*The Advanced Manufacturing Science
and Technology Program*

FY95 Annual Report

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*The Advanced Manufacturing Science
and Technology Program*

FY95 Annual Report

*Compiled by
Jeff Hill*

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Abstract

This is the Fiscal Year 1995 Annual Report for the Advanced Manufacturing Science and Technology (AMST) sector of Los Alamos' Tactical Goal 6, