in unprecedented levels of safety and security.

Skilled Labor Force. Ensuring that each successive generation will produce students interested in science has always been a concern of the DOE. Maintaining a stimulating environment where basic research is conducted and leading edge technologies are developed will help attract and maintain top quality scientists. RIM science and technology provides an ideal vehicle for achieving this objective.

1.3 The Purpose of Technology Roadmaps

Technology roadmaps serve as pathways to the future. They call attention to future needs for development in technology, provide a structure for organizing technology forecasts and programs, and communicate technological needs and expectations among end-users and the research and development (R&D) community.

As part of the development of a new model for R&D management, DOE is currently developing two series of roadmaps. Both series, the “Strategic Mission” roadmaps and the “Critical Technology” roadmaps, are meant to clearly articulate DOE’s programmatic and technical objectives. The Strategic Mission roadmaps plot future objectives from the perspective of individual DOE Principal Secretarial Officers (PSOs). Critical Technology Roadmaps developed for DOE, of which this Roadmap is one example, focus on “enabling” or “cross-cutting” technologies that address the needs of multiple DOE Program Offices. Critical Technology Roadmaps must be responsive to the mission needs of DOE; must clearly indicate how the science and technology can improve DOE capabilities; and must describe an aggressive vision for the future of the technology itself.

The purpose of this RIM Roadmap is to identify, select and develop objectives that will satisfy near- and long-term challenges posed by DOE’s mission objectives. Development of the RIM Roadmap began with a clear discussion of the major needs of each of the participating PSOs over the next several decades. From this, the Roadmapping Team was able to identify areas and timeframes—Functional Objectives—in which advances in RIM technology could play a role in enabling each PSO to meet its goals. After identifying a set of Functional Objectives, the Roadmapping Team determined underlying basis technology areas and individual RIM applications and technologies relevant to each Functional Objective—thus mapping the pathway a technology will follow for incorporation into each PSO’s operations. A notional illustration of this linkage is provided in Figure 1 on the following page. A more detailed overview of the roadmap process is described in Appendix B.

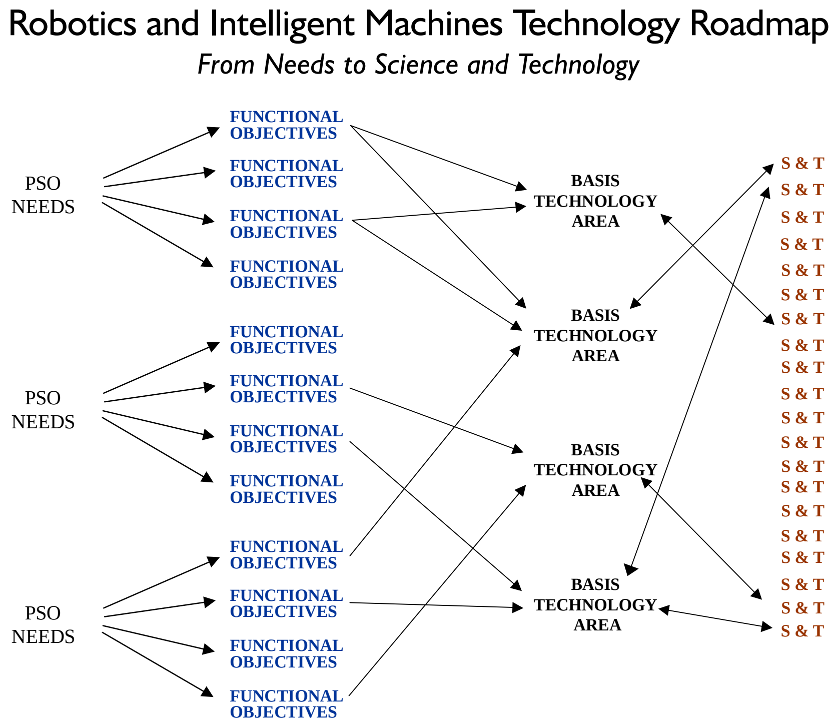


Figure 1. Structure of the RIM Roadmap.

1.4 The Structure of the RIM Roadmap

The RIM Roadmap is grounded in the missions of DOE. Section 2.0 of this document discusses these missions and the needs of nine DOE PSOs as they relate to present and future RIM technology. It is anticipated that advances in RIM will revolutionize DOE operations, most notably manufacturing, hazardous and remote operations, and monitoring and surveillance. These advances will be possible not only because of past DOE investments in this technology, but also because of the integration of developments in many other areas of science and technology, particularly those of computing, communications, electronics, software engineering, and micro-engineering. Descriptions of ways in which RIM technologies will revolutionize manufacturing, hazardous operations, remote operations, and monitoring and surveillance are presented in four stand-alone discussions included at the end of Section 2.0.

RIM will change the way DOE accomplishes its missions by providing DOE with a new array of processes and capabilities including mapping and modeling techniques, non-contact processes, contact processes and complex, multi-processes. This array, and the underlying basis science and technology areas of RIM, are presented in Section 3.0. Specific explanations of the four basis science and technology areas: perception, reasoning, action, and novel interfaces and integration, are provided at the end of Section 3.0.

Past investments in RIM science and technology, coupled with recent spectacular advances in computing, communications, electronics and microengineering leave these technologies poised to provide DOE and other Federal Agencies with a dramatically new set of tools. Section 4.0 explores the long-term vision of RIM and includes examples of DOE applications as they may exist in the year 2020.

2.0 GROUNDING THE ROADMAP IN DOE'S MISSIONS

The September 1997 DOE Strategic Plan identifies four business areas that use and integrate DOE's unique scientific and technological assets, engineering expertise, and facilities for the benefit of the Nation. The business areas are:

National Security. "Effectively support and maintain a safe, secure, and reliable enduring stockpile without nuclear testing; safely dismantle and dispose of excess weapons; and provide the technical leadership for national and global nonproliferation activities."

Environmental Quality. "Understand and reduce the environmental, safety, and health risks and threats from DOE facilities and decisions, and develop the technologies and institutions required for solving domestic and global environmental problems."

Science Leadership. "Use the unique resources of the Department's laboratories and the country's universities to maintain leadership in basic research, to increasingly focus applied research in support of the Department's other business lines, and to maintain world technical leadership through long-term, systemic reform of science and mathematics education."

Energy Resources. "Encourage efficiency and advance alternative and renewable energy technologies; increase energy choices for all consumers; assure adequate supplies of clean, conventional energy; and reduce U.S. vulnerability to external events."

Each of these business areas are supported by multiple PSOs. Nine PSOs, listed below, provided long-range, strategic or other plans to the Roadmapping Team. These plans served as the Team's starting point to ensure that the Roadmap was grounded in DOE's needs.

DOE offices contributing plans and guidance to the Roadmapping effort include:

- Defense Programs (DP)
- Fissile Materials Disposition (MD)
- Nuclear Energy Science and Technology (NE)
- Nonproliferation and National Security (NN)
- Environmental Management (EM)
- Energy Research (ER)
- Environment Safety and Health (EH)
- Energy Efficiency and Renewable Energy (EE)
- Fossil Energy (FE)

Many of these offices currently support R&D for use in applications such as manufacturing, dismantlement, materials handling and monitoring, facilities remediation, characterization, and stabilization.

2.1 Functional Objectives—the Core of the RIM Roadmap

The Functional Objectives are a central focus of this Roadmap. Each Functional Objective includes a metric; for example, one DP Functional Objective calls for the "reduction of manufacturing defects in refurbished stockpile hardware by 50 percent." Three to seven Functional Objectives were identified for each PSO. Specific values for the metrics are associated with time frames that the Roadmapping Team entitled "Epochs." Epoch I ends in year 2004, Epoch II in year 2012, and Epoch III in year 2020. The roadmap goals of Epoch I are well defined by specific PSO objectives, whereas the goals for Epoch III are driven more by the technical potential of RIM to serve the ongoing needs of the DOE programs.

A representation of a Functional Objective chart is provided in Figure 2. In each chart, a list of RIM technologies is provided in the left column under each Epoch, while applications important to the PSO are listed in the right column. The curve depicts the desired improvement in the Functional Objectives (*e.g.*, worker exposure to radiation, or manufacturing defects) and the words to the right of the curve indicate a numerical measure for the Functional Objective.

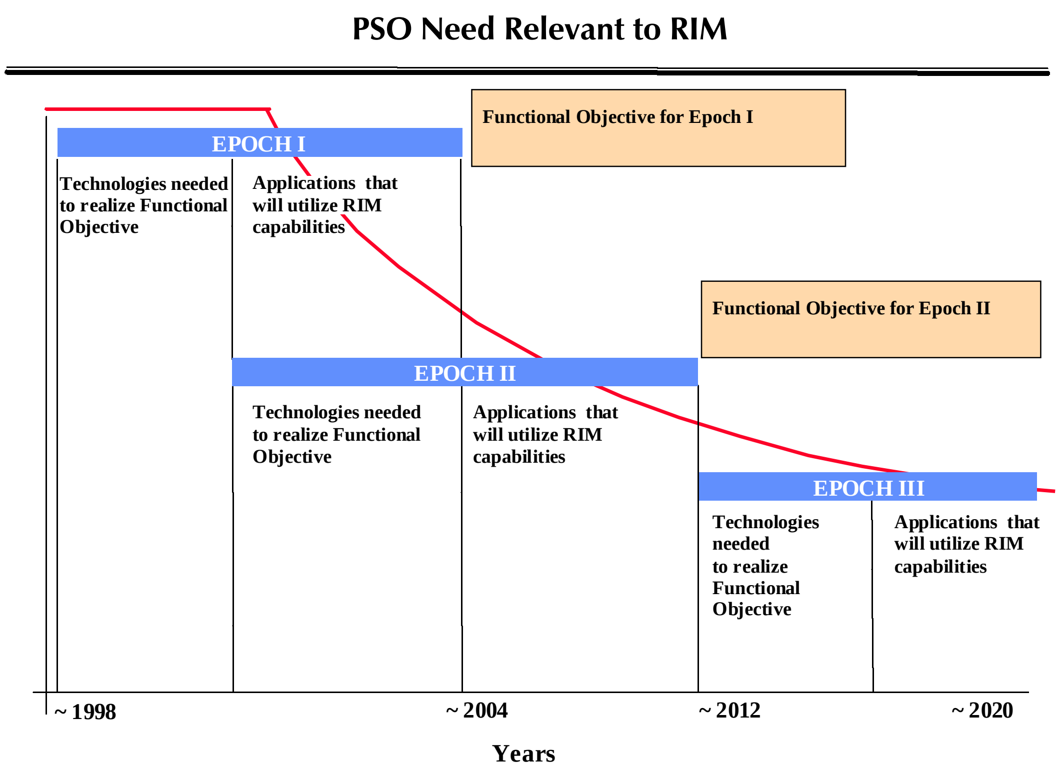


Figure 2. The organization of a Functional Objective chart.

PSO Functional Objectives are grouped and discussed below according to DOE's four business areas.

2.2 DOE's Four Business Areas

2.2.1 National Security

The end of the Cold War has led to significant changes in DOE's national security programs. International agreements such as the Strategic Arms Reduction Treaty (START I and START II), as well as unilateral decisions to retire most non-strategic weapons, mandated a large reduction in the size of the nation's nuclear stockpile. DOE is retiring a significant portion of its weapons-production complex and has developed a strategy to downsize the majority of the remaining facilities. Nevertheless, the maintenance of a safe and reliable nuclear deterrent continues to be an important part of U.S. national security policy.

Meeting the requirements for stockpile stewardship and management without nuclear testing or new weapons development, and in an environment of reduced production capacity, is a challenging task. DOE must maintain the capability to reconstitute some portion of the nuclear force, or conceivably reduce it further, in the event of future changes in national policy. In addition, the United States is committed to reducing global nuclear dangers. DOE supports this commitment by helping prevent the proliferation of nuclear weapons and by assisting Russia, the Ukraine, and other former states of the Soviet Union with the safety, security and disposal of nuclear weapons and material.

To meet these needs, a close alliance among DOE laboratories and weapons production plants has developed to improve surveillance and manufacturing techniques; to maintain the safety, reliability and flexibility of the nuclear weapon stockpile; and to minimize worker and environmental hazards. RIM technology holds the key to achieving many of these national security goals.

Office of Defense Programs

One of the most fundamental drivers for change facing DOE's Office of Defense Programs (DP) is the desire for a seamless manufacturing complex that will reduce defects, costs, cycle time, and the overall "footprint" of nuclear weapons-related activities. While few manufacturing defects occur, those that do are very expensive to fix and are therefore becoming a matter of increasing focus. DP also is concerned about retaining and attracting workers with necessary skills. In some cases, it is becoming difficult to find individuals to work in nuclear weapon environments. Qualified machinists, for example, prefer to take employment positions that do not require them to work with hazardous materials. With respect to DP's needs, the Roadmapping Team identified three Functional Objectives for which RIM is important:

- Reduce manufacturing defects;
- Reduce hazards to workers and the environment; and
- Reduce the time and cost of remanufacture.

As an example, a DP Functional Objective chart detailing reduction of manufacturing defects, with associated time-based metrics, applications, and technologies, is shown in Figure 3. It illustrates potential technologies and applications that will enable DP to reduce the occurrence of manufacturing defects in refurbished stockpile hardware by 50 percent by the end of Epoch I and to 10% of current levels by the year 2012. The complete set of DP's Functional Objective charts is provided in Appendix C.

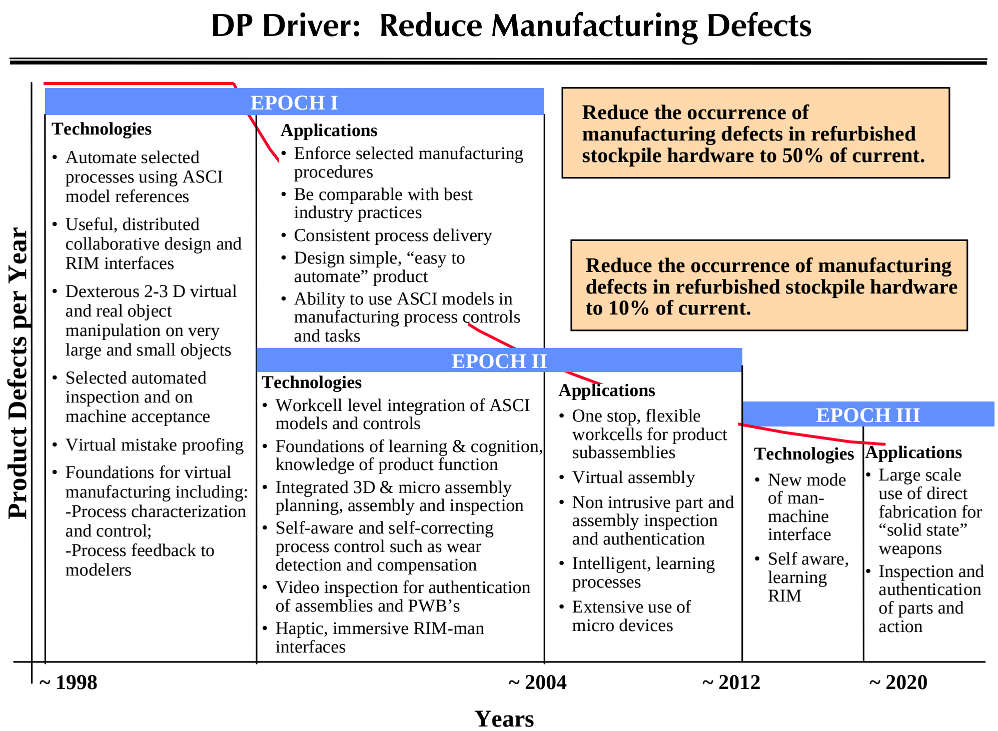


Figure 3. RIM technology and applications will enable DP to reduce manufacturing defects in refurbished stockpile hardware to 10% of current levels.

Office of Fissile Materials Disposition

DOE's Office of Fissile Materials Disposition (MD) was created in 1994 to aid in the U.S. nonproliferation effort of ensuring the safe, secure, long-term storage and disposition of surplus weapons-usable fissile plutonium (50 metric tons). MD will disposition this plutonium through immobilization and possibly fabrication of mixed-oxide (MOX) nuclear fuel for use in commercial power reactors. Both the immobilized forms, once surrounded by vitrified high-level waste, and the spent fuel plutonium forms will be suitable for disposal in a geologic repository. Potentially, three facilities could be required for the disposition missions¾ these will be designed and built by the year 2005 and have a limited life of only 10 years. MD's needs are immediate, therefore, the Office will not endeavor to develop technologies past Epoch I. In Epochs II and III MD will make use of available RIM technology, but will not fund research or technology development. MD's Functional Objectives related to all three planned facilities are:

- Exposure reduction in anticipation of increasingly stringent regulations specific to the Pit Disassembly and Conversion Facility (as an example, but applicable to all MD facilities); and
- Facility throughput as RIM becomes available to MD from cross-cutting efforts specific to the Pit Disassembly and Conversion Facility (as an example but applicable to all MD facilities).

An example of MD's Functional Objectives is shown in Figure 4, below. It illustrates RIM technologies and applications that will contribute to a reduction in operational exposure by 75 percent by the year 2020. The remainder of MD's Functional Objective charts is provided in Appendix C.

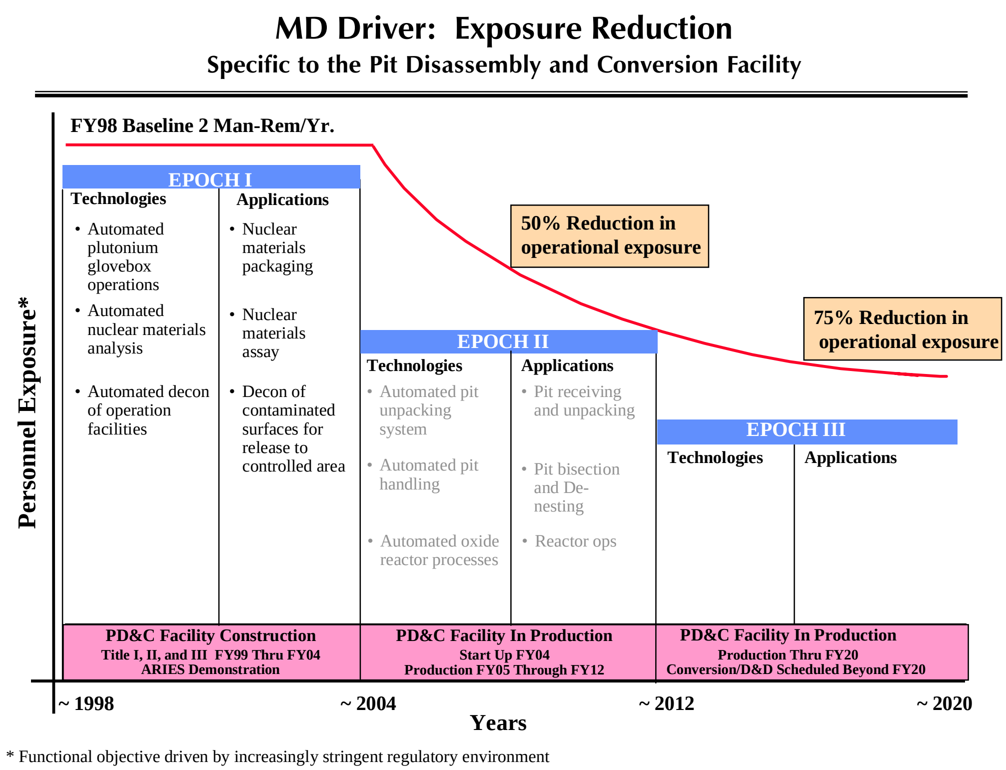


Figure 4. RIM technologies and applications will contribute to a 50% reduction in operational exposure by the close of Epoch II and 75% by the end of Epoch III.

Office of Nuclear Energy, Science and Technology

DOE's Office of Nuclear Energy, Science and Technology (NE) works to assure that the U.S. Government has the ability to respond to issues related to nuclear technology, including energy resource issues, nuclear safety, nuclear engineering education, nuclear research, and the production and distribution of isotopes for medical and research uses. Among the major challenges facing NE in the next decade is the need to improve, and in some situations enable, high-risk operations in extreme environments. With respect to NE's needs, the Roadmapping Team identified three Functional Objectives for which RIM is important:

- Enable extreme environment operations/reduce risk at Chornobyl;
- Improve DOE reactor and commercial reactor operations; and
- Enable automated maintenance of depleted uranium hexafluoride (UF_6) cylinders in storage.

An example of NE's Functional Objective charts is shown in Figure 5, below, with the remainder in Appendix C.

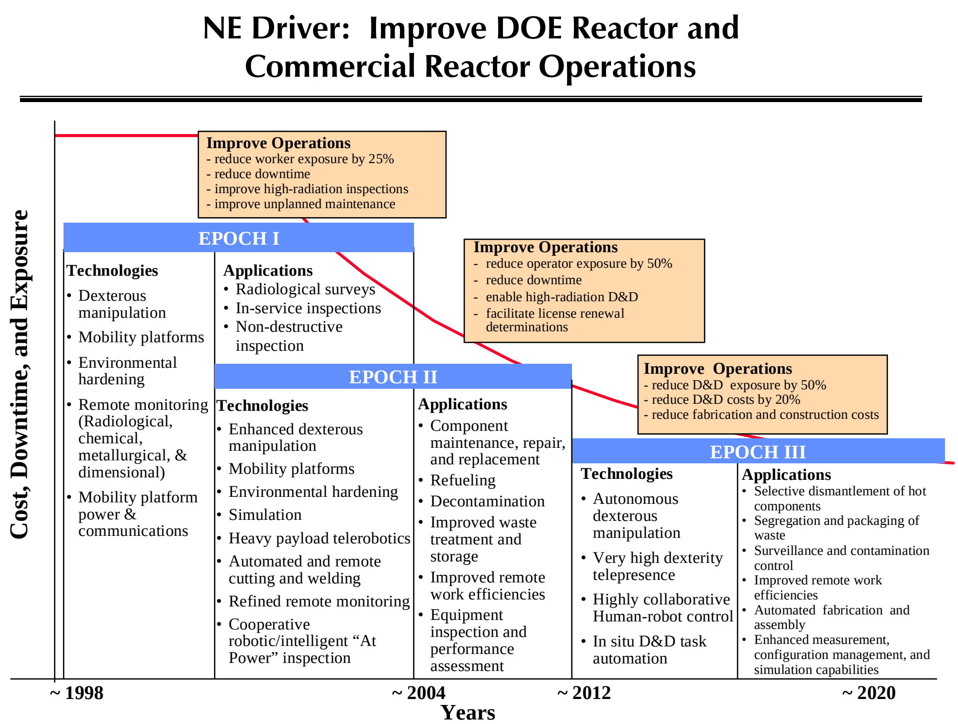


Figure 5. Application of RIM technologies can yield improvements over the various phases of a reactor life-cycle.

2.2.2 Environmental Quality

DOE manages the largest environmental stewardship program in the world, including more than 140 sites and facilities in 30 states and territories. The end of the Cold War left a legacy of thousands of contaminated areas and buildings, a backlog of waste awaiting treatment and disposal, and large amounts of special nuclear materials throughout the now-retired production complex.

Office of Environmental Management

Approximately 26 metric tons of plutonium-bearing materials, more than 100 million gallons of high-level radioactive waste, and approximately 1300 cubic meters of highly radioactive spent nuclear fuel are under the stewardship of DOE's Office of Environmental Management (EM). To meet EM's goals within the timeframe outlined in the report, *Accelerating Clean-up: Paths to Closure*, issued in June 1998, DOE must capitalize on opportunities to improve safety, efficiency and productivity in environmental remediation and waste storage and disposal. EM's Functional Objectives, found below, focus on four major areas: tank waste; mixed waste; decontamination and dismantlement; and nuclear materials operations.[1]

- Reduce personnel exposure and hazards;
- Reduce secondary waste; and
- Increase productivity.

An example of one of EM's Functional Objectives charts is shown in Figure 6 below, with the remainder provided in Appendix C.

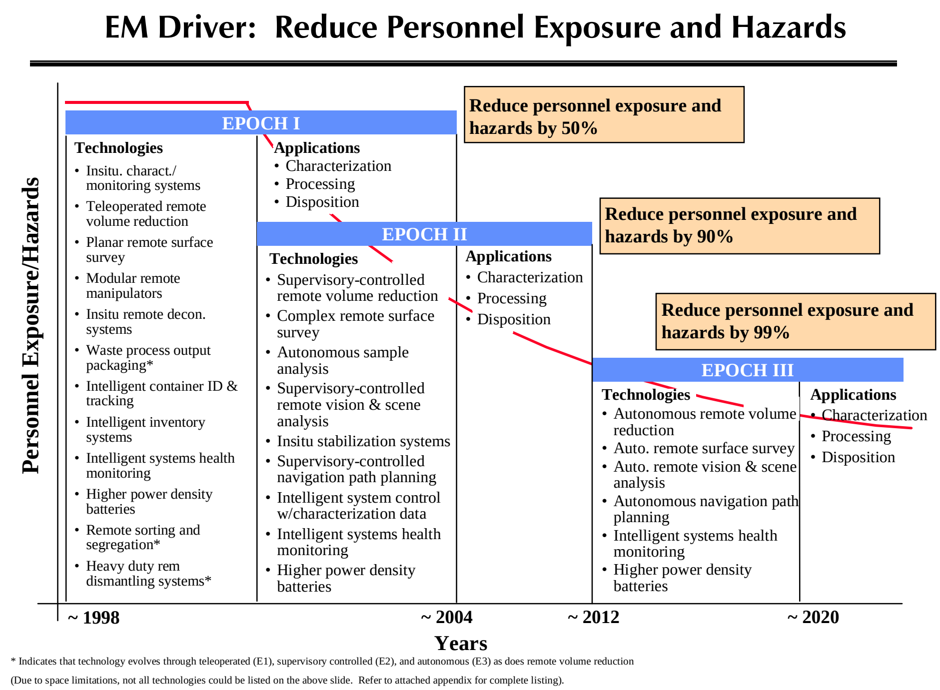


Figure 6. The use of RIM technologies in hazardous environments will essentially eliminate personnel exposure by the close of Epoch III.

2.2.3 Scientific and Technical Leadership

DOE's Strategic Plan emphasizes the Department's leadership role in basic research and advanced scientific knowledge. Publicly funded science and technology has been a cornerstone of our nation's economic strength for well over a century and is expected to continue to be a major contributor to the knowledge base responsible for sustained economic prosperity.

---

1 These operations are presently integrated into the EM Robotics Technology Development Program.

Office of Energy Research

With respect to RIM, the Office of Energy Research's (ER) mission is two-fold. The first objective is to support the regular maintenance and operation of the radioactive portions of ER facilities such as the Spallation Neutron Source facility, high-energy physics facilities, magnetic fusion energy facilities, etc. There is also the possibility of the usage of RIM in the construction of such facilities. A second objective is to develop, through innovative research, a core of excellence in the area of intelligent systems, science, and technology. ER's goal is to combine long-range, fundamental R&D in engineering sciences that may enable the emergence of revolutionary advances in intelligent systems with near-term, sustained technology transfer to other DOE programs, ER facilities, U.S. industry and universities. Advances in RIM will help ER enhance U.S. scientific and technological capabilities in strategic areas vital to national security, environmental cleanup, and energy independence. The Roadmapping Team identified seven Functional Objectives for ER that support its two-fold mission:

- Revolutionize capabilities for inherently distributed missions in dynamic, uncertain environments;
- Revolutionize sensor integration for distributed robot systems (*i.e.*, just plug-in the sensor, system will configure itself);
- Revolutionize collaborative research using remote and virtual RIM systems;
- Revolutionize intelligent machines concepts and controls methodologies for manipulative tasks;
- Revolutionize energy resources exploration and ecological land control;
- Predict and extend safe life of welded structures; and
- Improve operation of ER strategic facilities to meet programmatic missions.

An example of one of ER's Functional Objective charts is shown in Figure 7, below. The remainder is provided in Appendix C.

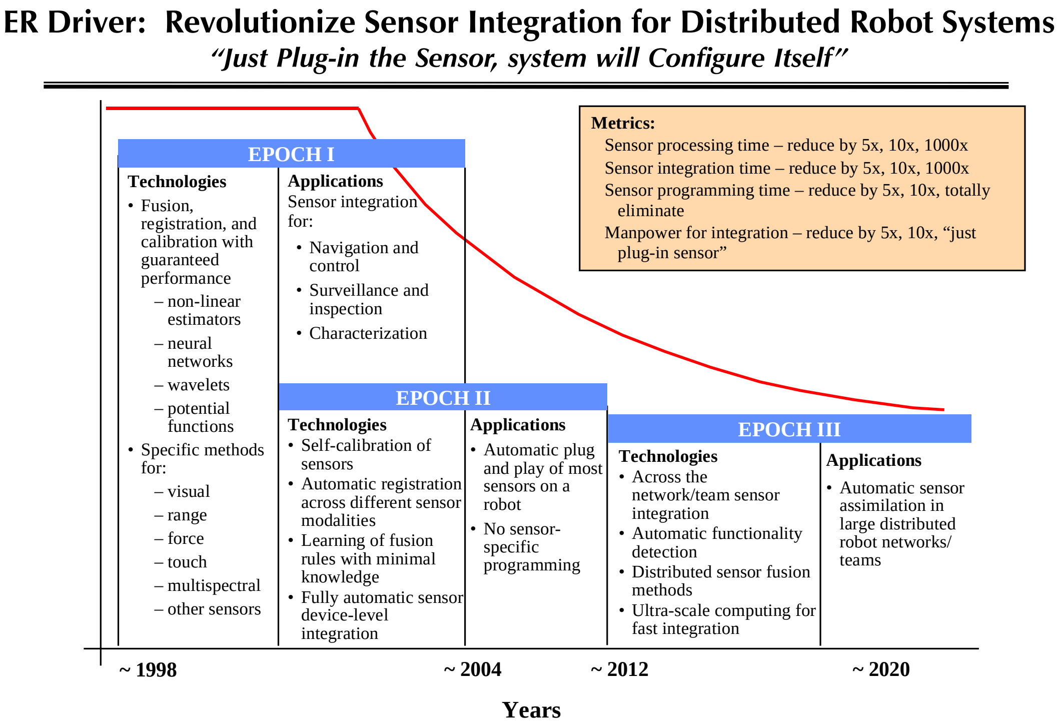


Figure 7. Dramatic advances in sensor processing, integration, and programming time will enhance 'plug and play' RIM technology.

2.2.4 Energy Security

Representatives of the Offices of Energy Efficiency and Renewable Energy and Fossil Energy participated in the development of the RIM Roadmap and identified the opportunities discussed below.

Office of Energy Efficiency and Renewable Energy

The Office of Energy Efficiency and Renewable Energy (EERE) saw several opportunities for its organization that might emerge as a result of the Roadmap including:

- New manufacturing techniques developed for the National Security business that could lower the production cost of renewable energy technologies such as photovoltaics; and
- Basis technologies developed for sensor-driven, intelligent delivery of processes by RIM that could extend to intelligent, waste-minimizing, energy-efficient control of batch processes.

In addition, EERE has the proven ability to work with industry for technology diffusion. It has supported a variety of industry-driven efforts as part of its Industries of the Future program. This program has identified seven energy and waste-intensive industries (agriculture, aluminum, chemicals, forest products, glass, metalcasting, and steel) that together use more than 60 percent of the energy consumed in all U.S. manufacturing. EERE anticipates working through its Industries of the Future Program, which could facilitate the diffusion of RIM technology developed by DOE for its other businesses.

Office of Fossil Energy

The Office of Fossil Energy (FE) also identified several possible areas where RIM could be useful:

- The underlying technologies being developed to revolutionize DOE's remote operations may be useful to companies doing energy resources exploration in extreme environments; and
- RIM safety concepts and technologies may be applicable to operations of energy companies such as oil tankers and coal mining.

2.3 Summary of Needs and Functional Objectives

The Functional Objectives of all nine PSOs are provided in the table below. (The complete set is provided in Appendix C.) Several cross-cutting themes are evident, including:

- **Worker health and safety.** DOE intends to continue to remove workers from the hazards of radioactive, explosive, toxic and other materials.
- **Product quality.** The advent of RIM provides the DOE with the opportunity to eliminate many design and production-related product defects.
- **Reduced cost.** The capabilities of RIM have the potential to advance so rapidly that initial capital costs of systems will be easily compensated for by lower operating costs.
- **Increased productivity.** Remote systems of the past were characterized by slow operation to ensure safety. RIM will provide much higher facility productivity.

Processes	Functional Objectives (Epoch II)
Defense Programs	• Time and cost for refurbishment of appropriate stockpile hardware reduced by 50% • Worker exposure to hazards reduced to 30% of current • Production defects reduced by 90%
Fissile Materials Disposition	• 75% reduction in exposure • 50% increase in operational throughput • 75% reduction in monitoring cost *These are examples. There are goals specific to different MD facilities.*
Nuclear Energy, Science and Technology	• Enable extreme environment operations/reduce risk at Chornobyl • Improve DOE reactor and commercial reactor operation • Reduce exposure (75%) and costs (50%) associated with maintenance of depleted UF_6 cylinders in storage
Nonproliferation and National Security	• Improve surveillance, accountability, and protection of domestic and international weapons-grade nuclear material
Environmental Management	• Personnel exposure reduced by 90% • Secondary waste reduced by 75% • Productivity increased by a factor of 2
Energy Research	• Inherently distributed missions in dynamic, uncertain environments • Sensor integration for distributed robot systems • Revolutionary collaborative research using remote and virtual systems • Intelligent machines concepts and controls methodologies for manipulative tasks • Predict safe life of welded structures • Energy resources exploration and ecological land control • Improved operation of ER strategic facilities to meet programmatic needs
Energy Efficiency and Renewable Energy	• Diffusion of manufacturing technology for renewable energy equipment • Diffusion of intelligent processes for resource efficiency/reduction of waste
Fossil Energy	• Technology diffusion, e.g., technologies for safety and productivity in extreme environments
Environment, Safety, and Health	• Worker health and safety

Table 1. RIM Functional Objectives.

RIM Will Revolutionize Manufacturing

DOE's nuclear weapons design and manufacturing complex consists of an integrated system of laboratories, production plants, and operations offices that are responsible for the design, development, remanufacture, maintenance, and safety of our Nation's nuclear stockpile. The complex is also responsible for the safety and security of certain components and materials retired from the active stockpile.

Since the end of the Cold War, mission goals related to nuclear weapons manufacturing have changed significantly. In addition, changes in the international political arena, including an increasing emphasis on worker and environmental safety, bans on nuclear testing, and a desire to reduce costs and improve efficiency are motivating DOE to change many of its practices.

Three major issues are driving a revolution in engineering and manufacturing within DOE's weapons complex:

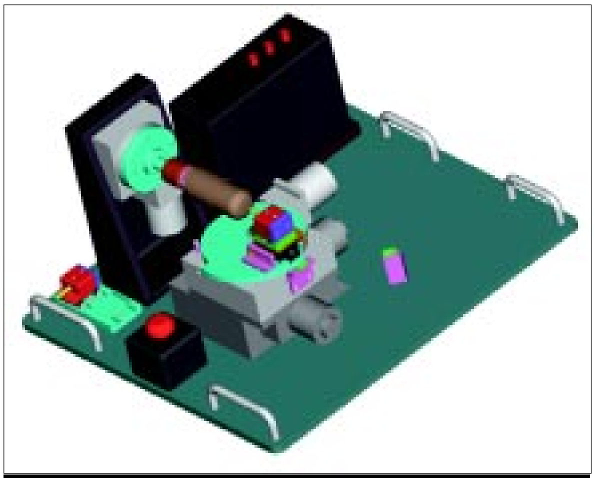
- **Stockpile stewardship and management** must be accomplished with a budget that is anticipated to decrease. To stay within its budget constraints, DOE is increasingly adopting commercial manufacturing technology rather than developing its own. Nevertheless, some DOE manufacturing is very specialized, and must be done by modifying and/or inventing advanced technologies. Thus, DOE must maintain a knowledge-based workforce capable of performing necessary manufacturing tasks, while transferring low-skill, repetitive, and high-risk tasks to intelligent machines.
- **Worker safety and environmental regulations** are anticipated to become more stringent each year, driven not only by the Defense Nuclear Facilities Safety Board, the Occupational Safety and Health Administration (OSHA), and local agencies, but also by comparison of DOE operations to those of industry.
- **Quality and surety of the stockpile** are increasingly important. The number of weapons and systems being produced has decreased and

Many weapons components are presently built by assemblers working with microscopes in clean rooms—a tedious process. Assembly by robotics and intelligent machines will permit the automatic enforcement of assembly procedures, will improve the cleanliness of operations, and will afford automated generation of process documentation.

individual warhead reliability has thus become more important. As the stockpile ages, retrofits will become necessary. Manufacturing defects that can occur during these retrofits create major problems for both DOE and the Department of Defense. As a result, prevention of defects is extremely important.

The Future

RIM of the future will enable dramatic changes in the way the DOE accomplishes its manufacturing goals:



DOE manufactures components that require coatings of a specified thickness to function properly. RIM systems that couple geometric reasoning with computer models of the spray process are being developed to apply these coatings with precision and first-time-right uniformity. Shown here is the development platform for the thickness sensor that will provide feedback to the motion controller of the RIM-based coating process.

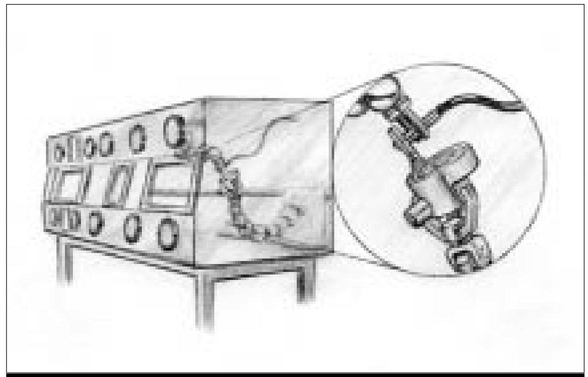
Seamless Design-to-Manufacturing

The design-to-manufacturing process will be computer-based and use interactive, collaborative environments to ensure the design of components that are manufacturable. Interactive simulations will be used routinely to evaluate product designs, manufacturing processes, and to download production information from design and manufacturing teams to the production floor. Feedback regarding manufacturing capabilities and status will be transmitted to the design team automatically. High-fidelity immersive interfaces will be available so that engineers at geographically dispersed sites can view real parts with very high fidelity at a remotely located plant. Design and production engineers will be able to manipulate the parts, identify potential manufacturing or design problems, and develop and assess possible solutions from a distance.

"Master Craftsman" Factories

Changes in the international political landscape may allow stockpile maintenance to stabilize at a low level. Individual changes to weapons components will number in the several hundreds per year but will be spread over many different weapons systems. Fewer systems mean that it will be more difficult for human operators to master the complicated, high-consequence tasks—even when the complex was making thousands of weapons per year, human error was the largest source of defects. Thus, extensive and continuous retraining and re-certification will be required to ensure safety and efficiency as long as these tasks are the responsibility of human operators.

With RIM, these problems can be alleviated. Process steps and their duration, energy level, forces, and geometric paths will be repeatable within very small tolerances. Information gained during manufacturing will be automatically fed forward to subsequent processing steps, and fed back to computational model databases and adaptive controllers so that models retain their accuracy. In effect, manufacturing will be conducted with the skill of a "master craftsman"—possessing a thorough understanding of the materials and their history through previous manufacturing steps, awareness of the intended function of the product, and the ability to accommodate past design and processing decisions to make the entire system function more effectively.



Components must be kept pristinely clean during production to ensure long, reliable shelf lives. Because bulk cleaning materials are no longer environmentally acceptable, manual cleaning has become a time-consuming, but critical, part of DOE's manufacturing processes. RIM, shown here spray-cleaning a component, enable substantial increases in the speed, accuracy, and quality of environmentally-friendly cleaning processes, while minimizing worker exposure to hazards.

"Solid State" Weapons Manufacturing Technologies

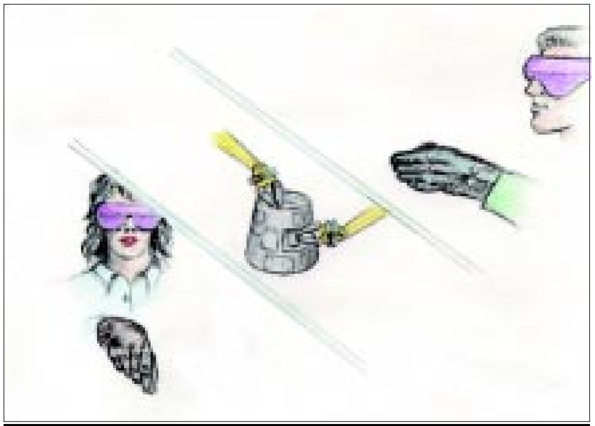
Weapons products will evolve toward a more "solid state" appearance—one that involves smaller, more monolithic and modular components activated with low power, resulting in higher reliability products at lower costs. Direct fabrication, MEMS (microelectromechanical systems), and other micro-technologies will be used extensively to create finished products with fewer moving parts and fewer manufacturing steps.

Developments in RIM are essential for this evolution. There is no other way to achieve the required cleanliness, path precision, fine three-dimensional motion dexterity, and capability to respond to sensors that are necessary for the design, production, and assembly of these "solid-state" weapons components.

Authentication and Consistent Inspection

Inspection will continue to play a major role in certifying and re-certifying parts. RIM will ensure that all features are automatically inspected the same way every time, guaranteeing the highest levels of quality control and the lowest levels of product defects and rework. Even features that are subjective, such as surface finish, color and process deviation (*e.g.*, weld penetration depth) will be systematically inspected and recorded. Collaborative video inspection will be used to verify the correct assembly of parts into systems.

As more microsystems are used, RIM will be necessary to work with these extremely small devices.



RIM of the future will enable the design of parts that are, from the outset, "manufacturable." Virtual part design will be integrated with virtual manufacturing process prototyping to create well-designed, easy-to-produce, first-time-right, final components. This illustration shows a product designer (lower left) and a manufacturing engineer (upper right) using virtual reality glasses and datagloves to collaborate to modify parts of a virtual assembly.

Reduced Regulation Sensitivity and Cost

DOE must conduct the processing and fabrication of products with precisely shaped high explosives, depleted and enriched uranium, salt, beryllium, tritium, and plutonium. These materials are generally processed in gloveboxes or other remote facilities at great cost. Tightening health and safety regulations related to radiation exposure will make future manual glovebox processing even more difficult and expensive. By contrast, completely remote, autonomous processing will eliminate human exposure and decrease costs by making facilities less affected by regulatory changes.

Pushing Bits Instead of Paper

One of the major costs of weapons production is the documentation of each lot, subassembly, etc. RIM will play an important role in creating systems that produce and organize documentation in a searchable format. RIM manufacturing systems will automatically generate production and design records with in-process parameters never previously retained. For example, RIM will produce a "history chip" individualized for each warhead. This chip will contain a database of information concerning the warhead that can be accessed in the field. If a stockpile defect is detected, this information will make the identification of manufacturing or design factors that contributed to the defect much easier.

RIM is essential to achieving the revolutionary advances in manufacturing required for DOE to meet its goals. Improved man-machine interactions, automatic, consistent repeatable inspection systems; and facilities with the knowledge of "master craftsman" will play a major role in reducing DOE's manufacturing costs, hazards, and defects.

RIM Will Revolutionize Hazardous Operations

Background

Safety and health (S&H) has been a concern of the nuclear technology community from the earliest days of the Manhattan Project.

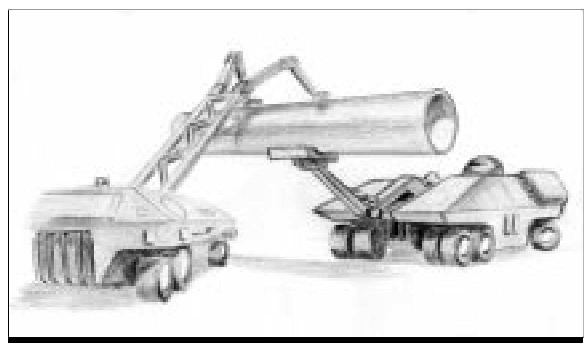
Statutory mandates to protect health and safety were evident throughout the Atomic Energy Commission, resulting in funding of R&D with the specific purpose of improving safety and health, in addition to the creation of an operational S&H division. An integral component of DOE's S&H program from the earliest days involved remote handling by machines. These activities continue to play a crucial role in protecting personnel, experiments, materials and the environment. As DOE moves into large scale deactivation and decommissioning of facilities throughout the weapons complex, the need for RIM will increase in step with the volume of these potentially hazardous activities and operations.

By developing sensor- and model-based automated processes, and by improving the capability of existing remote technologies, emerging RIM technologies are permitting DOE to significantly reduce the exposure of its workers to hazards. Present RIM technologies are beginning to make significant contributions to worker safety and protection of the environment. For example, recently developed mobile sensor platforms allow facility floor radiation mapping to be performed with reduced human exposure, improved data accuracy and integrity, and higher productivity; underground high-level nuclear waste tanks have been remediated using robotic systems instead of humans; and lastly, the dismantlement of explosive weapons components is being accomplished using RIM, greatly decreasing the risk to workers.

The Future

The RIM of the future will enable a revolution in how DOE operates in hazardous environments. We can envision a time in which advanced technologies will enable the near total removal of humans from

Disassembly of thousands of explosive weapon components is too dangerous to do by hand or by using traditional remote manipulation technology. RIM, using DOE-developed science and technology, can "see" and "feel" to perform these operations safely. This system, the Automated Gas Generator Disassembly workcell at a DOE plant, has recently completed the safe disassembly of more than 1000 explosive components.



Mobile robots with multi-tooled manipulators will be capable of removing large weapons material processing components from retired facilities. Sensor tools will examine the components to make decisions about locations where cuts can be made safely, and will determine the points at which a component must be supported so that it does not fall to the ground. The robots will also autonomously plan and execute inspections to determine whether the removed component can be decontaminated and recycled–thereby potentially reducing the amount of hazardous waste generated.

situations involving exposure to hazardous environments. DOE's approach to ensuring worker safety and health protection includes job hazard analysis and mitigation and the use of personal protective equipment. For example, some hazardous research, manufacturing, and operations in DOE today depend on gloveboxes, air supplied suits, and respirators to protect workers from hazards. While these techniques successfully served DOE missions in the past, improved methods are needed to meet the challenges of the future.

Members of DOE's Accident Response Group practice investigation of the site of a suspected spill of radioactively-contaminated materials. Shown here are workers in Class B Hazardous Materials suits. RIM of the future will be able to perform "human like" actions which will remove humans from hazardous situations.

Single-suited RIMs, not Double-suited People

The evolution of RIM will greatly improve the safety performance of DOE's missions. Through a commitment to the development of RIM technologies, DOE can pave the way for a major change in the philosophical approach to worker safety and environmental protection. The key to enabling the replacement of DOE workers in hazardous environments will be the cost-effectiveness of RIM solutions and the quality of the human-machine interfaces, *i.e.* how effective human supervision and control of multiple RIM systems can be. In addition, improved manipulation dexterity, sensory fidelity, and machine reasoning will allow new classes of RIM to be fielded, further improving the health and safety of workers and protection of the environment.

DOE intends to remove workers from the dangers of radioactive, explosive, toxic, and other hazardous materials. RIM is an obvious and, in some instances, the only means to accomplish this.

RIM Will Revolutionize Remote Operations

Background

Remote operation techniques were originally developed to allow Manhattan Project researchers and workers to safely perform tasks that involved dangerous or even lethal levels of ionizing radiation. Over the years, these techniques evolved from shielding walls and "long-handled tools" to the use of anthropomorphic mechanical master-slave manipulators, electro-mechanical and hydraulic manipulators, and other types of transport systems. In these systems the human operator is responsible for all of the control signals to the remote devices—a function requiring high levels of concentration and making the operator very susceptible to distraction and fatigue.

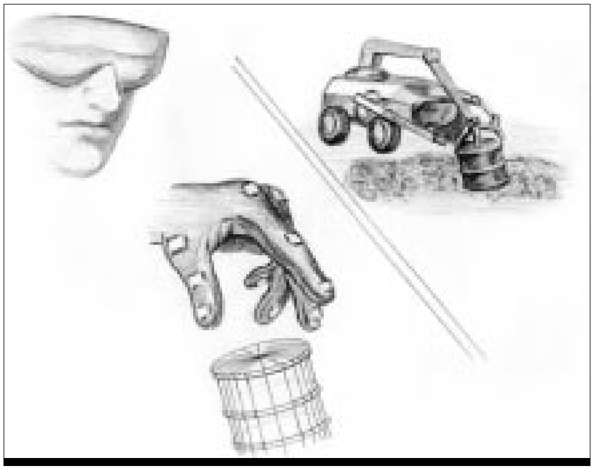
Pictured here is typical state-of-the-art remote manipulation control: a human operator uses a specially designed joy-stick and multiple video monitors to ensure safe handling of nuclear fuel. Much progress in interface design is required if the potential of RIM is to be achieved; important research is underway in academia and the DOE laboratories.

While decreasing worker exposure, teleoperation of remote equipment is extremely intense and time-consuming, because it requires constant human-intervention. Current remote manipulation systems are typically ten times slower than equivalent direct contact work, and in some cases, hundreds of times slower due to the level of care that the operator must use to ensure safety. Although advances in electronics and computers paved the way for significant improvements in operator interfaces, sensory feedback, and remote manipulator controls, the unstructured and uncertain environments that are typical of these operations limited their progress. New RIM technologies will increase productivity, decrease secondary waste generation, and increase the safety of remote operations by allowing significantly more autonomous operations in these unstructured environments.

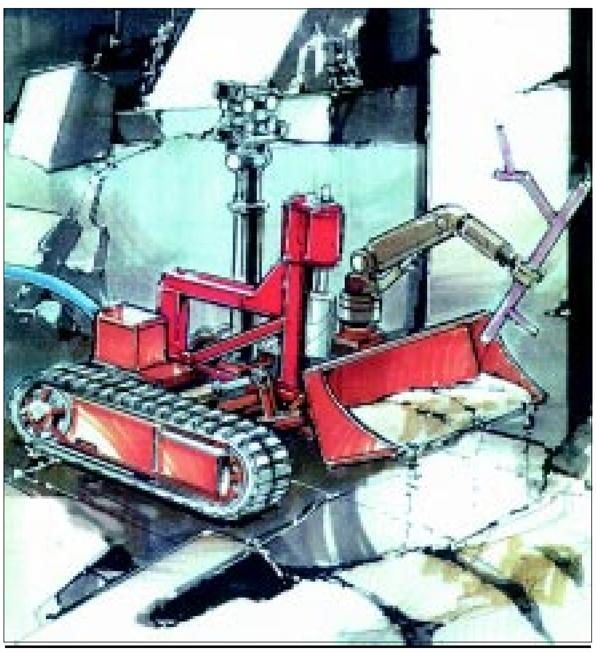
The Future

The Human-RIM Interface

Computing, electronics, and photonics will enable extraordinarily capable remote systems. For example, a host of new micro-sensors will be teamed to map the geometry and hazards of a retired radioactive chemical processing facility. A remote systems technician will use this digital map in conjunction with a dismantle-



To achieve the objective of increased productivity, interfaces of the future could use sensor-rich gloves to allow operators of remote RIM to "feel" a drum of mixed waste buried in the ground and command the RIM to exert just enough pressure to remove the drum while assuring its safe, intact removal.



This Pioneer robot will soon be deployed by the DOE and NASA at the Chornobyl reactor in the Ukraine. Pioneer will use its manipulator and sensors to characterize the "sarcophagus," which was the building constructed to contain the radioactive debris after the reactor accident.

ment expert system to develop a plan to optimize the cost, speed and safety of the facility dismantlement. A motion planning system will use the map to direct the robots and manipulators to navigate through pipe nests and avoid collisions. A pipe removal expert system will decide the correct points at which to cut a pipe, and will direct a team of robots to make the cuts, while simultaneously and safely supporting the removed section.

Reduce Mixed Waste Generation

Teams of robots and sensors will work together to precisely determine the contents of waste streams and automatically segregate different streams to minimize the cost of disposal and storage. These RIM will also improve safety by removing people from hazardous operations and improve speed by completing the sorting process more quickly.

Impossible or Extremely Difficult Operations

The disassembly of certain explosive devices is too dangerous for humans, and only recently has robotics technology advanced to the point that some of these devices can be automatically disassembled. There are also facilities that have not been inspected for years because they are too dangerous for people to access. RIM of the future will make these and other currently impossible activities possible.

RIM will improve the productivity, quality and cost of remote operations. Automation of tasks will free human operators from the tedious execution of teleoperated tasks. Instead, these operators will serve as managers and organizers of the teams of robotic systems doing the work. RIM will work together under human control and supervision. These remote systems will have some capabilities better than those of humans.

RIM Will Revolutionize Monitoring and Surveillance

Background

The United States no longer produces new weapons-grade fissile materials and must dispose of large amounts of existing materials in a way that makes them difficult to reconstitute for weapons use. In addition, management and disposal activities must be conducted with requisite levels of safety, security, and environmental protection, all at a reasonable cost.

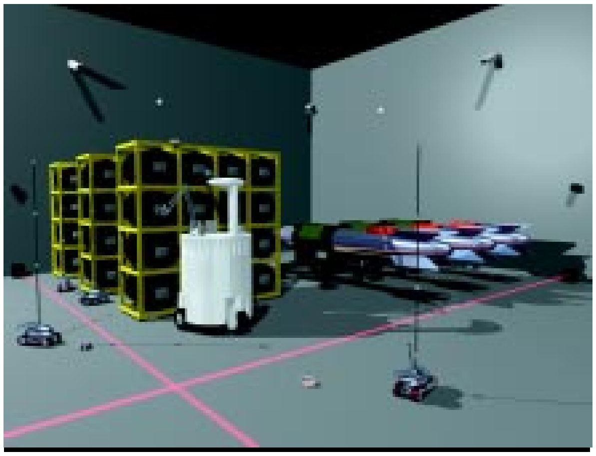
Today, dealing with existing quantities of nuclear materials (in differing compositions and varying levels of radiation) requires at least some level of worker exposure. Nuclear material storage containers must be monitored for fissile content and containment, as well as for changes in physical form that would indicate problems. High levels of security must be provided and an absolute ability to monitor and track the location and fate of these materials must be ensured. Russia and other nuclear powers have similar needs for materials management. Domestic and international pressures to perform these activities with greater accuracy and reliability, reduced worker exposure rates, and lower costs will necessitate a revolution in DOE's approach to materials handling, monitoring, and security.

The consolidated storage of nuclear weapons materials and components creates radiation levels that are too high to allow frequent human monitoring. Here, a sensor-rich RIM enters a nuclear weapons storage facility to autonomously test for radiation levels, gas emissions and the security of the stored materials.

The Future

Packaging and Handling

RIM can provide the capability to process plutonium from metal components to oxide while avoiding exposure to humans and reducing the generation of secondary waste. RIM technologies that use sensor suites and adaptive controls will be used for operations such as high integrity welding, swiping for contamination, and container integrity authentication. Detailed packaging records will be generated and downloaded to a secure database without human involvement.



Ensuring safe and secure storage of both domestic and international nuclear materials is crucial for preventing nuclear proliferation. In the future, micro-engineered sensors will permit around-the-clock surveillance of nuclear materials and their storage sites with better-than-human capabilities.

Storage and Retrieval

RIM will enable significantly higher density storage of radioactive materials by removing the need for human access to the storage vaults. Mobile RIM will be sealed in vaults and autonomously roam, respond to anomalies, and communicate over wireless networks.

Monitoring and Access Control

Advances in low power microprocessors, sensors, and power sources will allow automated sensing of an individual container's contents, integrity and location. RIM will incorporate high quality immersive human interfaces with hardware mounted on a small platform and wireless communications capable of transmitting visual images. Time delays in transmission will be unobtrusive. Authentication of the state of the platform, sensor suite and data transmission will be ironclad.

Security

RIM will provide the capability to extend security levels far beyond those of today. Automated guards will communicate constantly, respond collectively and intelligently, and will show no reluctance to signal if their performance is inadequate. In addition to sights and sounds, RIM will routinely observe and record small temperature differences and the presence of organic compounds and/or radiation.

Transportation

The transfer of materials will be accomplished in secure vehicles using sensors and locators similar to those in a vault. Additional security will be achieved by observing transportation paths (e.g., loading and unloading locations). RIM will be used to shadow personnel or containers, as necessary.

In summary, RIM technology will enable complete knowledge of fissile history to be passed electronically. Furthermore, radiation to RIM will eliminate human exposure during the processing, storage, disposition and reuse cycle by increasing high-density storage, eliminating the need for on-site human observers, and increasing the reliability of remote monitoring and surveillance.

3.0 RIM: AN INTEGRATED S&T PROGRAM

3.1 Organizing Constructs for RIM

Meeting the needs identified by the Functional Objectives will require advances in many areas of science and technology. Historically, the science and technology of RIM has been discussed in the context of whether something is or is not an "intelligent machine." However, using intelligence as the means to organize discussions of RIM has several drawbacks. First, it raises the concern in the eyes of some DOE users that these technologies will never have sufficient "intelligence" to avoid the possibility of making dangerous decisions. Today, however, there is ample evidence from operational systems within DOE that modern software engineering processes and reliable microcomputer and communication technologies enable machines to make decisions based on algorithms and sensed information without endangering the safety of the operations in which they are engaged. Indeed, in many cases operational safety is improved.

A second concern is that using the concept of intelligence to organize a discussion of RIM may not serve us well. If asked to define intelligence, the biologist, for example, may emphasize the ability to adapt, to adjust to the environment, and to learn how to learn. The philosopher will emphasize the capacity to perform abstract thought. The engineer is likely to emphasize capabilities that make the actions of an intelligent machine difficult to distinguish from human performance. The lay person may define intelligence as how people act most of the time or the ability to solve difficult problems quickly and efficiently. Thus, arriving at a single definition of intelligence is nearly impossible. Furthermore, the definition of machine intelligence evolves over time: once, building a machine that could defeat the world chess champion was considered a defining example of an intelligent system. Today, few would consider Deep Blue's defeat of Kasparov using "simple" rote exploration of huge numbers of possible moves and attendant outcomes a good example of "intelligence."

Finally, to use human intelligence as a way to organize a discussion of RIM might limit our thinking about broad, important new areas of science. For example, in addition to intelligence, these systems may have capabilities that are "extra-human" in a variety of ways: no human can coat a component with the quality of a RIM; and no human can sort waste with the speed and precision of a sensor-driven RIM. Thus, rather than emphasizing intelligence, the mechanism by which an outcome is achieved, the most meaningful discussions of RIM focus on behavioral outcomes we desire. From this viewpoint, the measure of a robotic system is determined by an assessment of performance on the basis of functional criteria which, taken together, create a machine that is "adaptable to the conditions at hand." Adaptability is the fundamental requirement for RIM to meet the needs of the PSOs; and operational safety is implicit.

3.2 RIM: Delivering New Capabilities to DOE

DOE PSOs do not usually think of RIM in the context of its "intelligence" or lack thereof—rather, their interest is in these technologies as deliverers of processes; in essence asking the question, "What, specifically, can RIM help me do better?" To answer this question, we can think of these robotic systems as providing DOE with four types of processes/capabilities; each of which is discussed below.

Mapping and Modeling. For the foreseeable future, reasoning using computer models will be the means to achieve the intelligence envisioned by the Roadmap. RIM will be able either to use existing computer maps and models to reason about the processes they are asked to deliver, or, lacking existing models, they will be able to gather the information required to build a map or model. Mapping and modeling are particularly important in the unstructured situations typical of environmental remediation. Any program plan for RIM R&D must address requirements for modeling and mapping.

Non-contact Processes. These include processes that do not require physical contact for their successful operation. RIM that apply precision coatings to objects, or that monitor materials storage vaults are obvious examples. The Mapping and Modeling processes mentioned above are also a form of non-contact processes, but have been addressed separately above because of their importance and pervasiveness in RIM.

Contact Processes. Contact process, as the name implies, involves RIM that can manipulate objects and materials. The reason for differentiation from non-contact processes is the greater danger of unsafe operating conditions. For example, in a contact process, much care must be taken to assure that the right amount of force—and no more—is applied to a hazardous object. A manipulator must apply enough force to maintain grip on a part during assembly, but must not apply so much force that the part is damaged. Contact processes are more complicated and involve more safety concerns than non-contact processes.

Complex, Multi-processes. These are complex processes, each of which requires many contact and non-contact processes to work together in an integrated way. For example, the sorting and segregating of buried waste requires robots to generate models of objects to be sorted, plan and direct graspers to pick up and manipulate objects, and use complex sensors (such as the new chemistry-labs-on-a-chip) to inform and enable automated decision-making about treatment, etc. Multi-processes are the most complex of the operations discussed here. Multi-processes demonstrate the highest form of RIM—it is with these operations that observers will most easily see and acknowledge the tremendous capabilities of the technologies.

Examples of the types of capabilities and processes that RIM will provide to the PSOs are presented in the Table 2, below. Mapping and modeling processes are included among the Non-contact Processes.

Non-contact Processes	Contact Processes	Complex Multi-Processes
Mapping/modeling	Grasp and place	Sort and segregate
Monitor	Pack/unpack	Dismantle
Inspect	Transport	Disassemble
Clean	Cut	Stabilize
Characterize	Join	Decommission
Coat	Volume reduce	Assemble
Encapsulate	Surface/edge finish	Manufacture
Decontaminate	Fixture/manipulate	Remediate
	Insert	
	Retrieve	

Table 2. The processes which the PSOs wish RIM to provide, and their organization into Non-contact, Contact, and Complex Multi-processes.

3.3 The Four Basis Technology Areas of RIM

This roadmap effort began with the individual and diverse business needs of the PSOs. From these, Functional Objectives evolved and potential applications for RIM were identified. Next, the basis technology areas needed to support each of the objectives were discussed and described. Specifically, the Roadmapping Team identified four basis areas, listed below, that can serve to organize the S&T that constitutes RIM for DOE.

- Perception Science and Technology;
- Reasoning Science and Technology;
- Action Science and Technology; and
- Novel Interfaces and Systems.

Each basis science and technology area is explored in detail in a stand-alone discussion at the end of this Section of the Roadmap.

Table 3, below, bridges the gap between the two organizational constructs of the RIM Roadmap: DOE's view of RIM as providers of processes and capabilities; and the basis technology areas identified as underpinning RIM. The Table highlights the S&T that must occur in each basis technology area to accomplish the underlying tasks of modeling and mapping; the performance of more difficult non-contact and contact operations, and the completion of very complex multi-processes that involve cooperative, integrated and autonomous functioning. The scientific and technical challenges associated with these capabilities increase in complexity as one moves from left to right across the rows of the table. This suggests that RIM capabilities will mature first with respect to mapping and modeling technologies, and then sequentially for non-contact, contact and multi-operations.

It is important to note that roadmapping is the development of the series of linkages which make the connections between programmatic needs and technologies; for the RIM roadmap, the *processes* provide the key linkage between the DOE's needs and the science and technology areas. Whereas earlier we had indicated the linkages were as follows - *needs → functional objectives → technologies* - in reality the *processes* are a link between functional objectives and technologies. The latter linkage is explained in the table below.

	Mapping and Modeling	Non-contact Processes	Contact Processes	Complex, Multi-Processes
Reasoning S&T for RIM	• Incremental mapping • Motion planning: geometry-based	• Motion planning: - Geometry-based - Process model- based - Sensor-based	• Fine-motion planning	• System-level planning • Planning for integration of operations
Perception S&T for RIM	• Geometry mapping • Survey for A, B, C • Safety	• Process quality assurance • Safety	• Sensor-based control • Process quality assurance • Safety	• Safety
Action S&T for RIM	• Mobile • Arm-type • Integration of mobile and motion	• Integration of mobile and process control	• Dexterous manipulators • Heavy and large object manipulation	• Cooperative control of multiple devices
Novel Interfaces and Systems	• Interface for safe mapping operations	• Interface for human manipulation of virtual objects	• Interface for human manipulation of remote real objects	• Interface for system-level interaction

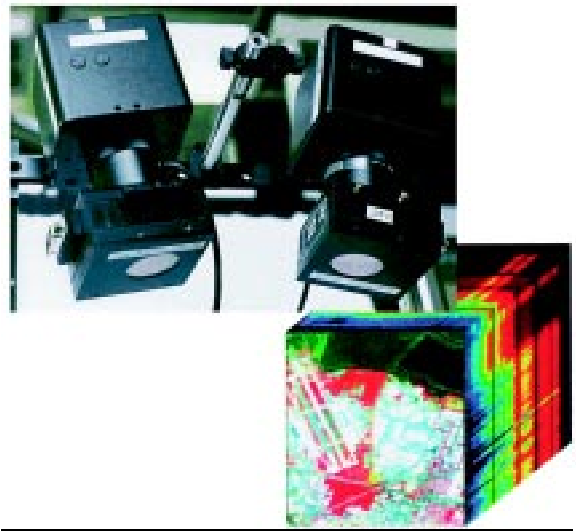
Table 3. RIM R&D Bridging Basis Technology Areas and DOE-needed Capabilities.

In the near term (i.e., Epoch I), the requirements for RIM—and thus the Roadmap—are very specifically defined by the plans of DOE's PSOs. Charts of relevant applications and technologies are provided in Appendix D of this document. Over the long term, PSO plans are less specific, and in that time-frame the Applications and Technologies portions of the charts were driven to a great extent by what the Roadmapping Team felt RIM technology would be capable of contributing to the PSO operations of the future. The 1994 National Technology Roadmap for Semiconductors very elegantly describes the relationships of the near-, mid- and far term: "The Roadmap is analogous to paved roads of proven technology, unimproved roads of alternative technologies, and innovative trails yet to be blazed."

By combining the understanding of the PSO needs, the RIM applications, and its science and technology base, this document provides the complete *line of sight* between the needs of the DOE businesses and the requisite, associated science and technology development for the next twenty years.

Perception Science and Technology For RIM

Perception systems provide a means for RIM to gather information about the working environment—information that permits operations such as manufacturing processing, navigation, monitoring, and manipulation to be accomplished safely and precisely. Recent developments in sensor technologies promise a new generation of devices that are more sensitive, more accurate, and extend the realm of perception to a broader range of phenomena. These sensors will increase efficiency in information processing, a function vital to RIM systems; enable quicker autonomous site characterization by teams of robots; and by virtue of their greater precision, will be able to minimize the creation of secondary waste. In addition, improved perception technologies will allow RIM to discriminate between different types of waste. Increases in perception accuracy and efficiency will assist DOE's weapon system programs to prevent manufacturing defects, enable smaller production runs, facilitate more flexible manufacturing operations, and lower costs.



Advances in electronics and photonics processing technologies are dramatically increasing the perception capabilities of RIM. Hyperspectral imaging cameras, illustrated here, can map the environment in many different spectral bands. The resulting 'data cube' shown above correlates spatial and spectral information. Such sensors are thus capable of detecting features invisible to conventional sensors.

Perception systems typically consist of multimodal sensor hardware with associated information processing (assimilation) modules. Current modules often combine real-time software with high-cost, specialized computing hardware. Revolutions in these technologies will make vast, integrated computing power available at low cost and with broad applicability within the DOE. For example:

- Facility mapping and treaty verification by robots will require ultrasonic, infrared, visual, and odometry sensors for navigation as well as a wide array of sensors to detect radioactive and chemical agents, and perform dimensional measurements. New perception technologies will enable many sensors to work together, to increase the safety and precision of operations.

- In precision manufacturing, a team of sensors will use product geometry and materials models to cooperatively monitor penetration depth, gases, and pool diameter to control the power supply and motion of a joining RIM. Newer and better sensory devices will improve the quality of weapons remanufacturing while decreasing costs.

Technology Trends of Sensor Hardware

The capabilities of RIM perception technologies are being dramatically affected by developments in electronics and photonics processing capabilities. For example, charge coupled devices (CCDs) are used extensively in today's electronic cameras and are considered state-of-the-art. However, a new technology, Active Pixel Sensor (APS), is emerging as a potential successor to CCDs. APS provides the same sensitivity and performance as CCDs, while providing random access capability, easy window-of-interest readout, non-destructive readout for signal-to-noise improvements, simplified clocking voltages, easy integration with other on-chip signal processing circuitry, and high radiation tolerances. Additional research to develop, demonstrate and test sensors that can withstand environmental hazards isa key to successful sensor performance in hazardous environments.

This robot manipulator has "extra-human" sensory capabilities in that the sensor pads on its surface provide it with whole-arm early warning of obstacles in its workspace. These sensors are part of an integrated safety system, and will be used to halt the motion of the arm if unexpected objects appear in the workspace.

Another emerging perception technology involves a novel approach to acoustic sensing. The acoustic lens—analogous to a sonar "eye"—consists of a thin hemispherical shell and a retina filled with transducers. The cavity between the retina and the shell is filled with a fluid that focuses incoming acoustic waves on the retina. Sound coming from a single direction is focused on a single transducer. When backscatter from a transmitted acoustic signal is received at the lens, the position of the receiving transducer on the retina yields bearing and elevation coordinates. The time delay between transmission and reception determines the range of the object in question. This acoustic sensing ability will allow RIM to detect obstacles and develop mapping for navigation. In addition, the lens can receive and transmit acoustic signals further improving the effectiveness of RIM systems.

These are only a few examples of sensors that hold promise for RIM. Other technologies, such as chemistr- labs-on-a-chip, hyperspectral imagers, millimeter-wave radiometers, ultrasonic phased arrays, microwave rangers, electron tunneling magnetometers, 3D-LIDAR, frequency modulated laser radars, and nanoscale devices for measuring pressure, temperature, and nanosize particles, will be valuable for robots deployed in DOE applications.

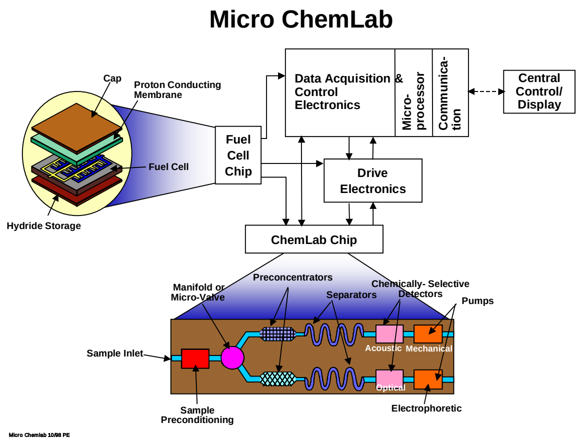
However, improvements in sensory devices can only be fully exploited if methodologies for effectively integrating such diverse sensors into the RIM systems are developed.

Integrating Perception Systems into RIM

At present, the integration of perception capabilities into RIM systems is more of an art than a science. Today, each sensor is carefully studied before it can be configured and assimilated into a system. This requires expertise in aspects of the specific devices such as physics, multi-sensor functionality and electronics. As a result, extensive sensor-specific programming is needed to assimilate each sensor into a RIM system, leading to significant manpower, time, and expertise startup costs. Development of novel sensors for RIM applications is likely to make the assimilation process even more challenging in the future unless new approaches are developed.

One of the ultimate goals for perception science and technology is to be able to simply plug-in a new sensor anywhere in a RIM system, and for the system to be able to configure and assimilate the sensor automatically. Since RIM systems will be very diverse, this goal will be very challenging. However, the capability to easily integrate new sensors into RIM systems will significantly reduce the cost of developing, deploying, and operating RIM systems for practical DOE applications. For example, consider a team of robots safeguarding a storage facility containing hazardous material. A new sensor has been developed that can non-destructively detect incipient reactions inside the containers that could cause future leaks. It is unrealistic to expect human operators of RIM to have the scientific expertise necessary to understand the sensor's operation sufficiently to be able to integrate it into the machine. However, using the RIM operating system and future automatic RIM assimilation capabilities, the operator will be able to simply plug in the new sensor to make the upgraded system operational. Each robot will then enter a training step to assimilate the sensor—perhaps employing a reasoning system element using a facility model running on the onboard ultrascale computer. Note that no further human intervention would be required. Such a capability is far beyond any presently available; currently

Better perception technologies will enable RIM to perform safe operations in otherwise hazardous situations. Here, a mobile robot uses visual and acoustic sensing to locate and orient itself to a drum to perform a radiation detection process.



Fully integrated micro-chemistry labs are in the late stages of applied research, and will be available as tooling for DOE intelligent systems.

numerous technical experts are required to understand each individual sensor before it is assimilated.

Achieving the future potential of RIM will require revolutionary and evolutionary advances in many aspects of perception systems. Fundamental science and engineering research challenges must be addressed to enable progress toward the stated goal, both in the area of innovative sensory devices and in approaches to assimilating them. Novel and high performance sensors will continue to be needed to meet RIM requirements, especially as they proliferate to address an increasing range of DOE needs. In addition to the sensing devices, the integration of revolutionary onboard computing and communication capabilities is vital to enable fast processing and intelligent analysis of the large amounts of data associated with perception systems. Also, automated methods are required for detecting the functionality of sensors, for registration and calibration, for sensor fusion, and for learning. These methods must be executed on fast, perhaps special purpose, ultrascale computational devices.

Reasoning Science and Technology For RIM

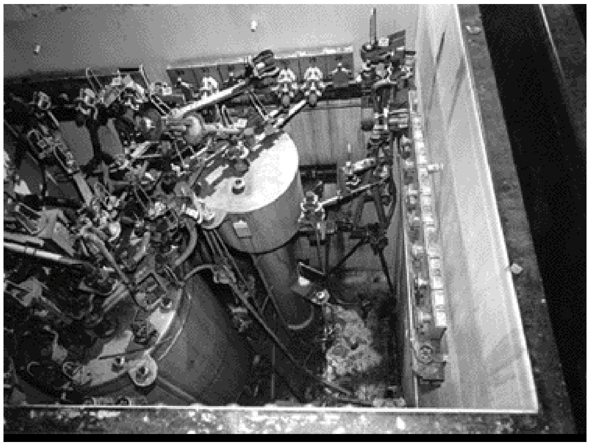
Reasoning is the "smarts" of an intelligent machine. It is the capacity to "reason" that provides the connection between perception and action. Without reasoning, machines are relegated to perform static, repetitive actions that do not respond or adapt to a changing environment without human intervention.

From the most basic perspective, reasoning is a collection of computer algorithms that interpret perceptual data and translate that understanding into appropriate actions needed to achieve a complex goal. However, reasoning for RIM systems is more challenging than most computer reasoning because of the coupling between RIM and the physical world. RIM must move about in hazardous environments and manipulate materials with the highest standards of safety. Furthermore, the real-world applications envisioned for the RIM of the future will often involve interaction with dynamic, unstructured environments, requiring machines to make intelligent decisions without explicit human guidance.

Significant cost and time savings, productivity improvements, and safety benefits can be realized by advancing the capabilities of RIM reasoning. For example:

- In the near-term, reasoning will enable small-lot production operations. DOE will be able to provide a RIM with a model of a part and a model a production operation and expect the RIM to use its reasoning capabilities to automatically produce a program to be employed by the production equipment.
- In the long-term, reasoning will enable teams of RIM to autonomously cooperate and communicate among one another to remove and separate hazardous material from buried waste sites. These systems will thoroughly plan and execute their coordinated actions, adapting as needed to the specific conditions of different locations in the waste site. With sufficient technical advances, these systems will be robust, reliable, flexible, and will be automatically designed and programmed.

Cooperative efforts among semi-autonomous RIM require substantial reasoning capabilities. The cylindrically-shaped RIM pictured here are examples of robots that can perform cooperative tasks such as collecting objects of interest to human operators.



Facilities such as this highly radioactive chemical processing plant will be retired and must eventually be decontaminated and decommissioned (D&D). Even though some of these facilities were designed for access by remote manipulators, dismantlement using traditional technology will be tedious, time consuming and expensive. D&D is a classic example of a 'multi-process' that RIM will vastly accelerate and make safer.

Communication

Communication between RIM and the human operator will be crucial, particularly when both the complexity of the tasks and the degree of autonomy of the RIM will continue to increase. Language understanding and interactive query-response methods will allow effective two-way communication between machines and their human partners. Communication will be increasingly applied to autonomous machines so their actions, results, accomplishments, problems, and deviations may be communicated to their human supervisors. RIM may then explain proposed contingency plans and corrective actions, leading to much smoother, more accurate, and faster operations.

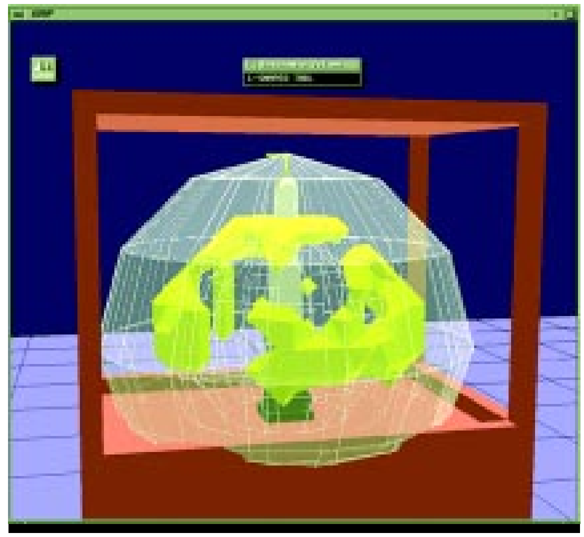
Decision-making

One of the most important aspects of reasoning is the ability to make tradeoffs to meet constraints. For example, finding and implementing a slightly sub-optimal solution or meeting an essential time constraint to avoid a collision, prevent an accident, etc., is often preferable to guaranteeing completeness of the information gathering process, exhaustiveness of the solution search space, and/or the optimality of the solution.

Real time tradeoff making capabilities involve multi-level reasoning with initial levels based on minimal models. Thus, one of the keys to such trade-off making capabilities is approximate reasoning, the ability to make decisions on the basis of incomplete, uncertain, and possibly intentionally reduced information sets. Research in this area holds the promise of providing future RIM with the ability to undertake increasingly complex jobs with greater levels of autonomy.

Memory and Foresight

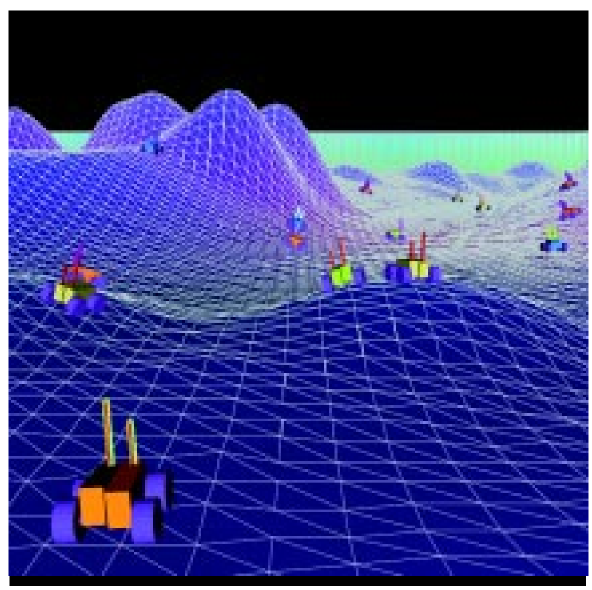
Future RIM will benefit from memory and processing power that far surpass human abilities. For example, humans are very "short sighted" in their ability to anticipate and plan for contingencies. These cognitive abilities strongly depend on previous experience, event space dimension, and hypothesis analysis. Consider a game of chess. Most humans cannot think more than a few moves ahead, whereas computers can map the ramifications of any one move, several hundred moves into the future. Hypothesis analysis on very large dimensional spaces is a specialty of computational machines and will allow tasks with large numbers of options to be fully investigated and analyzed in a relatively short period of time by the newer generation of processors. Advanced reasoning will allow computational machines to become cognitive-amplifiers for their human work partners. Aside from greatly enhancing job performance, these abilities will diminish, if not eliminate, the occurrence of human errors in both decision-making and in the execution of tasks.



Many manufacturing tasks require RIM to understand the optimal positioning of parts and tools in relation to each other. In this illustration, a RIM-based coating system uses geometric reasoning to establish the locations (yellow areas) in which a part can be placed to ensure that all of its complex surface can be reached and coated

Algorithms

Several complications arise when operating in the real world that must be taken into account in RIM reasoning systems. For example, unlike standard computer algorithms, RIM algorithms do not have full control over, or perfect access to, the data they use. Data acquisition through sensor readings is subject to error. RIM algorithms must apply to physical objects in the real world, which then must be controlled despite imperfectly understood and modeled laws of nature. The complexity of the physical space and its possible variations within the same robot task raise questions regarding the safety of operation. Developing robot-reasoning algorithms that will address generic safety concerns is a challenging scientific and technical goal.



Micro-engineering is enabling mass-producible, inexpensive small intelligent machines. Cooperating 'swarms' of these machines are envisioned for use in mapping, surveillance, and monitoring operations. However, the control of such swarms is at the frontier of computer science and is an important area of reasoning S&T.

Cooperation and Autonomy

For any given application, several reasoning technologies must be integrated to build an intelligent RIM system. For example, consider a monitoring and surveillance application of the future where teams of mobile robots will autonomously cooperate to ensure that an entire facility, site, or area is monitored in the time allotted. They will plan their mission and optimize their actions to achieve high levels of mission efficiency and reliability, including contingency considerations and possible needs for making trade-offs. They will use geometric reasoning to plan their movements through the facility to reach all areas of interest. The robots will learn and adapt their performance over time to improve their efficiency and quality of performance, or to adapt to changes in requirements. Throughout their mission, they will monitor the status of the multi-robot system and report it back to the human operators. Ideally, they will converse with their human overseers through natural language and gesture recognition. Ultimately, these teams of robots will be designed and programmed automatically for a given monitoring and surveillance application, further simplifying their use.

In summary, advances in reasoning technologies for RIM will have a significant positive impact on DOE missions. Through the use of reasoning technologies, which intelligently connect robot perception to robot action, we can revolutionize the approaches to complex problems and make dramatic advances toward RIM goals.

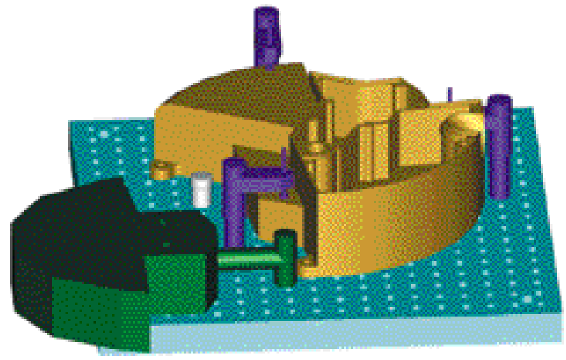
Action Science and Technology For RIM

The ability to move in space and to manipulate objects are critical capabilities of RIM. They are the means by which RIM delivers processes—thus the science and technology that enables them is critically important to DOE operations. RIM will be required to perform a host of different operations on materials in many different forms. Physically handling objects with traditional remote manipulators requires extreme care on the part of the operator and is slow, unproductive, and can become unsafe if an operator is required to spend too much time on the task. If RIM is to work on different forms and materials and to do so productively and safely, new manipulation technologies will be needed to automate much of the decision-making currently done by human operators. One key requirement is dexterity: the ability of a manipulator to adapt itself to the material being handled, and to ensure the safety of the operation.

RIM use mechanical arms to handle objects and to perform many processes. Future arms will use advanced kinematic configurations which are more dexterous. The photo above is a time-lapse exposure of a redundant kinematic manipulator which can maneuver around objects in confined areas. New RIM technology will incorporate robotic arms with 7 degrees of freedom (instead of the six degrees found in industrial robots) to increase their ability to operate in complex environments.

Twenty years from now, the goal for RIM is to develop more sophisticated robotic structures, actuators, controllers, human-machine interface controls, and auxiliary systems. Most of the tasks assigned to RIM require sensor and model-based manipulators with special purpose, end-effector devices and tools. Such devices and tools will include grasping systems and tactile hands, sensors, inspection and vision systems, cutting, digging, surface removal, coating tools, etc. General requirements for the robotic machines of the future include accommodating task-appropriate payload, precision, speed, and reach. Over the next twenty years, RIM research challenges related to "action" include:

- **Dexterous manipulators.** RIM of the future will have robotic hands which can automatically adapt to the shape, stiffness, and texture of objects being handled. To accomplish this, new electro-mechanical components will be required as described below. Sensors are needed which can serve the tactile functions and reasoning algorithms needed and which use models and sensed information to automatically generate safe grasping motions.



RIM research on manipulation has had important side benefits. Among these are improved techniques for holding products in place while they are being processed. Because each production process is unique, fixture designs—the means for "holding products in place" must also be unique, and are thus an expensive element in small lot production. RIM research on manipulation has provided algorithms which are being used for automated design of fixtures using only the CAD model of the product, promising substantial cost reductions in production.

- **General design techniques for systems with highly complex, nonlinear components.** Research to design control systems for performing highly complex, non-linear tasks will be a major area of emphasis. The challenge is to design control systems, including component selection, controller design, implementation, and tuning that will perform precisely what the operator wishes rather than an approximation. Extensive use of recent advances in high performance simulations, including virtual prototyping, will support innovative approaches and methodology development in this area. The ability to perform hardware verification tests over the network—as proposed in the concept of the virtual laboratory—will also greatly extend the envelope of what is possible.

- **Developing simulation and modeling techniques to accurately predict the performance of systems and components.** Design of control algorithms that are able to adapt to significant changes in operating conditions will provide additional capabilities for machines to operate reliably in uncertain and unmodeled environments. These will also be useful for model-based control and performance evaluation.

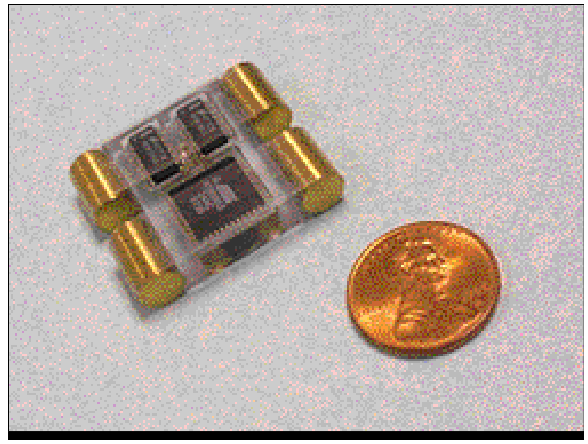
- **Development of controllers for human amplification/de-amplification techniques.** Because of the high levels of gain generally required (large to magnify the human force in the case of human amplifiers or large to magnify the environmental force in the case of human de-amplifiers), new controller design and stability criteria are needed. Controller design techniques, modeling and simulation technologies, and verification with hardware are areas where major research is focused.

- **Monitoring systems and design for fault tolerance for maintenance and error recovery.** Monitoring systems will improve the reliability of RIM, enabling systems that will operate autonomously in uncertain and hazardous environments or in close physical collaboration with humans.

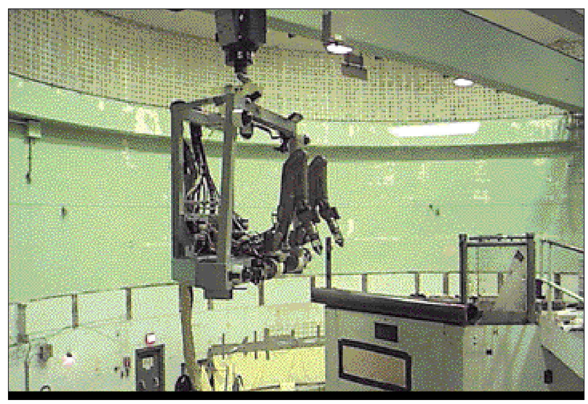
- **Integration of sensors and control algorithms.** Integration of these items will improve operation and increase the applicability of future autonomous systems. Integration of sensor characteristics (*e.g.*, performance, accuracy, dynamic range) into the control algorithm design and function is a new research area. Development of control algorithms that are capable of adapting their performance according to sensor characteristics will be useful for high-performance systems.

- **Development of new structural and assembly concepts, control elements and actuators having higher power-to-weight ratio.** Fluid-based actuators will be the primary focus for the near term and will allow major energy efficiency improvements in currently very energy-inefficient components (e.g., 30 percent energy loss is common in servo valves). These advances will significantly improve the payload and power capacity over size, weight, and energy use ratios of RIM, allowing machines to perform high payload tasks not currently feasible today due to size-related constraints.

In summary, research on action science and technology will focus on the integration of design and control for highly nonlinear systems to achieve high performance capabilities with respect to dexterity and combined high payload, precision, speed and reach for next generation manipulation. RIM concepts, including human amplifiers and de-amplifiers, new end-effector tools, and sensor designs with improved reliability and fault tolerance are essential.



Integrated action *systems of micro-actuators and micro-sensors, such as the small robot shown here, will enable a wide variety of new capabilities important to DOE. For example, facilities being readied for decontamination and decommissioning will be mapped in detail without requiring worker exposure to hazards. Such mass-producible systems will also perform DOE's monitoring and surveillance operations with unprecedented levels of reliability.*



The Dual Arm Work Platform, pictured here deployed at a DOE site., consists of two cooperating manipulators that sense and compensate for each other's activities. Research on cooperative control technologies is an important part of emerging RIM S&T, and will enable these. systems to addrress many of DOE's needs.

RIM abilities to model and manipulate virtual machines are becoming so realistic that a human operator may feel as if he or she were working with real machines, rather than simulations. Here, a RIM computer programmer is using virtual RIM and a virtual material shipping container to develop a mathematical equation for radiation monitoring.

Integration Science and Technology For RIM

The future of RIM envisioned for DOE operations suggests that these systems will be as commonplace as current automation in today's office operations. For this vision to be realized, RIM systems must be easy to use, and components that provide perception, reasoning and action capabilities must be easy to integrate. The integrated RIM of the future will offer many benefits:

- They will have interfaces that are as intuitively understandable as the best personal computers and applications programs;
- They will be easy to bring into a state of safe and reliable operation; and
- They will be easy to program.

RIM Interfaces

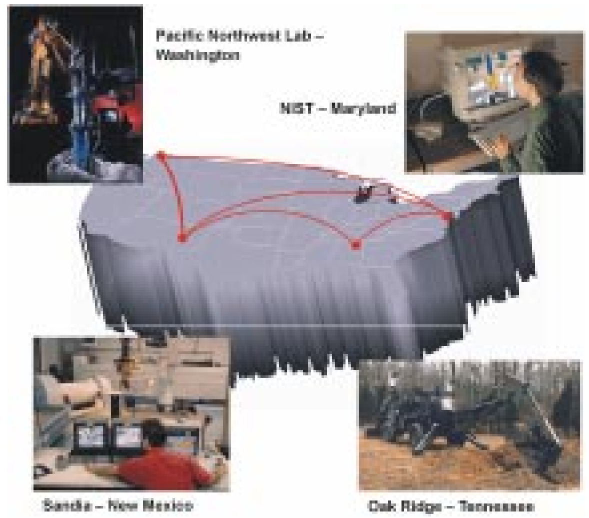
The intuitive human-computer-machine interface for RIM systems does not yet exist. Robotics engineers, for example, still program with outdated computer languages and non-intuitive hand held devices called "teach pendants." The interfaces of today's industrial robots are not much more advanced than the computer interfaces of 15-25 years ago. This is one reason that robotic systems for the DOE remain expensive on a per-unit-processed basis. Making RIM accessible to non-specialists will involve more research to improve interfaces and virtual reality devices for manipulation of virtual and real objects.

The interfaces envisioned for RIM of the future will make them as accessible as the word processors of today. Imagine the following steps a human operator might want a DOE RIM system to do to separate explosive hemispheres:

1. Apply forces and torques of no more than A and B during the separation.
2. While moving through the workspace to approach the two hemispheres, do not collide with surfaces C, D or E.

Today a robot software engineer must develop a few thousand lines of code to implement these two simple commands. In the future, the RIM operator will "put on" his/her virtual explosives handling tools, virtually instrument them with the required force and torque limits, reach for the hemispheres, and separate them. The system itself will be smart enough to avoid unintentionally bumping into objects in its workspace.

User interfaces that can accomplish these tasks do not need to be application-specific; one can easily imagine that the user interface for the explosive disassembly operation might have the same look and feel as a container recovery operation at a buried waste site.



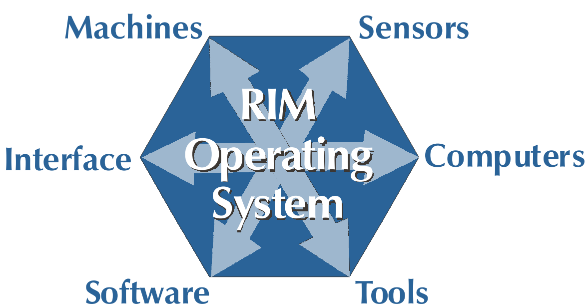
Integration science and technology will permit the easy integration of systems for application in the field, and will permit diverse teams of researchers to collaborate remotely on real equipment via virtual models. DOE's laboratories, working with the National Institute of Standards and Technology, have already demonstrated the potential of this capability.

RIM Modeling Systems

Today much of a RIM's control software depends heavily on the geometry of the workcell and its ultimate workspace. It is difficult to begin any software development before a workcell is fully designed and laid out. Because hardware and software engineers are working on the project in series versus in parallel, the project's duration increases substantially and it becomes vulnerable to cost overruns. To overcome this, the RIM community must work closely with the computer modeling community to develop systems that permit incremental development of Computer Aided Design (CAD) models of workcells, enabling software engineers to begin work in the early phase of projects.

Modeling systems must be developed that will be capable of supporting a new human-machine interface. For example, today's modeling systems have difficulty "understanding" that the two explosive hemispheres are joined, or that the waste container is buried within the soil. This limitation is not of consequence when detailed programs are written which explicitly direct each motion of the RIM (*e.g.*, move to point H, close gripper, move to point I). If virtual tools of the future are to function properly, these systems must automatically understand that the two hemispheres are related in specific ways, and that the drum is surrounded by soil. This will require modeling systems with new capabilities.

The RIM of the future will offer human-machine interfaces that are as easy to operate as the current personal computer. Integration of RIM perception, action and reasoning capabilities enable this welder to operate a robotic cutting tool from a safe distance.



Operating systems allow the rapid integration of RIM capabilities—the key which will enable RIM to perform with high levels of safety and reliability in DOE operations.

RIM Operating System

The RIM systems of the future will require operating systems (OS) that:

- **Provide all the usual capabilities provided by an OS**—resource management, process scheduling, communications, etc. Today there are concepts on how to accomplish this for future sensor and model-based machines, and limited prototypes abound, but these provide only a starting point.
- **Are nearly 'invisible' to users.** We are far from having invisible operating systems today. Currently, specifically trained robotics engineers are relied upon to develop required programs; in the future, RIM must move away from the requirement for an "expert" to develop and integrate RIM technologies.
- **Assure the safety requirements of DOE processes.** RIM OS must be a tool for the development of system safety so that peripherals—the elements that provide perception, action, and reasoning capabilities to RIM—can be quickly, reliably and safely added. The RIM OS of the future must avoid introduction of surprise side effects as peripherals are added—a too common occurrence with today's commercial operating systems.
- **Support "plug and play."** Inter-system communications must be accomplished in ways that are standard for the developers of subsystems. Subsystems must be able to communicate their capabilities and interfaces in the background and operate safely together. If the RIM vision is to be achieved, integration of systems for complex, delicate operations must be as simple as today's pointing and clicking on a personal computer.

4.0 THE LONG-TERM VISION FOR RIM

4.1 RIM of the Future

Over the next few decades, advanced RIM technologies will fundamentally change the manner in which people use machines, and by extension, the way DOE accomplishes its missions. New robotic systems, fueled by improvements in computing, communication and micro-engineered technologies, will transform many of our most difficult tasks. It is expected, for example, that:

- Micro-scale robots with the ability to crawl, fly, and swim will be able to work together to perform monitoring, surveillance and intelligence operations;
- Environmental facility remediation, monitoring and inspection, as well as resource exploration, will be performed with high efficiency and low risk through autonomous teams of robots; and
- Automated methods closely coupling design and manufacturing will allow cost-effective, totally automated production of both large- and small-lot manufacturing products.

In the future, people will work directly with teams of cooperating RIM in complete safety and will interact with multiple intelligent machines through sensory, immersive interfaces that intelligently adapt to human and supervisor desires. Health monitoring and maintenance will be fully automated. Power sources and communications will no longer inhibit missions, and all RIM systems will be constructed and configured through fully automatic “plug-and-play” approaches. By the year 2020, RIM will both duplicate and extend human dexterity, perception, and work efficiencies in a broad range of tasks—these technologies will be as pervasive and indispensable in DOE operations and the National economy as the personal computer is today.

4.2 RIM Applications in the Year 2020: Two Examples

RIM Applications In Manufacturing

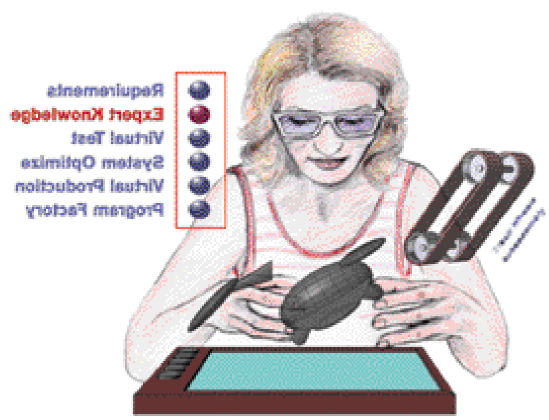
For many years, DOE’s Office of Defense Programs has considered the use of automation to perform many of its operations. However its attempts to introduce standard industrial automation have met with mixed success. The small-lot nature of DP’s manufacturing operations has made the use of automation uneconomical bacause in many cases not enough units of a product were built to amortize the cost of setting up a workcell. Although automation has proven to increase quality and productivity in industrial settings, and can improve DOE worker health and safety, it has been prohibitively expensive.

Today, dramatic changes are occurring. The Accelerated Strategic Computing Initiative (ASCI), fueled by the ongoing revolution in computing, is fundamentally changing the capabilities and processes for integrating the design and manufacture of products. Simultaneously, weapon subassembly systems—parts of a weapon's safety, security and reliability system—are reaching the end of their design lives. Many were originally designed decades earlier, and most of their parts and components are no longer available. Furthermore, the requirements for safety, security, and reliability have become significantly more stringent since the subassembly was originally designed. Thus many subassembly systems must be entirely redesigned and re-manufactured.

In the future, the application of industrial equipment in DP's operations, combined with the next generation of RIM, will permit DP to improve the safety of its workplace and will allow it to achieve the gains in quality and productivity that have been available to civil industry for several decades. The following is a vision of how RIM of the future will enable new ways of accomplishing old tasks. It emphasizes manufacturing, but also illustrates the interaction of manufacturing and product design.

In the year 2020 . . .

A product designer sits down with her electronic design pad. Using embedded models of various parts and components, the pad works with her to successively refine her concepts until she has a preliminary design of the subassembly she believes will meet the performance requirements. She—with assistance from the pad—decides on a micron-size robot to be built from a number of micromachined parts and gears. The design pad uses ASCI-developed models to test whether her preliminary design will, in fact, meet performance requirements. Concurrently, the pad also tests whether the design can be produced in the production facility—a "Master Craftsman" factory—which it schedules to be available when the design is complete. During the design process, the pad runs precision models of the factory and its equipment to assess the product's manufacturability. When the design is finalized, the pad will load the electronically stored production programs into the physical production equipment with instructions to produce the subassembly.



Future designers will use electronic interfaces capable of assisting with all phases of product design from the 'cocktail napkin' concept stage through the final design and its testing in virtual factories. Illustrated here is a fanciful view of how this interface may work: the designer is wearing 'magic' glasses that permit her to manipulate the components of a small vehicle she is designing. She has completed design of one subassembly, and has placed its icon out of her way on the display. The designer has a powerful suite of computer models available to her and she uses them to continuously test the manufacturability of her design. Once she is satisfied with the design, she pushes the "Program Factory" button and the programs for the production equipment are automatically generated and downloaded to the factory.

During production, "inspector RIM," knowledgeable about the overall system specifications and the potential failure modes of the various piece parts, select optimal sensors and program themselves to perform the necessary nano-inspections. The piece parts are then delivered to a RIM workcell responsible for joining operations. The workcell automatically configures itself to accommodate the geometry of the parts and joints, selects sensors needed for online inspection and control of the joining process, and programs itself to perform the necessary tasks. Finally, the RIM system generates all the required documentation.

All DP manufacturing RIM will operate in a similar manner: incorporating sensors for inline inspection and control, and using models of the product, process and sensors to automate programming of the operation.

RIM Applications in Hazardous and Remote Operations

In 1993, the predecessors of RIM were in operation. However, the use of remote manipulators, in which a person directly controls every movement of a robot arm, was substantially limited to simple grasping actions and the movement of objects from one space to another. Any use of a remote manipulator required continuous operator attention to ensure the safety and success of the task. No autonomous operation was possible. The same was true of robotic vehicles: those that existed were controlled with a joystick and employed a television monitor to provide the human operator with a view of what the mobile robot was doing. RIM that will operate autonomously, and thus increase DOE's productivity and the safety of its workers in hazardous environments were still years away.

These more capable systems were being researched, however, and are among the reasons we have greatly improved RIM today. In contrast to 1993, RIM is now being used in DOE operations involving handling and processing of radioactive and hazardous materials and waste. Among the most successful are the Automated Explosive Gas Generator Disassembly System and the "Stage Right" materials storage and inspection robot. (These robots are pictured on pages 20 and 24, respectively, of this document.) The success of these systems stands as proof that software and sensor-driven machines can gain approval within some of the most extremely safety-conscious organizations within DOE.

By the year 2020, teams of RIM will be sent to buried waste sites and in a few weeks could map the location of contamination and buried waste; retrieve, sort, treat, and package the waste; and complete the requisite documentation, with only orchestration from remote human operators.

We have begun the transition from the early people-based systems and "dumb" machines to the RIM anticipated for the year 2020. Following is one vision of this future, illustrating futuristic RIM in an environmental management application.

In the year 2020 . . .

A team of specialized RIM systems is delivered to a buried waste site and works cooperatively over several weeks to remediate the site. First, RIM mappers make an initial survey to locate objects and measure contaminant levels. During the course of the remediation, the mappers work continuously and cooperatively with the other RIM to update the site survey and to perform additional surveys as necessary. Using these maps, other “retriever RIM” program themselves to recover objects. The dexterity of these RIM, made possible by real-time perception and control using a combination of force and contaminant sensors, allows the system to avoid creation of hazardous situations or additional waste.

Next, a team of “pack mule RIM” delivers the recovered waste and contaminated media to “sorting and segregation RIM.” Using many of the underlying sensing and manipulation technologies developed for the mapping and retrieving RIM, the sorting and segregating RIM separate the waste into different streams depending on levels of radiation, solvents, explosives, etc. More specialized RIM then take over, processing each type of waste in an appropriate manner and packing the treated waste for storage. “Storage RIM” deliver the packed waste to appropriate locations.

Throughout this process, a human supervisor observes the activities of all RIM and is available to solve problems beyond the RIM’s skill level. If necessary, the observer has the computer and interface tools needed to develop and insert new machine intelligence. Again, the RIM create all the required documentation.

4.3 Concluding Thoughts

Today, the U.S. Department of Energy is poised to simultaneously improve its operations and significantly accelerate the evolution of RIM. For the first time, this Roadmap provides a framework through which one can see how R&D across the entire spectrum of basis technology areas will contribute to the development of robotic systems that will meet DOE’s needs. The identification of Functional Objectives and their associated timeframes serve as guideposts for end-users and the R&D community for anticipating technological needs and capabilities over the next twenty years. The structure provided by the Roadmap in describing RIM S&T in terms of the processes and capabilities needed by DOE allows those in the R&D community to look across the landscape of RIM, locate their own contributions, and understand the relation of their activities to the larger effort.

It is in providing this sweeping view of the future of RIM and its applications within DOE that the Roadmap serves its function. It presents us with an understandable, credible, and common vision of how these technologies will evolve over the next two decades to lower costs, improve safety, and increase productivity for DOE.

Robotic systems have not always been associated with these benefits. However, the combination of past investments in RIM and the recent spectacular advances in computing, communications, electronics and micro-engineering, leaves the technology poised to provide DOE and other Federal Agencies with a dramatically new set of tools at their disposal.

Now, many understand that emerging RIM technologies are the key to reducing cost in many of DOE's operations, and for safely accomplishing others. In fact, it is difficult to imagine how DOE will reduce its manufacturing costs while increasing productivity, or will perform some of its more dangerous disassembly, decontamination and decommissioning activities without the widespread integration of RIM in many facets of DOE operations.

DOE's motivations and the breadth of its missions will endure into the foreseeable future. No other agency, Federal or civil, possesses a comparable breadth of responsibilities for manufacturing, environmental management, materials accountability and scientific endeavor. For this reason, DOE can and should take the long view, deploying mature RIM technologies to meet its current goals while pushing the forefront of this critical technology through investments in its basis science and technology. This must surely fall within the role of an agency whose mission spans the desire to further basic scientific understanding as well as the need to protect the health, safety and security of its workers and of our Nation's citizens.

Appendix A
LETTER FROM SENATE TASK FORCE ON MANUFACTURING

Senator Olympia Snowe, Co-Chair
250 Russell Senate Office Building
Washington, DC 20510
ph: 202-224-5344
Staff Contact: Tom Geier

Task Force Liaison:
Geoffrey Brown
202-224-0606

SENATE TASK FORCE ON MANUFACTURING

Senator Joseph Lieberman, Co-Chair
706 Hart Senate Office Building
Washington, DC 20510
ph: 202-224-9184
Staff Contact: Joe Michels

November 5, 1997

The Honorable William S. Cohen
Secretary of Defense
The Pentagon
Washington, D.C. 20301

The Honorable Federico Peña
Secretary of Energy
Washington, D.C. 20585

The Honorable Neal Lane
Director, National Science Foundation
4201 Wilson Boulevard
Arlington, Virginia 22230

The Honorable William M. Daley
Secretary of Commerce
Washington, D.C. 20230

The Honorable Daniel S. Goldin
Administrator, National Aeronautics and Space Administration
Washington, D.C. 20546

Gentlemen:

On September 30, 1997, the Congressional bipartisan Task Force on Manufacturing and the Senate bipartisan Task Force on Manufacturing co-sponsored a Congressional Expo on Intelligent Machines, in coordination with Sandia National Laboratories and the Robotics and Intelligent Machines Cooperative Council. The Congressional Expo featured presentations and panel discussions involving key figures from the robotics and intelligent machines industry, labor movement representatives, research institutions, and federal agencies.

The Congressional Expo demonstrated that the U.S. robotics and intelligent machines industry is on the cusp of major advances. The United States currently leads the world in enabling technologies such as software, sensors, and controls. These next generation technologies are opening the door to new markets and may enable the United States to regain its dominant position in the robotics and intelligent machines industry.

We are writing today to urge your agencies to work together and help the U.S. robotics and intelligent machines industry exploit this opportunity. Both Senator Jeff Bingaman and Senator Pete Domenici addressed the Congressional Expo. Senator Domenici, observing that robotics and intelligent machines are essential in government missions, promoted research partnership efforts between government, industry, universities and the national laboratories as the best way to leverage national technical resources. A successful, coordinated partnership effort will enable the U.S. to take the lead in this new industry. Senator Bingaman developed these same themes by offering an eight-point program for joint action by your agencies that we wholeheartedly endorse. Outlined below, the program focuses on improving communication and integrating the activities of your agencies in order to create a strong American robotics and intelligent machines industry.

1. The Department of Energy (DoE), NASA, the Department of Defense (DoD), the Department of Commerce (DoC) through its technology programs, and the National Science Foundation (NSF), in consultation with industry, should develop a common technological road-map for advanced robotics and intelligent machines that identifies areas where fundamental research is most needed. These agencies should then issue a plan for a national robotics and intelligent machines initiative that addresses those needs in an integrated fashion.

2. Using existing authorities, DoE, NASA, NSF and DoD should begin to exchange personnel, who serve as technical managers for robotics and intelligent machines, in order to promote communication and cross-fertilization of ideas and approaches.

3. The Department of Energy and NASA should take the three primary centers of their existing robotics efforts and turn them into testbed centers for robotics and intelligent machines open to other federal agencies and private sector researchers. Such centers would be analogous to DoE's current user facilities for other scientific disciplines. These centers would be located at Sandia National Laboratories, funded by DoE and grants from the NSF, and at Carnegie Mellon University and the Jet Propulsion Laboratory, which are both funded by NASA.

4. The National Institute for Standards and Technology (NIST) within the Department of Commerce should take the lead in using its standard-setting capacity to encourage open system architectures for advanced robots and intelligent machines. NIST

5. Through its Manufacturing Extension Centers, NIST should develop an infrastructure that encourages small businesses to develop and use robotics and intelligent machines. Every effort should be made to disseminate technology developed from robotics research into the small, high-tech companies.

6. The robotics initiative should include studies of the ethical, legal, and social issues involved in the development and dissemination of such technologies.

7. The relationship between robotics and intelligent machines and the work force of the future should also be systematically explored. This exploration should include establishing a discussion forum, at a neutral site such as the National Academy of Sciences, for manufactures, labor groups, government, and other public interest groups. The three prime federal agencies, along with interested private foundations, should provide fiscal support for this endeavor.

8. Top leadership from DoE, NASA, DoD, NSF and DoC (NIST), in consultation with the

Robotics and Intelligent Machines Cooperative Council, should work out a high-level Memorandum of Understanding among the five agencies, so that program managers and other experts in each agency have both the mandate and the high-level direction needed to initiate a national robotics and intelligent machines initiative as quickly as possible.

We endorse this proposed program, and request the following:

1. That each of your agencies designate a senior-level official to move forward quickly on formulating the Memorandum of Understanding discussed above.

2. That, at the time of the submission of the President's Budget Request for fiscal year 1999, representatives from your agencies make a joint presentation to the Congressional and Senate Task Forces on Manufacturing on the status of cooperation and integration of your programs in robotics and intelligent machines.

We thank you for your attention and look forward to your speedy and cooperative response to our requests.

Sincerely,

Joseph I. Lieberman (Co-Chair, Senate Task Force on Manufacturing)

Olympia J. Snowe (Co-Chair, Senate Task Force on Manufacturing)

Jeff Bingaman

Pete V. Domenici

Alfonse M. D'Amato

Bob Franks (Co-Chair, Congressional Task Force on Manufacturing)

Marty Meehan (Co-Chair, Congressional Task Force on Manufacturing)

Appendix B
RIM ROADMAP DEVELOPMENT

RIM ROADMAP DEVELOPMENT

Technology roadmapping is a needs-driven technology planning process used to identify, select, and pursue technology alternatives that meet a set of anticipated customer needs. The process relies on a team of experts to develop a framework for organizing and presenting critical technology planning information to improve the selection and potential leverage of technology investments. Ideally the steps involved in each initiative will adhere to certain fundamental guidelines with modifications reflecting individual situations and the decisions the team wishes to make.

Each technology roadmap is different, reflecting the nature of the technologies themselves as well as the types of decisions one expects to make as a result of the roadmap. Nevertheless, fundamental steps remain consistent from roadmap to roadmap. The structure of the RIM roadmap was based on lessons learned from roadmapping initiatives by the SIA (Semi-Conductor Industry Association) and the NEMI (National Electronics Manufacturing Initiative), in addition to work within Sandia National Laboratories.[1]

Development of the Robotics & Intelligent Machines Roadmap involved two phases:

1. Preliminary activity to build support among the stakeholder Principal Secretarial Officers (PSOs) for the roadmapping initiative and obtain their help in defining the Roadmap's scope and boundaries.

2. Subsequent team work to identify PSO needs and their relation to RIM functional objectives, metrics, and goals.

The actual content of the RIM Roadmap was developed through a series of Core and Support Team meetings (a total of six occurred over a three-month period) and much off-line Support Team work. Representatives from nine DOE PSOs formed the Core Team and representatives from four DOE national laboratories, Sandia National Laboratories (SNL), Oak Ridge National Laboratory (ORNL), Idaho National Engineering Laboratory (INEL), and Lawrence Livermore National Laboratory (LLNL), formed the Support Team.[2] Meetings of the Core and Support Team alternated. The Core Team provided guidance to the group as a whole, and ensured that the effort remained grounded in DOE's needs. The Support Team generated the details of the Roadmap, reaching into its respective laboratories and imaginations to identify the technologies and R&D that would be required to meet the DOE vision.

---

1 *Fundamentals of Technology Roadmapping* (SAND Report #97-0665) and *Introduction to Technology Roadmapping: The Semiconductor Industry Association's Technology Roadmapping Process* (SAND Report #97-0666).

2 Representatives of the nine PSOs and DOE laboratory staff participating in the RIM Roadmap are listed on the inside front cover of this document.

The sequence of meetings reflected a top-down approach, starting from the level of DOE business plans, and included the following steps:

- **Identification of Needs:** The high-level program objectives provided by DOE businesses in their long-term and strategic plans (*e.g.*, "support and maintain a safe, secure and reliable stockpile");
- **Identification of Functional Objectives, Metrics, and Goals:** The capabilities and timeframes deemed by DOE to be key in meeting their needs (*e.g.*, "Reduce manufacturing defects by 90% by the year 2012");
- **Identification of the Capabilities and Process desired by the PSOs and the RIM Basis Technology Areas:** The capabilities PSOs will desire of RIM and the underlying areas of technology needed to achieve the functional objectives, metrics, and goals; and
- **Identification of RIM S&T:** The specific RIM S&T alternatives for satisfying the metrics and goals.

The result was an integrated approach for satisfying DOE's needs through RIM S&T between now and the year 2000. The team approach built a common vision of the future of RIM, and of the investment decisions that will be needed as the technology progresses.

A brief summary of the Core and Support Team meetings is provided below.

1. **Core Team Meeting:** [March 11, 1998, at SNL Rosslyn Office in Washington, DC] The purpose of the RIM's initial meeting was for stakeholders to discuss and develop a common understanding of the "roadmapping" process and its product; to agree on the scope of the effort and participant level of participation; to develop a schedule for a Fall 1998 delivery of the Roadmap; and to assign the Support Team off-line work to identify high-level PSO needs for which robotics/intelligent machine technology is a possible solution.
2. **Core Team Meeting:** [April 7, 1998, at SNL Rosslyn Office in Washington, DC] The purpose of this meeting was to obtain agreement from the PSO representatives on the collective set of high-level needs for which RIM was a possible solution; to identify a vision of "why RIM R&D is needed;" and to assign the Support Team off-line work to identify the next level of detail below that of PSO needs.
3. **Support Team Meeting:** [April 22, 1998, at SNL in Albuquerque, NM] The purpose of this meeting was to define RIM and its boundaries; to complete the identification of Functional Objectives, metrics, and goals begun through off-line work; to begin the identification of basis RIM technologies for addressing these needs; and to discuss the new technologies' impact on the vision of RIM.

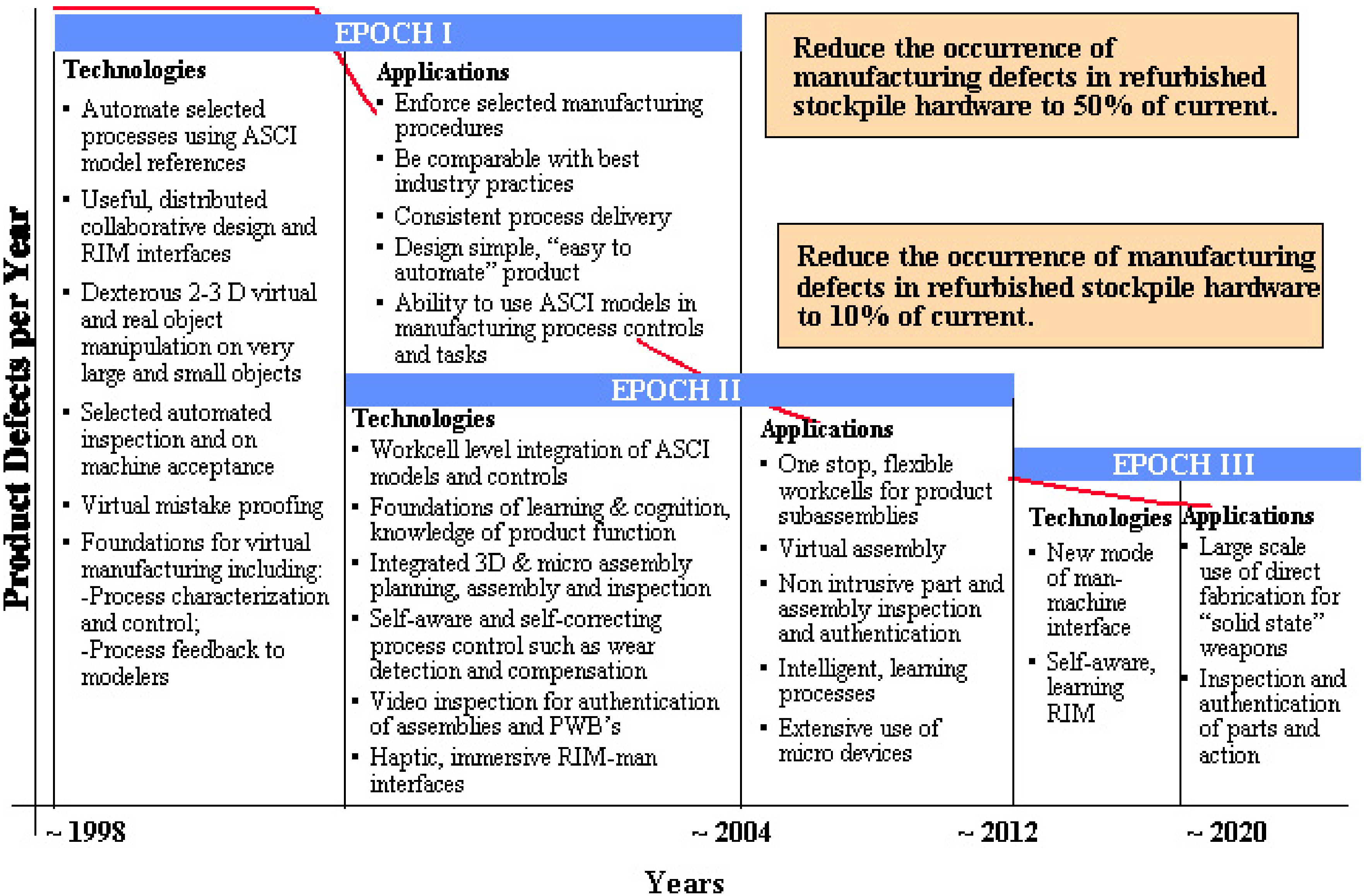
4. **Core Team Meeting:** [May 7, 1998, at SNL Rosslyn Office in Washington, DC] The purpose of this meeting was to obtain agreement from the PSO representatives on the collective set of functional objectives, metrics, and goals; to finalize the list of basis RIM technology areas; to make assignments for writing the Roadmap document and prepare the briefing for Dr. Ernest J. Moniz, Under Secretary of Energy, and Michael L. Knotek, Program Advisor for Science and Technology; and to assign the Support Team off-line work to identify specific RIM S&T activities that would support the functional objectives.

5. **Support Team Meeting:** [May 13, 1998, at DFW Hyatt in Dallas, TX] The purpose of this meeting was to finalize the identification of specific RIM S&T objectives (for Epochs 1 & 2); to understand how each is related to the PSO needs and functional objectives; to determine what RIM basis S&T will be capable of in Epoch 3, and thus how RIM will revolutionize the way PSO missions are performed; and to make final adjustments to the Roadmap document production schedule and briefing assignments.

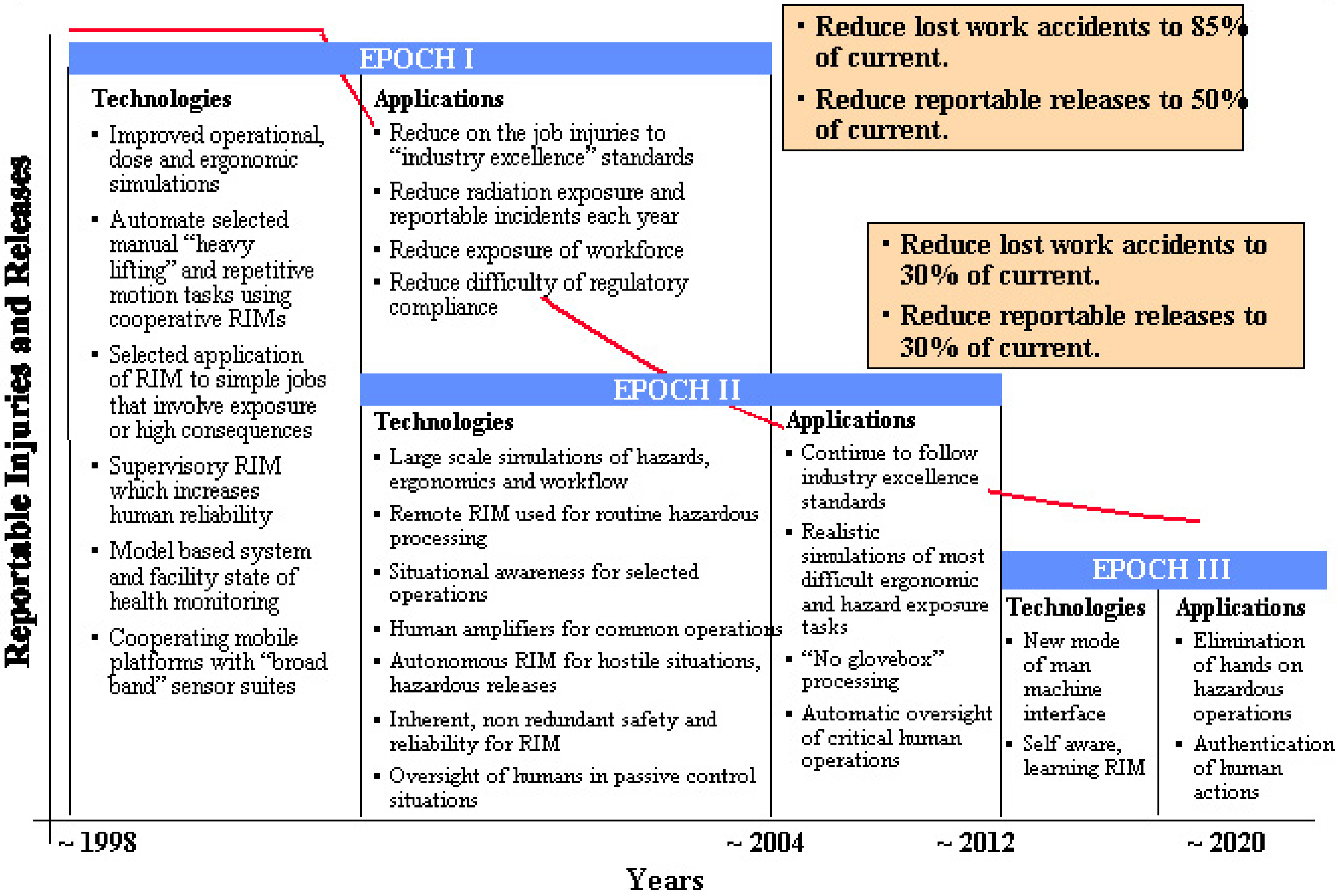
6. **Core Team Meeting:** [June 2, 1998, at SNL Rosslyn Office in Washington, DC] The purpose of this meeting was to obtain agreement from the PSO representatives on the collective set of information generated from the meetings and off-line work; to test the roadmap's rationale and presentation clarity to its DOE stakeholders; to dry-run the briefing of the Roadmap content to be given to high-level DOE personnel; and to make final assignments for briefings to the Under Secretary and the Program Advisor for Science and Technology.

Appendix C
FUNCTIONAL OBJECTIVE CHARTS

DP Driver: Reduce Manufacturing Defects



DP Driver: Reduce Hazards to Workers & Environment



DP Driver: Reduce Costs

EPOCH I

Technologies

- Design simple, "easy to automate" product using distributed, collaborative interfaces
- Automate special skill processes and processes sensitive to regulation
- Virtual manufacturing developed for selected processes using distributed, collaborative interfaces
- Adaptive, model reference process control
- Semi-autonomous service RIM for security, custodial, and material handling duties
- Foundations of flexibility including:
  - Dexterous 2-3D virtual and real object manipulation on large and small scales;
  - Reconfigurable fixturing and tooling

Applications

- Reduce cost of regulatory compliance
- Optimize product realization process
- Reduce manpower/increase efficiency
- Reduce cycle time
- Decrease infrastructure costs such as security, use of floor space…

Reduce time and cost for refurbishment of appropriate stockpile hardware by 20% of current.

EPOCH II

Technologies

- Remote RIM used for routine hazardous processing
- Haptic and immersive man-machine interfaces for design and manufacturing
- Near human presence on mobile platforms and over networks
- Autonomous rover RIMs for monitoring, material delivery, etc.
- Natural language programming of RIM
- Automated programming classes of RIM
- Integrated, autonomous mobile devices for heavy operations
- Cooperative multi-arm manipulators

Applications

- "Near fully flexible" product lines
- Routine virtual manufacturing using immersive interfaces
- Automated security, MC&A and material handling
- Regulation and workload insensitive facilities

Reduce time and cost for refurbishment of appropriate stockpile hardware by 50% of current.

EPOCH III

Technologies

- New mode of man-machine interface
- Self aware, learning RIM

Applications

- Master craftsman plants
- Large scale use of direct fabrication for "solid state" weapons

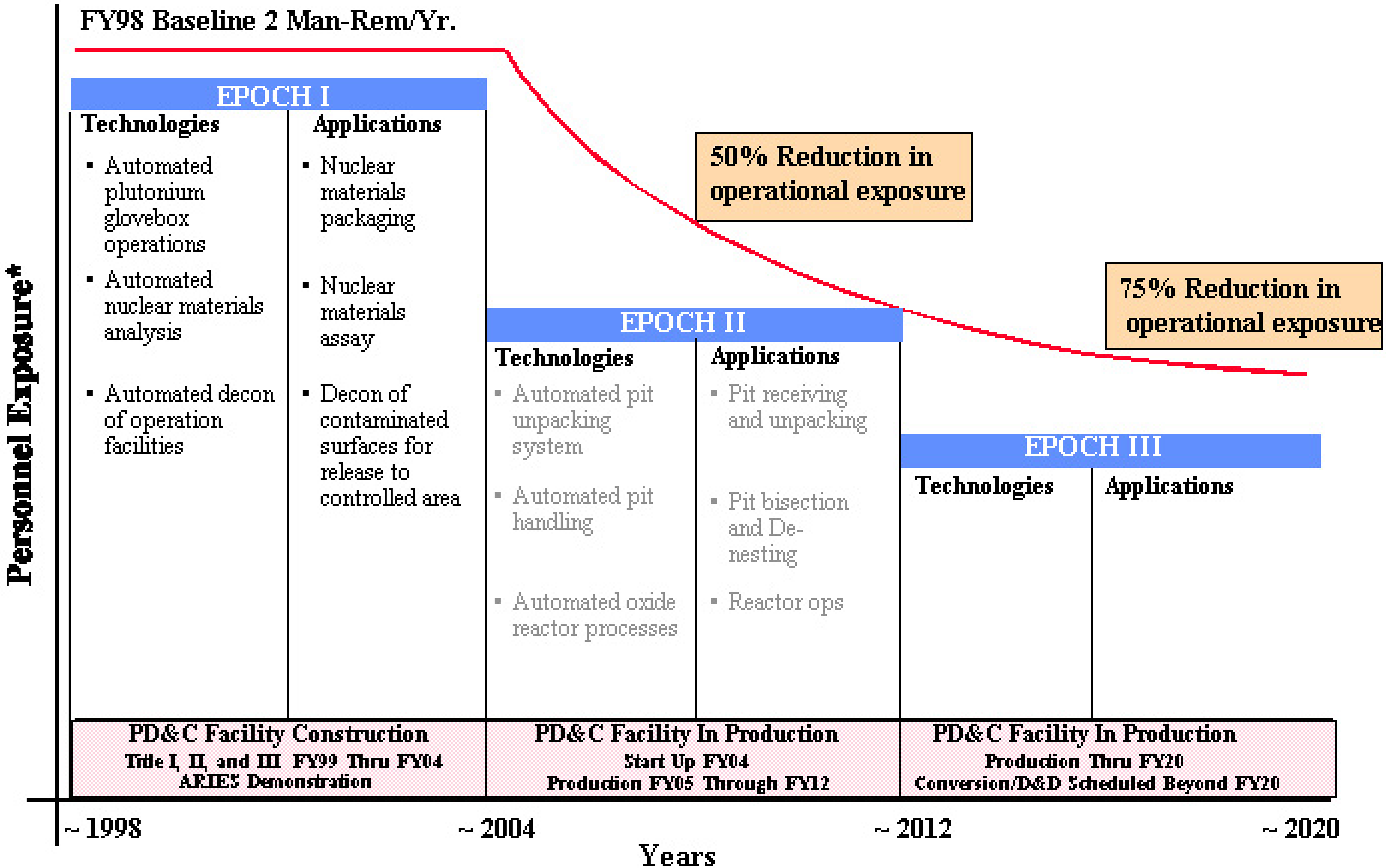
Available Yearly Budget

~ 1998 ~ 2004 ~ 2012 ~ 2020

Years

MD Driver: Exposure Reduction

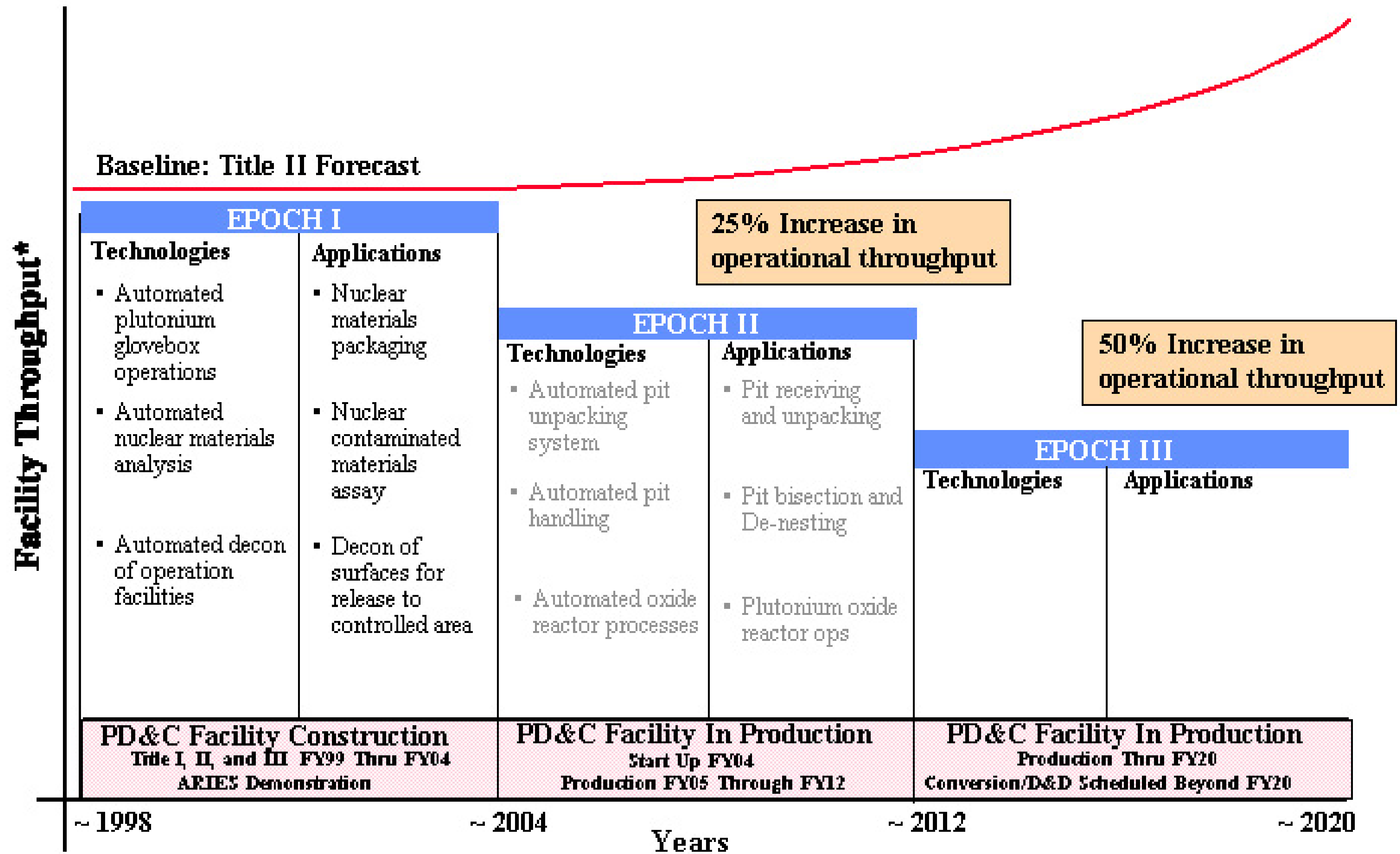
Specific To The Pit Disassembly and Conversion Facility



* Functional objective driven by increasingly stringent regulatory environment

MD Driver: Facility Throughput

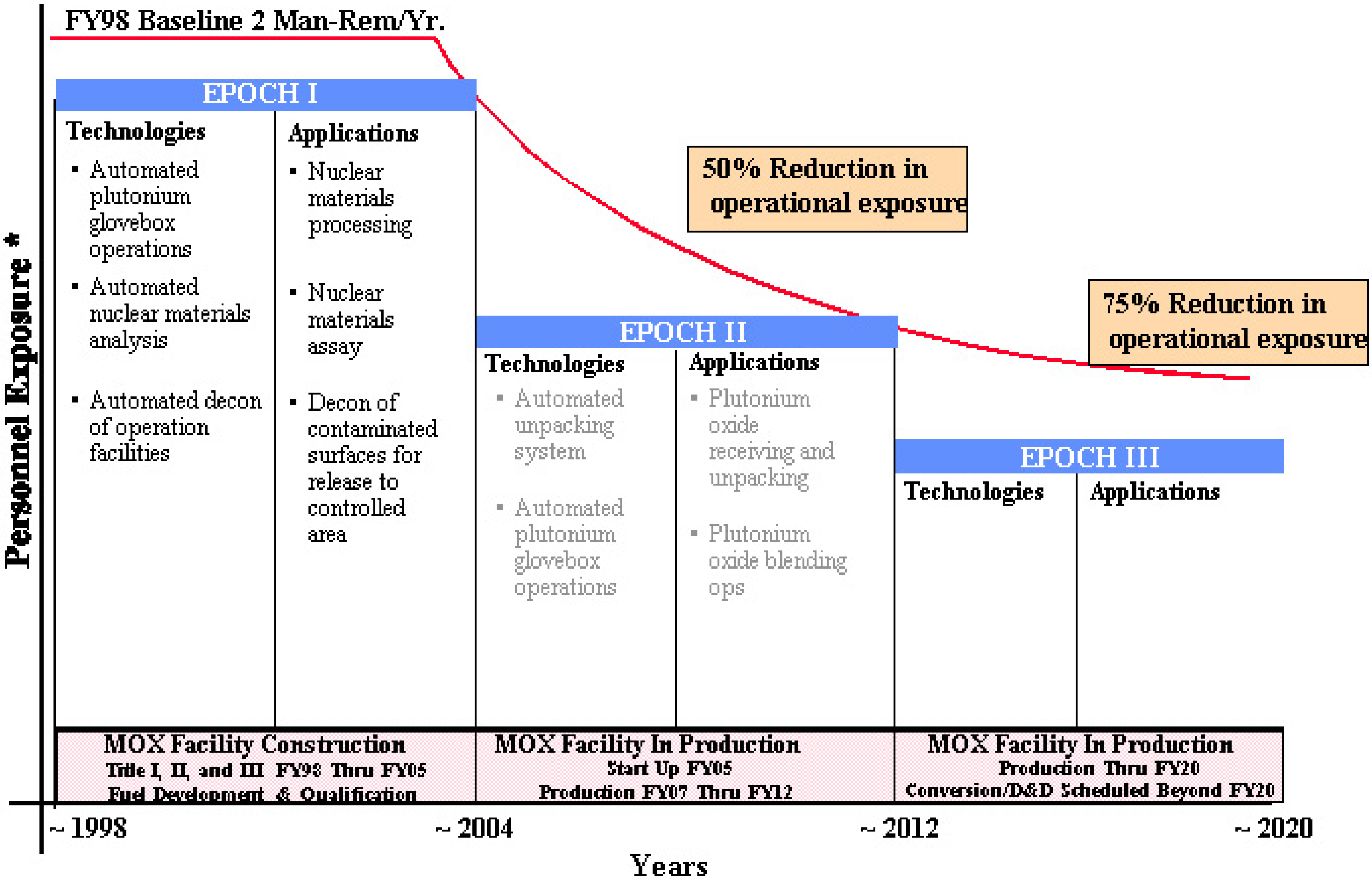
Specific To The Pit Disassembly and Conversion Facility



* Functional objective metric defines possible productivity improvements based on technology becoming available through cross-cutting RIM development

MD Driver: Exposure Reduction & Throughput Increase

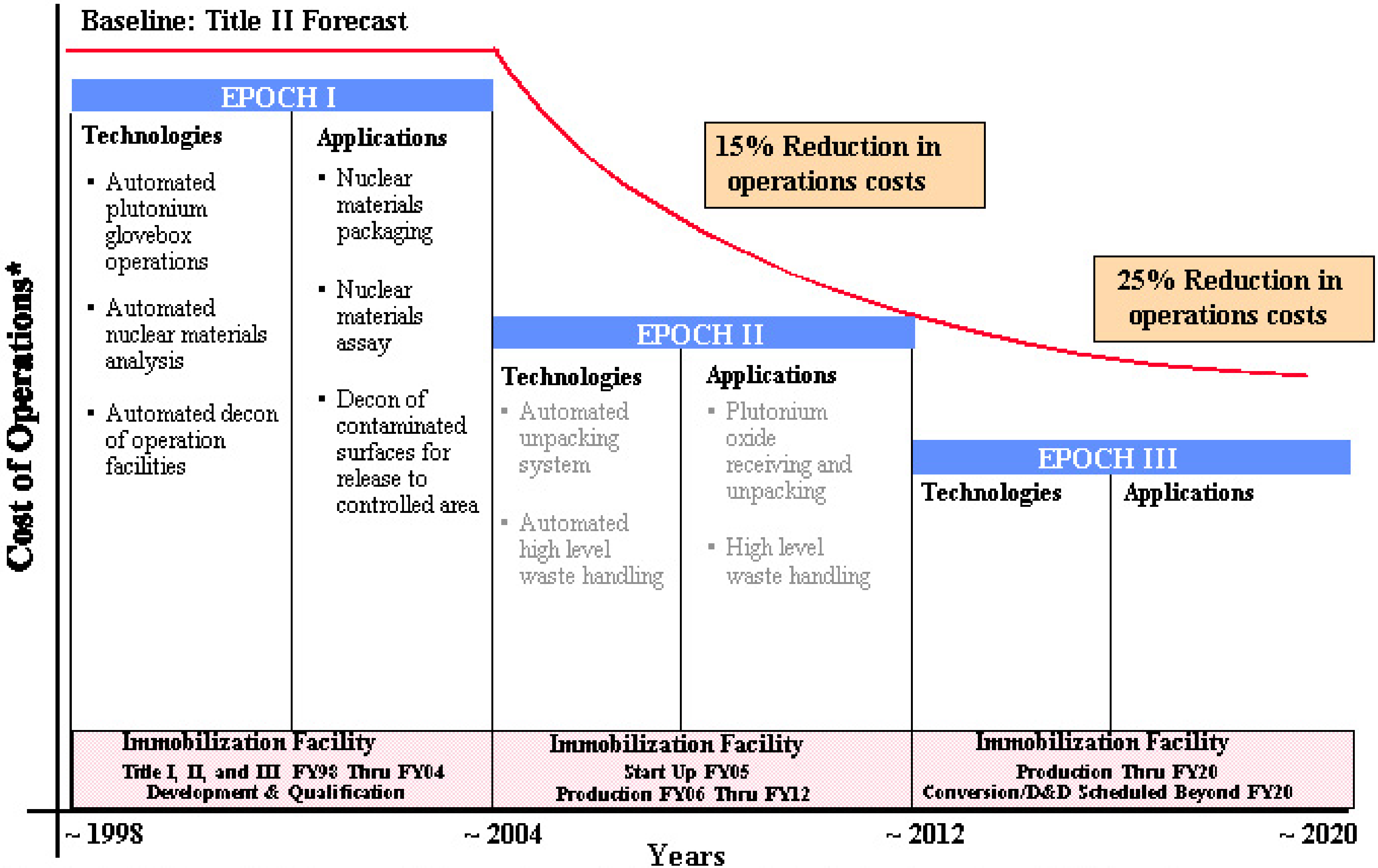
Specific To The MOX Fuel Fabrication Facility



* Functional objective driven by increasingly stringent regulatory environment

MD Driver: Operations Cost Reduction

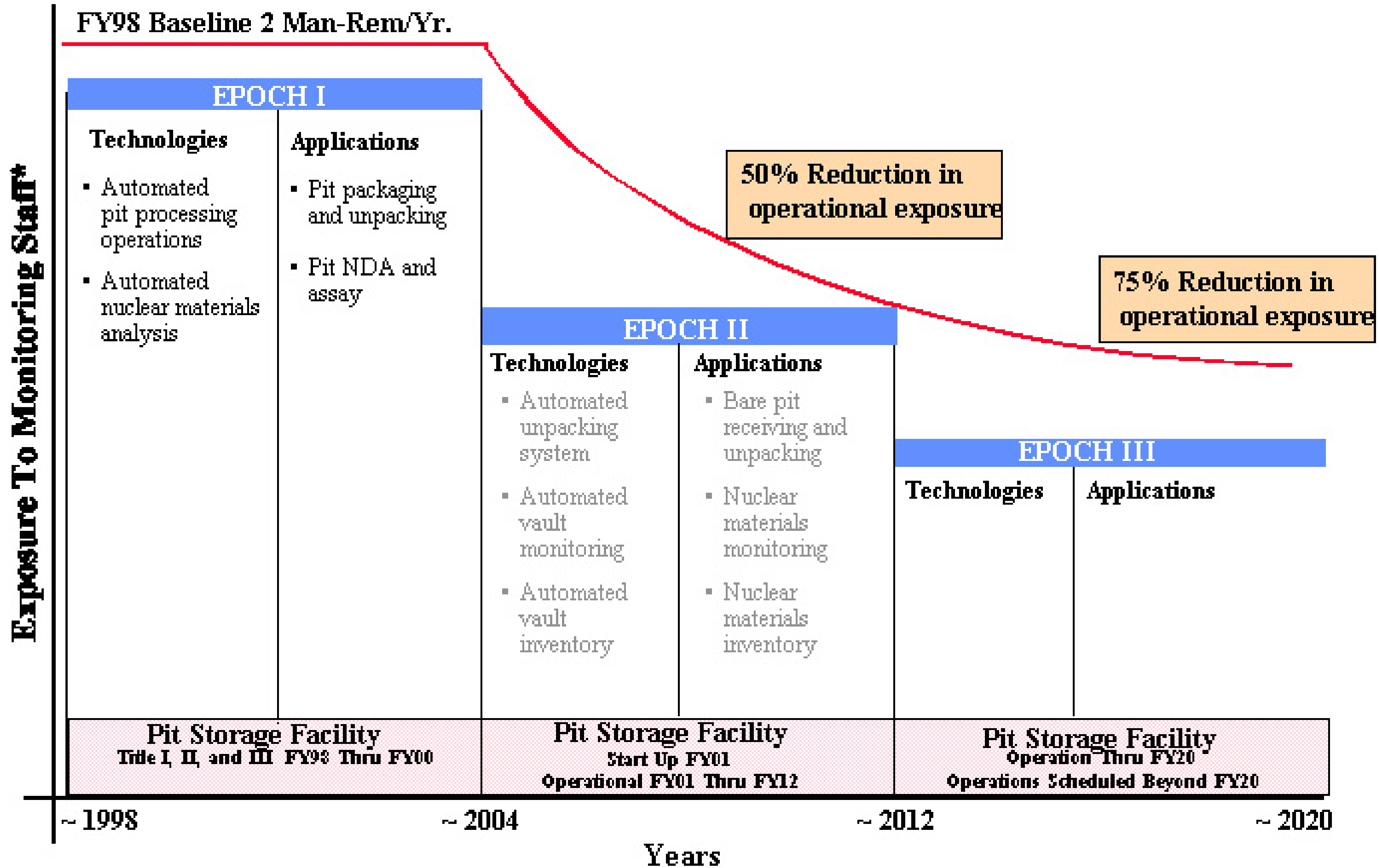
Specific To The Immobilization Facility



* Functional objective metric defines possible decreased operational costs based on technology becoming available through cross-cutting RIM development

MD Driver: Exposure Reduction

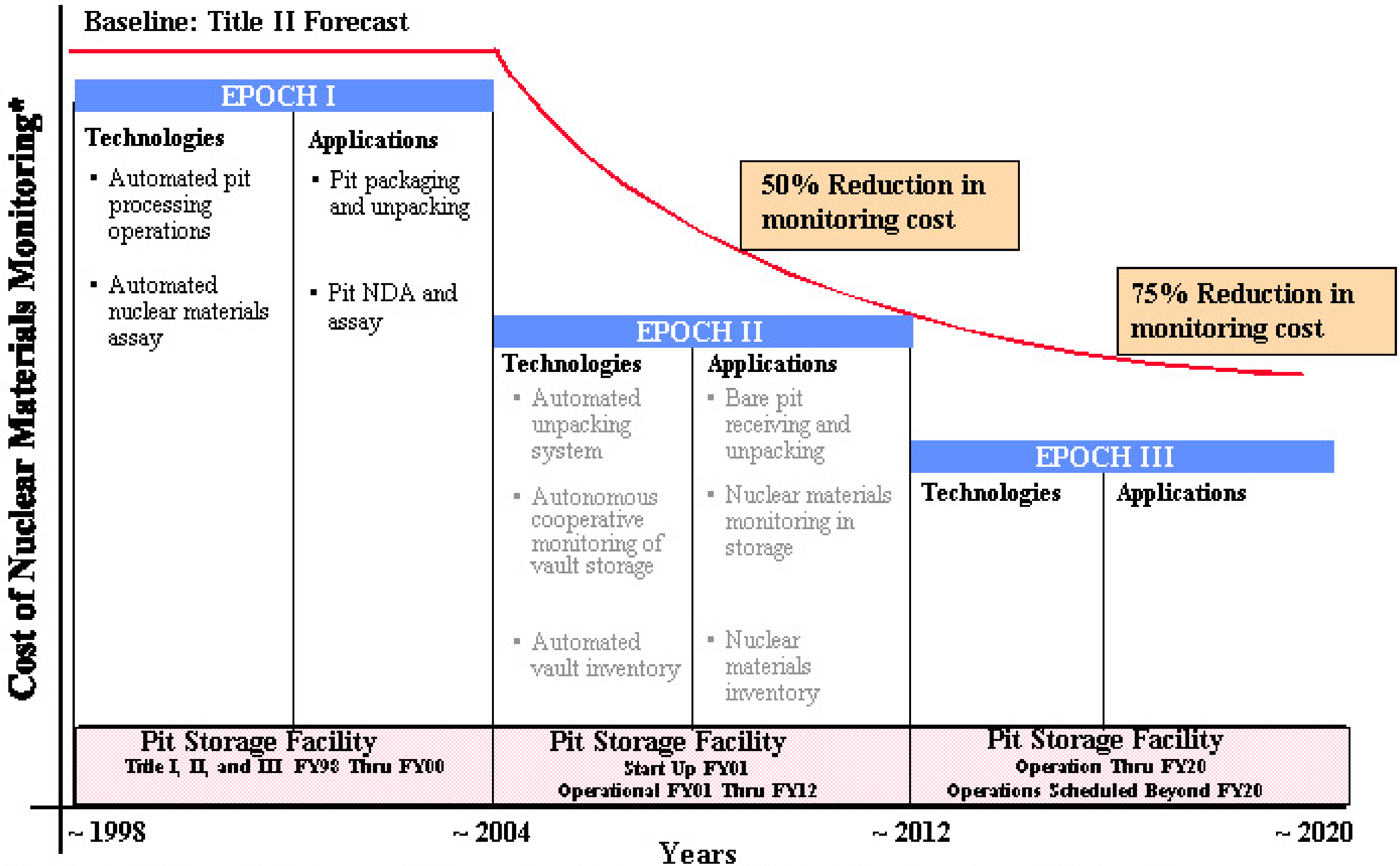
Specific To The Pit Storage Facility



* Functional objective driven by increasingly stringent regulatory environment

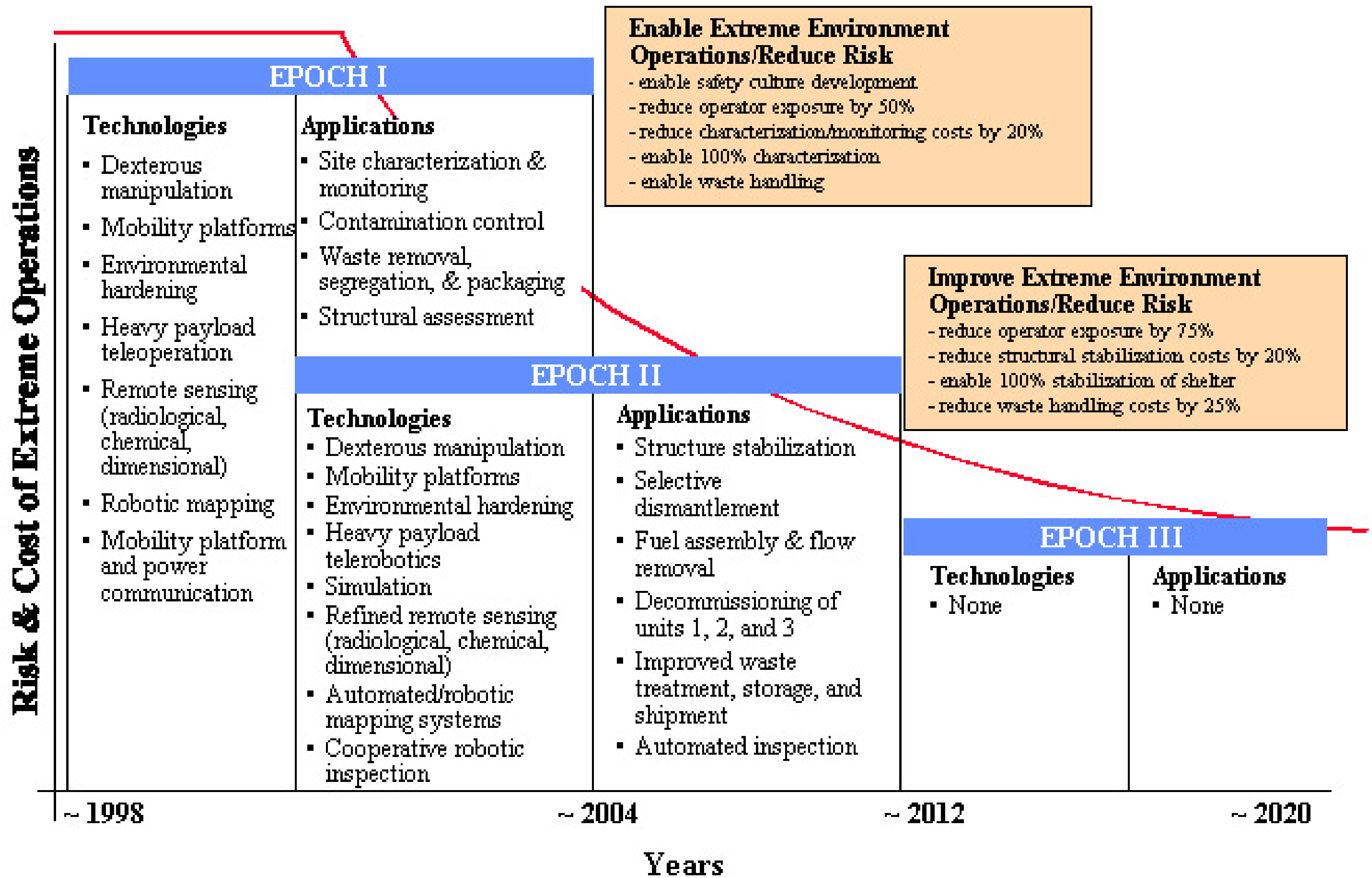
MD Driver: Cost Reduction

Specific To The Pit Storage Facility

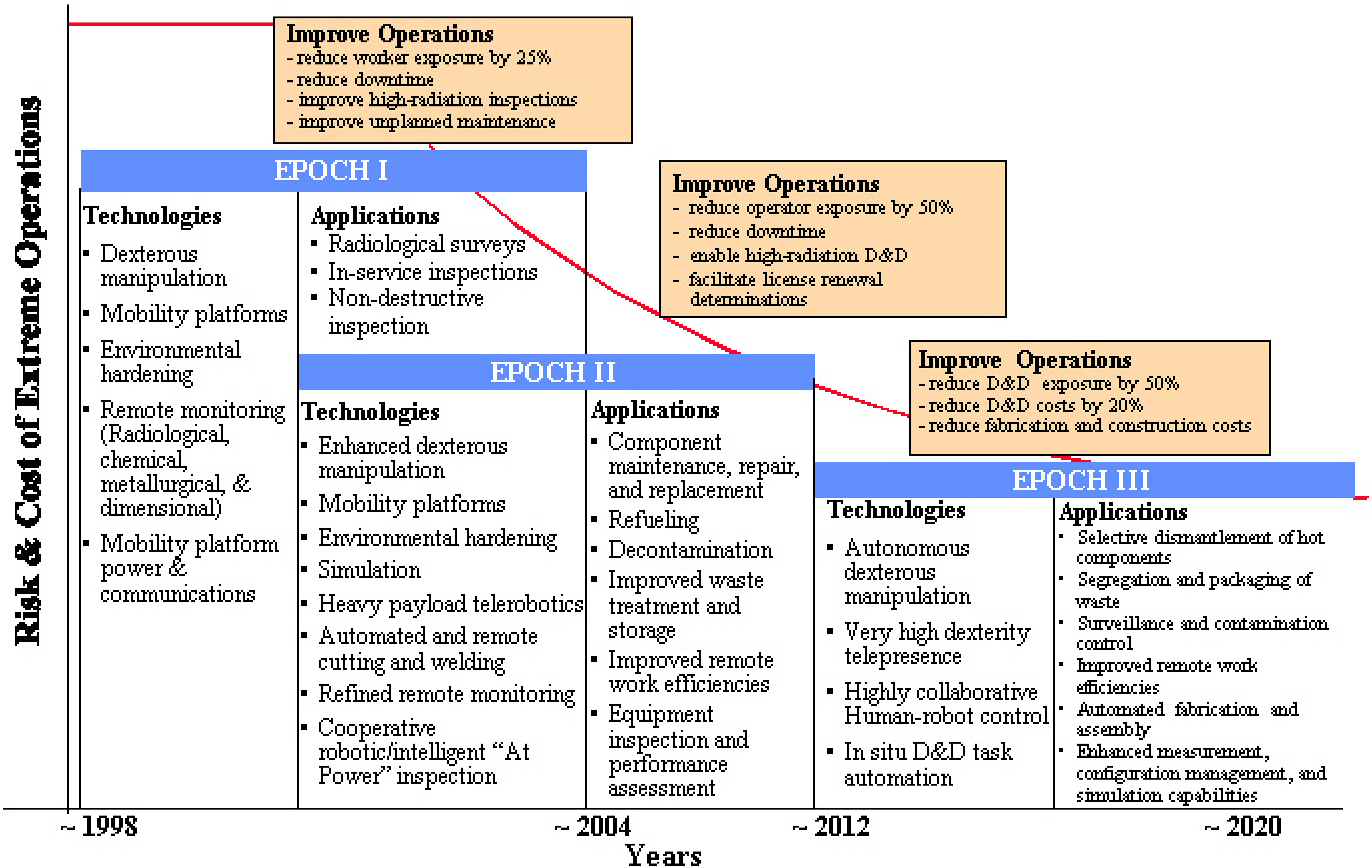


* Functional objective metric defines possible decreased monitoring costs based on technology becoming available through cross-cutting RIM development

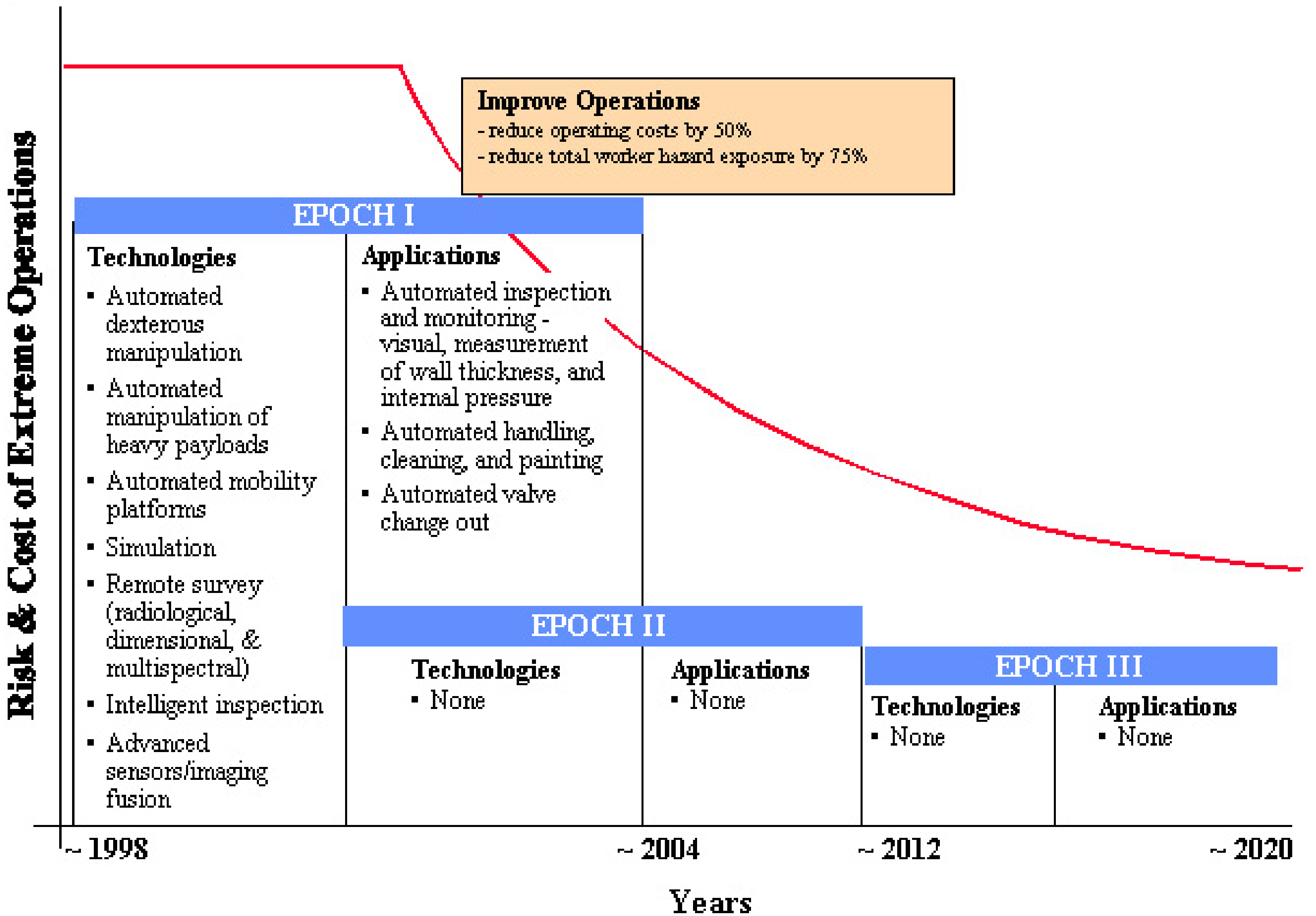
NE Driver: Integrate Remote Systems into Chornobyl Shelter and Follow-on Activities



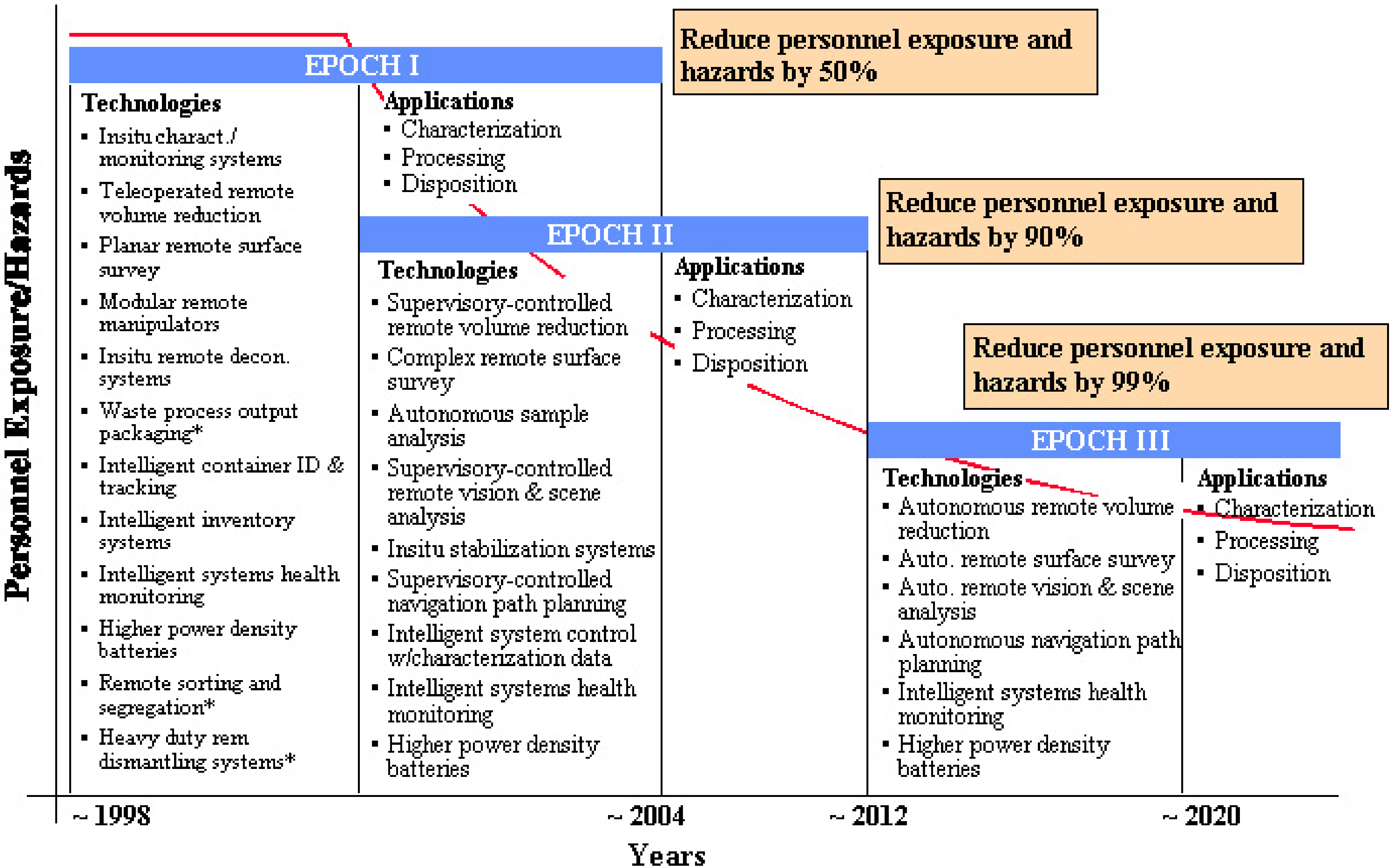
NE Driver: Improve DOE Reactor and Commercial Reactor Operations



NE Driver: Enable Automated Maintenance of Depleted UF_6 Cylinders in Storage



EM Driver: Reduce Personnel Exposure and Hazards



* Indicates that technology evolves through teleoperated (E1), supervisory controlled (E2), and autonomous (E3) as does remote volume reduction.

(Due to space limitations, not all technologies could be listed on the above slide. Refer to attached appendix for complete listing).

EM Driver: Reduce Secondary Waste

Secondary Waste

EPOCH I

Technologies

- Insitu charact./monitoring systems
- Teleoperated remote volume reduction
- Planar remote surface survey
- Modular remote manipulators
- Insitu remote decon. systems
- Waste process output packaging*
- Intelligent container ID & tracking
- Intelligent inventory systems
- Intelligent systems health monitoring
- Bagless automate systems
- Remote sorting and segregation*
- Heavy duty rem dismantling systems*

Applications

- Characterization
- Processing
- Disposition

Reduce secondary waste by 50%

EPOCH II

Technologies

- Supervisory-controlled remote volume reduction
- Complex remote surface survey
- Autonomous sample analysis
- Supervisory-controlled remote vision & scene analysis
- Insitu stabilization systems
- Supervisory-controlled navigation path planning
- Intelligent system control w/characterization data
- Intelligent systems health monitoring

Applications

- Characterization
- Processing
- Disposition

Reduce secondary waste by 75%

EPOCH III

Technologies

- Autonomous remote volume reduction
- Auto. remote surface survey
- Auto. remote vision & scene analysis
- Autonomous navigation path planning
- Intelligent systems health monitoring

Applications

- Characterization
- Processing
- Disposition

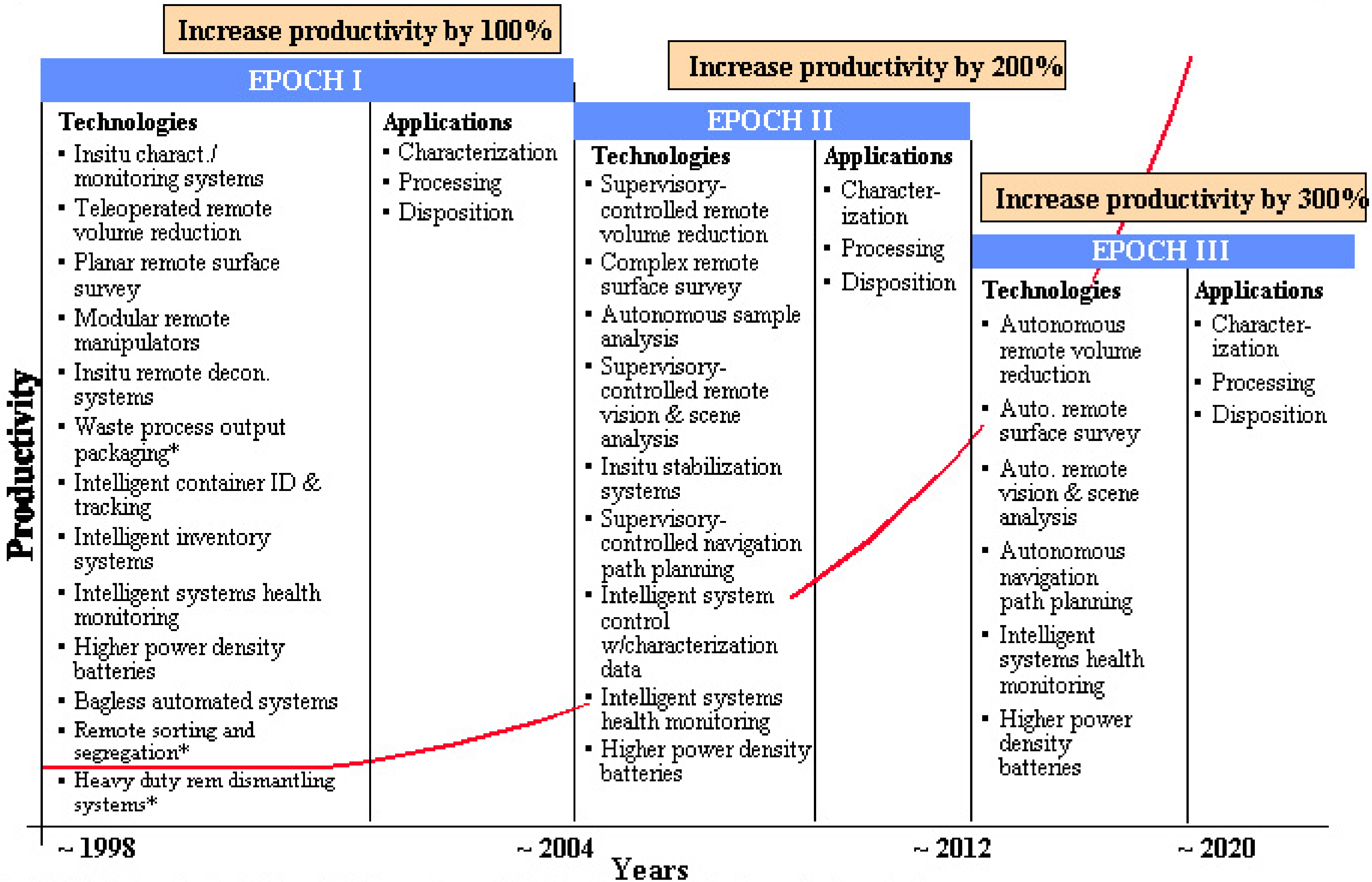
Reduce secondary waste by 90%

~ 1998 ~ 2004 ~ 2012 ~ 2020

Years

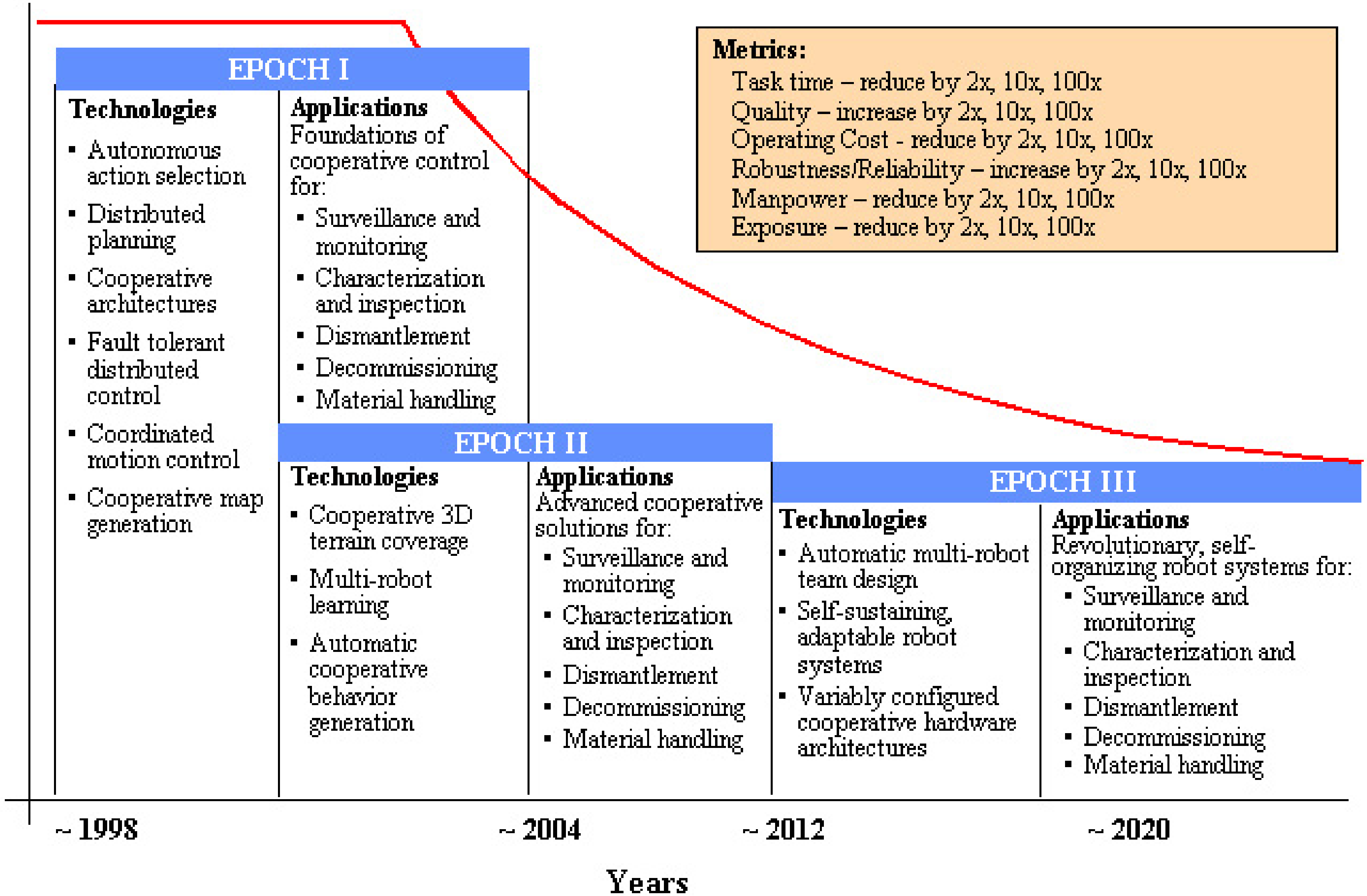
* Indicates that technology evolves through teleoperated (E1), supervisory controlled (E2), and autonomous (E3) as does remote volume reduction.
(Due to space limitations, not all technologies could be listed on the above slide. Refer to attached appendix for complete listing).

EM Driver: Increase Productivity



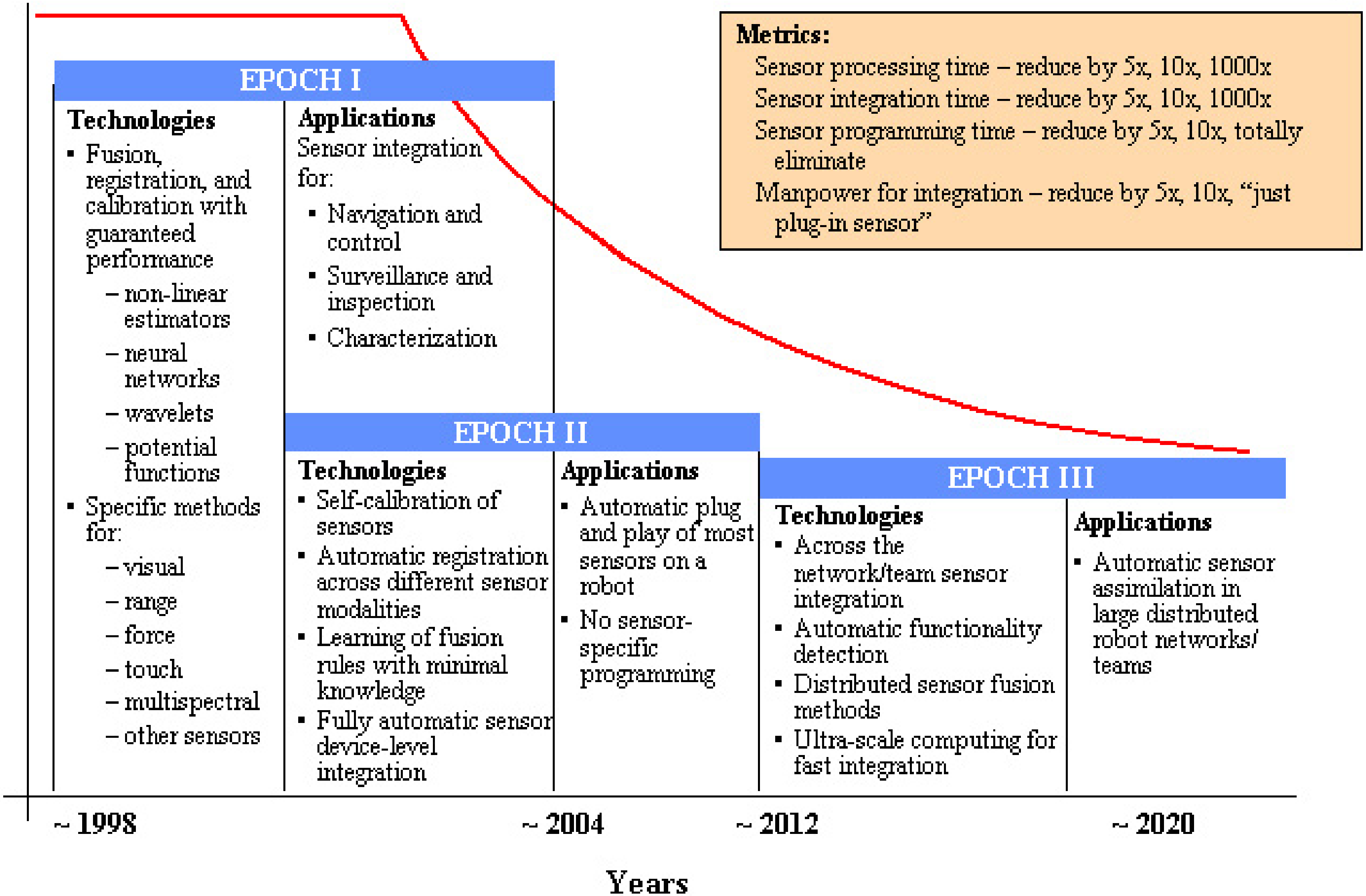
* Indicates that technology evolves through teleoperated (E1), supervisory controlled (E2), and autonomous (E3) as does remote volume reduction
(Due to space limitations, not all technologies could be listed on the above slide. Refer to attached appendix for complete listing).

ER Driver: Revolutionize Capabilities for Inherently Distributed Missions in Dynamic, Uncertain Environments

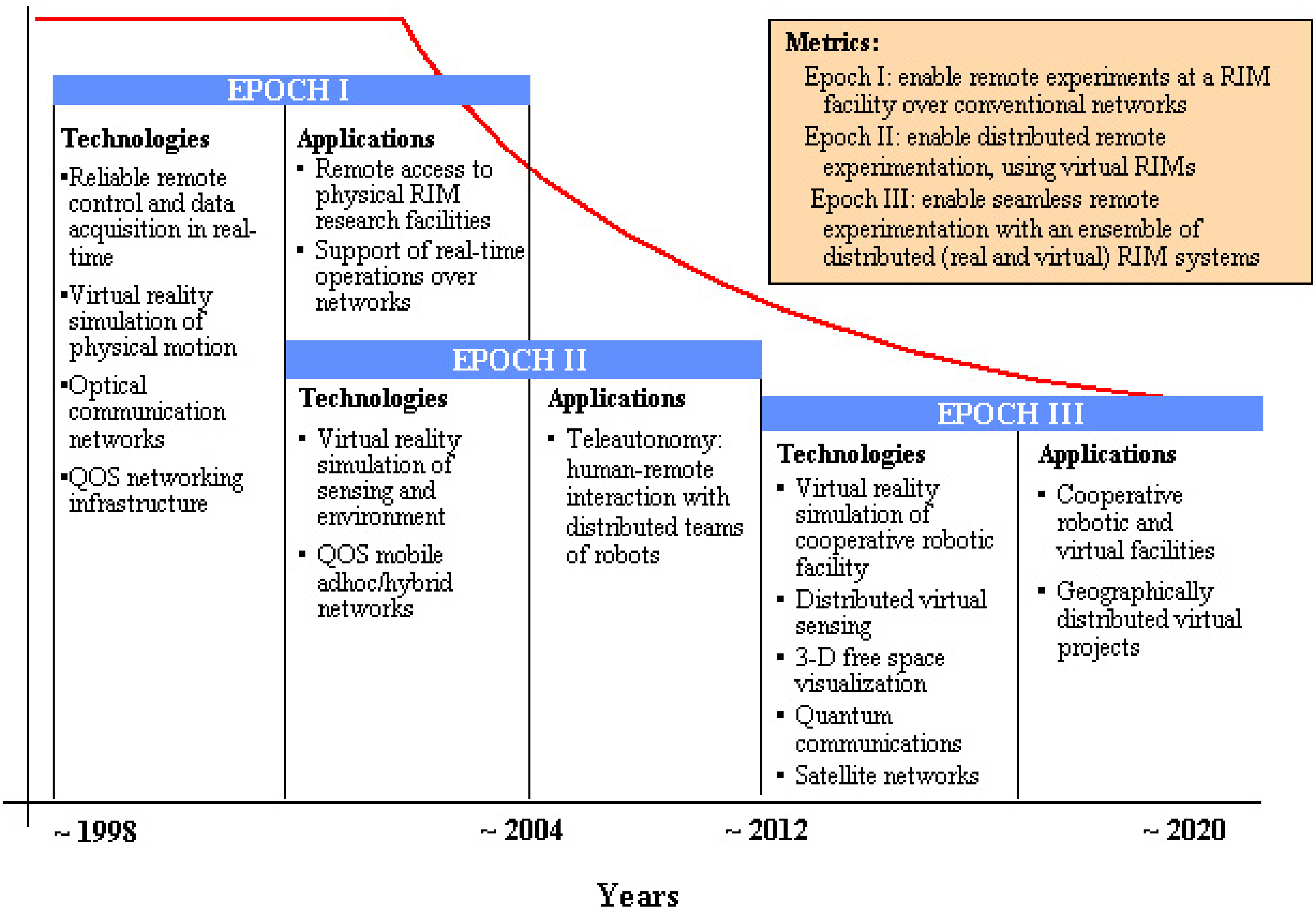


ER Driver: Revolutionize Sensor Integration for Distributed Robot Systems

"Just Plug-in the Sensor, System will Configure Itself"



ER Driver: Revolutionize Collaborative Research Using Remote and Virtual RIM Systems



ER Driver: Revolutionize Intelligent Machines Concepts and Controls Methodologies for Manipulative Tasks

Metrics:

- Personnel needs – reduce by 2x, 5x, 10x
- Personnel exposure – reduce by 2x, 5x, 10x
- Turn-around time – reduce by 2x, 5x, 10x
- Personnel injuries – reduce by 2x, 5x, 10x
- Human errors – reduce by 2x, 5x, 10x
- Energy consumption – reduce by 2x, 10x, 100x
- Payload range handling capability – increase by 10x, 100x, 1000x
- Precision for payloads – increase by 10x, 100x, 1000x

EPOCH I (~1998 – ~2004)

Technologies

- Nonlinear systems and structures control
- Mobile manipulators
  - high-payload
  - long-reach
  - tactile hands
- Human electromotor skills amplification
- Motion learning
- Interface for human-computer-machine manipulation of 3D physical objects
- Mobile 3D shape measurement
- Communicative collaboration

Applications

- Novel paradigm for human interaction with RIM systems
- Precise manipulation of wide range of payloads

EPOCH II (~2004 – ~2012)

Technologies

- Task learning
- Perception, cognitive, and electromotor amplification and collaboration
- Intelligent, collaborative mobile manipulators
- Dexterous collaborative handlers of wide range of payloads

Applications

- Efficient operations, without risk to humans, for inhospitable and inaccessible areas

EPOCH III (~2012 – ~2020)

Technologies

- Job learning
- Collaborative control
- "Superman- strength suit" (heavy duty tasks)
- Intelligent micromanipulation
- Nanosystems control

Applications

- Eliminate need for workers in hazardous operations
- Revolutionize DOE's remote handling processes

~ 1998 ~ 2004 ~ 2012 ~ 2020

Years

ER Driver: Revolutionize Energy Resources Exploration and Ecological Land Control

Metrics:
- Task time – reduce by 2x, 5x, 10x
- Quality – increase by 2x, 5x, 10x
- Operating Cost - reduce by 2x, 5x, 10x
- Robustness/Reliability – increase by 3x, 5x, 10x
- Manpower – reduce by 2x, 5x, 10x
- Exposure – reduce by 2x, 5x, 10x

EPOCH I

Technologies
- Automated sensors (satellite, ground-based, surface, underground)
- Autonomous land robots
- Teleoperated land robots
- Data fusion and interpretation
- Hyperspectral remote sensing

Applications

Efficient land assessment (soil, plant conditions):
- Satellite data
- Robotic land surveillance
- Underground sensing

EPOCH II

Technologies
- Autonomous robotic manipulation of land sensors
- Inter-robotic communication and control
- Ultraspectral remote sensors
- Data fusion

Applications

Advanced land and littoral assessment:
- Obtain robust requirements through data fusion (weather, moisture, etc.)
- "Needs" prediction algorithms

EPOCH III

Technologies
- Inter-robotic control for autonomous land exploration/exploitation
- Robotic application technologies (water, fertilizer, harvest)
- Data fusion technology
- Intelligent decision algorithms
- Thematic classification methods
- Subsurface robotic operations

Applications

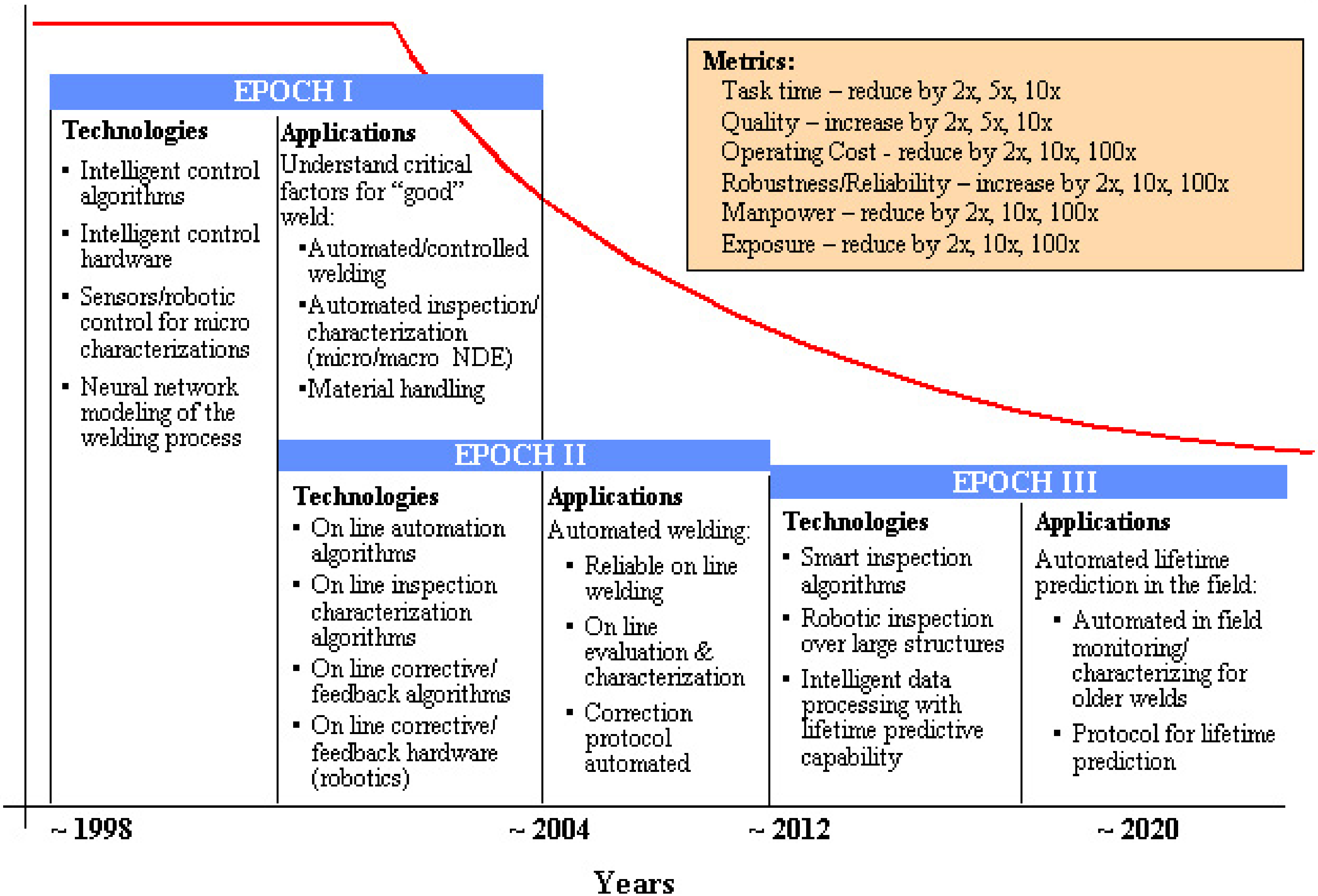
Autonomous land exploitation:
- Robotic manipulation of environmental conditions (moisture, fertilizer, harvesting, etc.)

Efficient, nonrenewable resources exploration:
- Minerals, oil, gas

~ 1998 ~ 2004 ~ 2012 ~ 2020

Years

ER Driver: Predict and Extend Safe Life of Welded Structures



ER Driver: Improve Operation of ER Strategic Research Facilities to Meet Programmatic Missions

Enable High Risk Operations
- reduce construction costs by 2.5%
- reduce operator exposure by 25%
- reduce downtime by 25%
- increase inspection accuracy by 5x

EPOCH I

Technologies
- Dexterous manipulation
- Mobility platforms
- Environmental hardening
- Simulation
- Heavy payload teleoperation
- Remote metrology
- Autonomous and remote cutting/welding

Applications
- Facility design basis
- Facility construction
- Facility concept mockup testing
- Dimensional inspection
- Facility operation & maintenance

Improve High Risk Operations
- reduce construction costs by 5%
- reduce operator exposure by 75%
- reduce downtime by 75%
- increase inspection accuracy by 15x
- increase data handling eff. by 10x

EPOCH II

Technologies
- Dexterous manipulation
- Mobility platforms
- Environmental hardening
- Simulation
- Heavy payload telerobotics
- Virtual lab technologies
- Refined remote metrology
- Refined autonomous and remote cutting/welding
- Intelligent processing and interpretation of experimental data

Applications
- Facility operation & maintenance
- Facility mockup testing
- Virtual lab operation
- Remote dimensional inspection
- Intelligent exper. data handling

Improve High Risk Operations
- reduce operator exposure by 99%
- reduce downtime by 90%
- increase data handling eff. by 30x

EPOCH III

Technologies
- Autonomous dexterous Manipulation of all payloads
- Highly collaborative control
- Virtual exper. with telepresence
- Refined intelligent exper. data handling

Applications
- Semi-autonomous Maintenance
- Mockup Elimination thru metrology
- Human-like experiment dexterity
- Highly refined virtual experimentation

~ 1998 ~ 2004 ~ 2012 ~ 2020

Years

Appendix D
RELEVANT APPLICATIONS AND TECHNOLOGIES

Robotics and Intelligent Machines Roadmap

Rim Technology Roadmap Level	Functional Objective Example #1	Functional Objective Example #2	Functional Objective Example #3
1. DOE PSO	DP	DP	DP
2. PSO Program Driver (High-level Need) The handful of high-level, program-specific goals (not necessarily related to RIM) that are shaping what the PSO will do to meet its mission over the next 20 years.	Maintain the nuclear stockpile in a safe and secure manner, and at a reduced cost.	Maintain the nuclear stockpile in a safe and secure manner, and at a reduced cost.	Maintain the nuclear stockpile in a safe and secure manner, and at a reduced cost.
3. Epoch 1 - Functional Objective A "next-level" PSO need as it could be addressed by RIM technology, and including a technical goal within a given time frame.	Reduce the occurrence of manufacturing defects in refurbished stockpile hardware to 50% of current.	Reduce lost work accidents to 85% of current. Reduce reportable releases to 50% of current.	Reduce time and cost for refurbishment of appropriate stockpile hardware by 20% of current.
4. Epoch 1 - Applications	• Enforce selected manufacturing procedures • Be comparable with best industry practices • Consistent process delivery • Design simple, "easy to automate" product • Ability to use ASCI models in manufacturing process controls and tasks	• Reduce on the job injuries to "industry excellence" standards • Reduce radiation exposure and reportable incidents each year • Reduce exposure of workforce • Reduce difficulty of regulatory compliance	• Reduce cost of regulatory compliance • Optimize product realization process • Reduce manpower/increase efficiency • Reduce cycle time • Decrease infrastructure related costs such as security, use of floor space….
5. Epoch 1 - RIM Technologies	• Automate selected processes using ASCI model references • Useful, distributed collaborative design and RIM interfaces • Dexterous 2-3 D virtual and real object manipulation on very large and small objects • Selected automated inspection and on machine acceptance • Virtual mistake proofing • Foundations for virtual manufacturing including: -Process characterization and control; -Process feedback to modelers	• Improved operational, dose and ergonomic simulations • Automate selected manual "heavy lifting" and repetitive motion tasks using cooperative RIMs • Selected application of RIM to simple jobs that involve exposure or high consequences • Supervisory RIM which increases human reliability • Model based system and facility state of health monitoring • Cooperating mobile platforms with "broad band" sensor suites	• Design simple, "easy to automate" product using distributed, collaborative interfaces • Automate special skill processes and processes sensitive to regulation • Virtual manufacturing developed for selected processes using distributed, collaborative interfaces • Adaptive, model reference process control • Semi-autonomous service RIM for security, custodial, and material handling duties • Foundations of flexibility including: -Dexterous 2-3D virtual and real object manipulation an large and small scales; -Reconfigurable fixturing and tooling

Rim Technology Roadmap Level	Functional Objective Ex. #1 (cont.)	Functional Objective Ex. #2 (cont.)	Functional Objective Ex. #3 (cont.)
6. Epoch 2 - Functional Objective A “next-level” PSO need as it could be addressed by RIM technology, and including a technical goal within a given time frame.	Reduce the occurrence of manufacturing defects in refurbished stockpile hardware to 10% of current.	Reduce lost work accidents to 30% of current. Reduce reportable releases to 30% of current.	Reduce time and cost for refurbishment of appropriate stockpile hardware by 50% of current.
7. Epoch 2 - Applications	• One stop, flexible workcells for product subassemblies • Virtual assembly • Non intrusive part and assembly inspection and authentication • Intelligent, learning processes • Extensive use of micro devices	• Continue to follow industry excellence standards • Realistic simulations of most difficult ergonomic and hazard exposure tasks • “No glovebox” processing • Automatic oversight of humans in critical operations	• “Near fully flexible” product lines • Routine virtual manufacturing using immersive interfaces • Automated security, MC&A and material handling • Regulation and workload insensitive facilities
8. Epoch 2 RIM -Technologies	• Workcell level integration of ASCI models and controls • Foundations of learning and cognition, knowledge of product function • Integrated 3D and micro assembly planning, assembly and inspection • Self-aware, self-correcting process control such as wear detection and compensation • Video inspection for authentication of assemblies and PWB’s • Haptic, immersive RIM-man interfaces	• Large scale simulations of hazards, ergonomics and workflow • Remote RIM used for routine hazardous processing • Situational awareness for selected operations • Human amplifiers for common operations • Autonomous RIM for hostile situations, hazardous releases • Inherent, non redundant safety and reliability for RIM • Oversight of humans in passive control situations	• Remote RIM used for routine hazardous processing • Haptic and immersive man-machine interfaces for design and manufacturing • Near human presence on mobile platforms and over networks • Autonomous rover RIMs for monitoring, material delivery, etc. • Natural language programming of RIM • Automated programming classes of RIM • Integrated, autonomous mobile devices for heavy operations • Cooperative multi-arm manipulators

Robotics and Intelligent Machines Roadmap

Rim Technology Roadmap Level	Functional Objective Example #1	Functional Objective Example #2	Functional Objective Example #3
1. DOE PSO	MD	MD	MD
2. PSO Program Driver (High-level Need) The handful of high-level, program-specific goals (not necessarily related to RIM) that are shaping what the PSO will do to meet its mission over the next 20 years.	Reduce the global danger associated with inventories of surplus weapons-usable fissile materials by converting it for use as MOX fuel or placing it into unusable form via immobilization.	Reduce the global danger associated with inventories of surplus weapons-usable fissile materials by converting it for use as MOX fuel or placing it into unusable form via immobilization.	Reduce the global danger associated with inventories of surplus weapons-usable fissile materials by consolidating and storing it in a secure facility.
3. Epoch 1 - Functional Objective A "next-level" PSO need as it could be addressed by RIM technology, and including a technical goal within a given time-frame.	Facilities designed to meet current and future regulatory activity. Designs to be ALARA per 10-CFR-835.1002.	Facilities designed to meet current and future regulatory activity. Designs to be ALARA per 10-CFR-835.1002. Designs to meet throughput levels established.	Facilities designed to meet current and future regulatory activity. Designs to be ALARA per 10-CFR-835.1002.
4. Epoch 1 - Applications	• Automated Nuclear Materials Packaging • Automated Nuclear Materials Assay • Automated Decontamination Technology	• Automated Nuclear Material Handling • Automated Nuclear Materials Processes	• Automated Vault Monitoring • Automated Vault Inventory/Inspection • Remote Surveillance Systems
5. Epoch 1 - RIM Technologies	Remote plutonium processing operations per ALARA guidelines that reduce exposure to the staff while packaging and preparing nuclear materials for storage and transfer to the MOX fuel fabrication facility or the immobilization facility	• Remote plutonium processing operations per ALARA guidelines that reduce exposure to the staff while processing nuclear materials through the PC&D Facility	• Remote monitoring and surveillance of materials in storage per MM&C criteria that reduce exposures to staff
6. Epoch 2 - Functional Objective A "next-level" PSO need as it could be addressed by RIM technology, and including a technical goal within a given time-frame.	Remote plutonium processing operations that reduce exposure to the staff, (reduce human operational exposure by 50% assuming a starting baseline of 2 man-rem/year).	Automated plutonium processing operations that increase operational throughput 25%.	Remote monitoring and surveillance of materials in storage per MM&C criteria that reduce exposures to staff by 50% assuming a starting baseline of 2 man-rem/year.
7. Epoch 2 - Applications	• Automated Pit Unpacking • Automated Pit Bisection • Automated Plutonium Oxide Reactor Ops	Fully Automated Reactor Operations • Hydox Operations • Hydride/Dehydride Operations • Direct Oxidation Processes	• Autonomous Robotic Monitoring of Vault Operations
8. Epoch 2 - RIM Technologies	• Remote pit handling processes that support pit receiving and unpacking operations that result in a reduction in human exposure	• Remote pit handling processes that support pit reactor loading operations that result in a reduction in human exposure and increase in productivity	• Remote monitoring and surveillance of materials in storage per MM&C criteria that reduce exposures to staff

Robotics and Intelligent Machines Roadmap

Rim Technology Roadmap Level	Functional Objective Example #4	Functional Objective Example #5	
1. DOE PSO	MD	MD	
2. PSO Program Driver (High-level Need) The handful of high-level, program-specific goals (not necessarily related to RIM) that are shaping what the PSO will do to meet its mission over the next 20 years.	Reduce the global danger associated with inventories of surplus weapons-usable fissile materials by converting it for use as MOX fuel or placing it into unusable form via immobilization	Reduce the global danger associated with inventories of surplus weapons-usable fissile materials by consolidating and storing it in a secure facility	
3. Epoch 1 - Functional Objective A "next-level" PSO need as it could be addressed by RIM technology, and including a technical goal within a given time-frame.	Facilities designed to meet current and future regulatory activity. Designs to be ALARA per 10-CFR-835.1002 Establish operations cost per designs.	Facilities designed to meet current and future regulatory activity per DOE 470.1 Chg. 1 Safeguard and Security Program.	
4. Epoch 1 - Applications	• Automated Nuclear Material Handling • Automated Nuclear Materials Detection • Automated Process Decontamination	• Automated Vault Monitoring • Automated Vault Inventory/Inspection • Remote Surveillance Systems	
5. Epoch 1 - RIM Technologies	• Remote vitrified nuclear material loading operations that result in a reduction in human operations	• Decreasing cost of monitoring and surveillance of materials in storage using remote operations	
6. Epoch 2 - Functional Objective A "next-level" PSO need as it could be addressed by RIM technology, and including a technical goal within a given time-frame.	Remote high level waste processing operations that enable higher canister filling and processing rates resulting in a 15% decrease in operations costs.	Remote monitoring and surveillance of materials in storage per MM&C criteria that reduce costs of safeguarding and security of stored materials by 50%.	
7. Epoch 2 - Applications	• Automated High Level Waste Handling • Automated Unpacking System	• Autonomous Cooperative Response to Off Normal Incidents	
8. Epoch 2 - RIM Technologies	• Remote high level waste processing operations that increase process through put	• Remote monitoring and surveillance of materials in storage per MM&C criteria that reduce required staff operations	

Robotics and Intelligent Machines Roadmap

Rim Technology Roadmap Level	Functional Objective Example #1	Functional Objective Example #2	Functional Objective Example #3
1. DOE PSO	NE	NE	NE
2. PSO Program Driver (High-level Need) The handful of high-level, program-specific goals (not necessarily related to RIM) that are shaping what the PSO will do to meet its mission over the next 20 years.	Integrate remote systems into Chornobyl shelter and follow-on actions.	Improve DOE Reactor and Commercial Reactor Operations.	Enable automated maintenance of depleted UF_6 cylinders in storage.
3. Epoch 1 - Functional Objective A "next-level" PSO need as it could be addressed by RIM technology, and including a technical goal within a given time frame.	Enable extreme environment operations/reduce risk: enable safety culture development. reduce operator exposure by 50%. reduce characterization/monitoring costs by 20%. enable 100% characterization. enable waste handling.	Improve operations: reduce worker exposure by 25%. reduce downtime. improve high-radiation inspections. improve unplanned maintenance.	Improve operations: reduce operating costs by 50%. reduce total worker hazard exposure by 75%.
4. Epoch 1 - Applications	• Site characterization & monitoring • Contamination control • Waste removal, segregation, & packaging • Structural assessment	• Radiological surveys • In-service inspections • Non-destructive inspection	• Automated inspection and monitoring - visual, measurement of wall thickness, and internal pressure • Automated handling, cleaning, and painting • Automated valve change out
5. Epoch 1 - RIM Technologies	• Dexterous manipulation • Mobility platforms • Environmental hardening • Heavy payload teleoperation • Remote sensing (radiological, chemical, dimensional) • Robotic mapping • Mobility platform and power communication	• Dexterous manipulation • Mobility platforms • Environmental hardening • Remote monitoring (Radiological, chemical, metallurgical, & dimensional) • Mobility platform power & communications	• Automated dexterous manipulation • Automated manipulation of heavy payloads • Automated mobility platforms • Simulation • Remote survey (radiological, dimensional, & multispectral) • Intelligent inspection • Advanced sensors/imaging fusion

Rim Technology Roadmap Level	Functional Objective Ex. #1 (cont.)	Functional Objective Ex. #2 (cont.)	Functional Objective Ex. #3 (cont.)
6. Epoch 2 - Functional Objective A "next-level" PSO need as it could be addressed by RIM technology, and including a technical goal within a given time frame.	Improve extreme environment operations/reduce risk: Reduce operator exposure by 75%. Reduce structural stabilization costs by 20%. Enable 100% stabilization of shelter. Reduce waste handling costs by 25%.	Improve operations: Reduce worker exposure by 50%. Reduce downtime. Enable high-radiation D&D. Facilitate license renewal determinations.	None
7. Epoch 2 - Applications	• Structure stabilization • Selective dismantlement • Fuel assembly & flow removal • Decommissioning of units 1, 2, and 3 • Improved waste treatment, storage, and shipment • Automated inspection	• Component maintenance, repair, and replacement • Refueling • Decontamination • Improved waste treatment and storage • Improved remote work efficiencies • Equipment inspection and performance assessment	• None
8. Epoch 2 - RIM Technologies	• Dexterous manipulation • Mobility platforms • Environmental hardening • Heavy payload telerobotics • Simulation • Refined remote sensing (radiological, chemical, dimensional) • Automated / robotic mapping systems • Cooperative robotic inspection	• Enhanced dexterous manipulation • Mobility platforms • Environmental hardening • Simulation • Heavy payload telerobotics • Automated and remote cutting and welding • Refined remote monitoring • Cooperative robotic/intelligent "At Power" inspection	• None

Robotics and Intelligent Machines Roadmap

Rim Technology Roadmap Level	Functional Objective Example #1	Functional Objective Example #2	Functional Objective Example #3
1. DOE PSO	EM	EM	EM
2. PSO Program Driver (High-level Need) The handful of high-level, program-specific goals (not necessarily related to RIM) that are shaping what the PSO will do to meet its mission over the next 20 years.	Reduce personnel exposure and hazards.	Reduce secondary waste.	Increase productivity.
3. Epoch 1 - Functional Objective A "next-level" PSO need as it could be addressed by RIM technology, and including a technical goal within a given time frame.	Reduce personnel exposure and hazards by 50%.	Reduce secondary waste by 50%.	Increase productivity by 100%.
4. Epoch 1 -Applications	• Characterization • Processing • Disposition	• Characterization • Processing • Disposition	• Characterization • Processing • Disposition
5. Epoch 1 - RIM Technologies	• Insitu. Charact./Monitoring systems • Teleoperated remote volume reduction • Teleoperated remote NDE/NDA • Planar remote surface survey • Multi Sensor integration • Supervisory-controlled limited access remote systems • Teleoperated heavy duty remote dismantling systems • Teleoperated remote retrieval systems • Modular remote manipulators • Insitu remote decon. Systems • Teleo waste process output packaging • Intelligent container ID & tracking • Intelligent inventory systems • Failure analysis and recovery for rem. • Remote maintenance and repair of systems • Teleoperated remote sorting and segregation • Rad hardened rem components • Intelligent systems health monitoring • Improved sensors (faster, smaller, disposable) • Higher power density batteries • Higher capacity RF links	• Insitu. Charact./Monitoring systems • Teleoperated remote volume reduction • Teleoperated remote NDE/NDA • Planar remote surface survey • Multi Sensor integration • Supervisory-controlled limited access remote systems • Teleoperated heavy duty remote dismantling systems • Teleoperated remote retrieval systems • Modular remote manipulators • Insitu remote decon. systems • Teleoperated waste process output packaging • Intelligent container ID & tracking • Intelligent inventory systems • Failure analysis and recovery for rem. • Remote maintenance and repair of systems • Teleoperated remote sorting and segregation • Rad hardened rem components • Intelligent systems health monitoring • Bagless automated systems	• Insitu. Charact./Monitoring systems • Teleoperated remote volume reduction • Teleoperated remote NDE/NDA • Planar remote surface survey • Multi sensor integration • Teleoperated heavy duty remote dismantling systems • Teleoperated remote retrieval systems • Modular remote manipulators • Insitu remote decon. systems • Teleoperated waste process output packaging • Intelligent container ID & tracking • Intelligent inventory systems • Failure analysis and recovery for rem. • Remote maintenance and repair of systems • Teleo remote sorting and segregation • Rad hardened rem for components • Intelligent systems health monitoring • Bagless automated systems • Improved sensors (faster, smaller, disposable) • Higher power density batteries • Higher capacity RF links • Higher payload electrical actuators

Rim Technology Roadmap Level	Functional Objective Ex. #1 (cont.)	Functional Objective Ex. #2 (cont.)	Functional Objective Ex. #3 (cont.)
5. Epoch 2 - Functional Objective A "next-level" PSO need as it could be addressed by RIM technology, and including a technical goal within a given time frame.	Reduce personnel exposure and hazards by 90%.	Reduce secondary waste by 75%.	Increase productivity by 200%.
7. Epoch 2 - Applications	• Characterization • Processing • Disposition	• Characterization • Processing • Disposition	• Characterization • Processing • Disposition
8. Epoch 2 - RIM Technologies	• Supervisory-controlled remote volume reduction • Supervisory-controlled rem. NDE/NDA • Complex remote surface survey • Autonomous sample analysis • Multi Sensor integration • Supervisory-controlled remote vision and scene analysis • Autonomous limited access remote systems • Supervisory-controlled heavy duty remote dismantling systems • Supervisory-controlled remote retrieval systems • Supervisory-controlled waste process output packaging • Supervisory-controlled remote surveillance and monitoring systems • Supervisory-controlled navigation/path planning • Insitu stabilization • Intelligent system control w/ characterization data • Failure analysis and recovery for rem. • Remote maintenance and repair of systems • Sensory based remote sorting and segregation • Rad hardened rem components • Intelligent systems health monitoring • Improved sensors (faster, smaller, disposable) • Higher power density batteries • Higher capacity RF links	• Supervisory-controlled remote volume reduction • Supervisory-controlled remote NDE/NDA • Complex remote surface survey • Autonomous sample analysis • Multi Sensor integration • Supervisory-controlled remote vision and scene analysis • Autonomous limited access remote systems • Supervisory-controlled heavy duty remote dismantling systems • Supervisory-controlled remote retrieval systems • Supervisory-controlled waste process output packaging • Supervisory-controlled remote surveillance and monitoring systems • Supervisory-controlled navigation/path planning • Insitu stabilization • Intelligent system control w/ characterization data • Failure analysis and recovery for rem. • Remote maintenance and repair of systems • Sensory based remote sorting and segregation • Rad hardened rem components • Intelligent systems health monitoring	• Supervisory-controlled remote volume reduction • Supervisory-controlled remote NDE/NDA • Complex remote surface survey • Autonomous sample analysis • Multi Sensor integration • Supervisory-controlled remote vision and scene analysis • Supervisory-controlled heavy duty remote dismantling systems • Supervisory-controlled remote retrieval systems • Supervisory-controlled waste process output packaging • Supervisory-controlled remote surveillance and monitoring systems • Supervisory-controlled navigation/path planning • Insitu stabilization • Intelligent system control w/ characterization data • Failure analysis and recovery for rem. • Remote maintenance and repair of systems • Sensory based remote sorting and segregation • Rad hardened rem components • Intelligent systems health monitoring • Improved sensors (faster, smaller, disposable) • Higher power density batteries • Higher capacity RF links • Higher payload electrical actuators

Robotics and Intelligent Machines Roadmap

Rim Technology Roadmap Level	Functional Objective Example #1	Functional Objective Example #2	Functional Objective Example #3
1. DOE PSO	ER	ER	ER
2. PSO Program Driver (High-level Need) The handful of high-level, program-specific goals (not necessarily related to RIM) that are shaping what the PSO will do to meet its mission over the next 20 years.	Revolutionize capabilities for inherently distributed missions in dynamic, uncertain environments.	Revolutionize sensor integration for distributed robot systems*: "Just plug-in the sensor, system will configure itself"*.	Revolutionize collaborative research using remote and virtual RIM systems.
3. Epoch 1 - Functional Objective A "next-level" PSO need as it could be addressed by RIM technology, and including a technical goal within a given time frame.	Reduce task time by 2x. Increase quality by 2x. Reduce operating cost by 2x. Increase robustness/reliability by 2x. Reduce manpower by 2x. Reduce exposure by 2x.	Reduce sensor processing time by 5x. Reduce sensor integration time by 5x. Reduce sensor programming time by 5x. Reduce manpower for integration by 5x.	Enable remote experiments at a RIM facility over conventional networks.
4. Epoch 1 - Applications	Foundations of cooperative control for: • Surveillance and monitoring • Characterization and inspection • Dismantlement • Decommissioning • Material handling	Sensor integration for: • Navigation and control • Surveillance and inspection • Characterization	• Remote access to physical RIM research facilities • Support of real-time operations over networks
5. Epoch 1 - RIM Technologies	• Autonomous action selection • Distributed planning • Cooperative architectures • Fault tolerant distributed control • Coordinated motion control • Cooperative map generation	• Fusion, registration, and calibration with guaranteed performance: -non-linear estimators -neural networks -wavelets -potential functions • Specific methods for: -visual -range -force -touch -multispectral -other sensors	• Reliable remote control and data acquisition in real-time • Virtual reality simulation of physical motion • Optical communication networks • QOS networking infrastructure

Rim Technology Roadmap Level	Functional Objective Ex. #1 (cont.)	Functional Objective Ex. #2 (cont.)	Functional Objective Ex. #3 (cont.)
. Epoch 2 - Functional Objective A "next-level" PSO need as it could be addressed by RIM technology, and ncluding a technical goal within a given ime frame.	Reduce task time by 10x. Increase quality by 10x. Reduce operating cost by 10x. Increase robustness/reliability by 10x. Reduce manpower by 10x. Reduce exposure by 10x.	Reduce sensor processing time by 10x. Reduce sensor integration time by 10x. Reduce sensor programming time by 10x. Reduce manpower for integration by 10x.	Enable distributed remote experimentation, using virtual RIMs.
7. Epoch 2 - Applications	Advanced cooperative solutions for: • Surveillance and monitoring • Characterization and inspection • Dismantlement • Decommissioning • Material handling	• Automatic plug and play of most sensors on a robot • No sensor-specific programming	• Teleautonomy: human-remote interaction with distributed teams of robots
. Epoch 2 - RIM Technologies	• Cooperative 3D terrain coverage • Multi-robot learning • Automatic cooperative behavior generation	• Self-calibration of sensors • Automatic registration across different sensor modalities • Learning of fusion rules with minimal knowledge • Fully automatic sensor device-level integration	• Virtual reality simulation of sensing and environment • QOS mobile adhoc/hybrid networks

Robotics and Intelligent Machines Roadmap

Rim Technology Roadmap Level	Functional Objective Example #4	Functional Objective Example #5	Functional Objective Example #6
1. DOE PSO	ER	ER	ER
2. PSO Program Driver (High-level Need) The handful of high-level, program-specific goals (not necessarily related to RIM) that are shaping what the PSO will do to meet its mission over the next 20 years.	Revolutionize intelligent machines concepts and controls methodologies for manipulative tasks.	Revolutionize energy resources exploration and ecological land control.	Predict and extend safe life of welded structures.
3. Epoch 1 - Functional Objective A "next-level" PSO need as it could be addressed by RIM technology, and including a technical goal within a given time frame.	Reduce personnel needs by 2x. Reduce personnel exposure by 2x. Reduce turn-around time by 2x. Reduce personnel injuries by 2x. Reduce human errors by 2x. Reduce energy consumption by 2x. Increase payload range handling capability by 10x. Increase precision for payloads by 10x.	Reduce task time by 2x. Increase quality by 2x. Reduce operating costs by 2x. Increase robustness/reliability by 3x. Reduce manpower by 2x. Reduce exposure by 2x.	Reduce task time by 2x. Increase quality by 2x. Reduce operating costs by 2x. Increase robustness/reliability by 2x. Reduce manpower by 2x. Reduce exposure by 2x.
4. Epoch 1 - Applications	• Novel paradigm for human interactions with RIM systems • Precise manipulation of wide range of payloads	Efficient land assessment (soil, plant conditions): • Satellite data • Robotic land surveillance • Underground sensing	Understand critical factors for "good" weld: • Automated/controlled welding • Automated inspection/characterization (micro/macro NDE) • Material handling
5. Epoch 1 - RIM Technologies	• Nonlinear systems and structures control • Mobile manipulators – high-payload – long-reach – tactile hands • Human- electromotor skills amplification • Motion learning • Interface for human-computer-machine manipulation of 3D physical objects • Mobile 3D shape measurement • Communicative collaboration	• Automated sensors (satellite, ground-based, surface, underground) • Autonomous land robots • Teleoperated land robots • Data fusion and interpretation • Hyperspectral remote sensing	• Intelligent control algorithms • Intelligent control hardware • Sensors/robotic control for micro characterizations • Neural network modeling of the welding process

Rim Technology Roadmap Level	Functional Objective Ex. #4 (cont.)	Functional Objective Ex. #5 (cont.)	Functional Objective Ex. #6 (cont.)
6. Epoch 2 - Functional Objective A "next-level" PSO need as it could be addressed by RIM technology, and including a technical goal within a given time frame.	Reduce personnel needs by 5x. Reduce personnel exposure by 5x. Reduce turn-around time by 5x. Reduce personnel injuries by 5x. Reduce human errors by 5x. Reduce energy consumption by 10x. Increase payload range handling capability by 100x. Increase precision for payloads by 100x.	Reduce task time by 5x. Increase quality by 5x. Reduce operating costs by 5x. Increase robustness/reliability by 5x. Reduce manpower by 5x. Reduce exposure by 5x.	Reduce task time by 5x. Increase quality by 5x. Reduce operating costs by 10x. Increase robustness/reliability by 10x. Reduce manpower by 10x. Reduce exposure by 10x.
7. Epoch 2 - Applications	• Efficient operations, without risk to humans, for inhospitable and inaccessible areas	Advanced land and littoral assessment: • Obtain robust requirements through data fusion (weather, moisture, fertilizer etc.) • "Needs" prediction algorithms	Automated welding: • Reliable on line welding • On line evaluation & characterization • Correction protocol automated
8. Epoch 2 - RIM Technologies	• Task learning • Perception, cognitive, and electromotor amplification and collaboration • Intelligent, collaborative mobile manipulators • Dexterous collaborative handlers of wide range of payloads	• Autonomous robotic manipulation of land sensors • Inter-robotic communication and control • Ultraspectral remote sensors • Data fusion	• On line automation algorithms • On line inspection characterization algorithms • On line corrective/feedback algorithms • On line corrective/feedback hardware (robotics)

Robotics and Intelligent Machines Roadmap

Rim Technology Roadmap Level	Intermediate Strategic Objective Example #7		
1. DOE PSO	ER		
2. PSO Program Driver (High-level Need) The handful of high-level, program-specific goals (not necessarily related to RIM) that are shaping what the PSO will do to meet its mission over the next 20 years.	Improve operation of ER strategic research facilities to meet programmatic missions		
3. Epoch 1 - Functional Objective A "next-level" PSO need as it could be addressed by RIM technology, and including a technical goal within a given time frame.	Enable high risk operations: reduce construction costs by 2.5%. reduce operator exposure by 25%. reduce downtime by 25%. increase inspection accuracy 5x.		
4. Epoch 1 - Applications	• Facility design basis • Facility construction • Facility concept mockup testing • Dimensional inspection • Facility operation and maintenance		
5. Epoch 1 - RIM Technologies	• Dexterous manipulation • Mobility platforms • Environmental hardening • Simulation • Heavy payload teleoperation • Remote metrology • Autonomous and remote cutting/welding		

Rim Technology Roadmap Level	Functional Objective Ex. #7 (cont.)		
6. Epoch 2 - Functional Objective A "next-level" PSO need as it could be addressed by RIM technology, and including a technical goal within a given time frame.	Improve high risk operation Reduce construction costs by 5% Reduce operator exposure by 75% Reduce downtime by 75% Increase inspection accuracy 15x Increase data handling efficiency 10x		
7. Epoch 2 - Applications	• Facility operation and maintenance • Facility mockup testing • Virtual lab operations • Remote dimensional inspection • Intelligent exper. data handling		
8. Epoch 2 RIM - Technologies	• Dexterous manipulation • Mobility platforms • Environmental hardening • Simulation • Heavy payload teleorobotics • Virtual lab technologies • Refined remote metrology • Refined autonomous and remote cutting/welding • Intelligent processing and interpretation of experimental data		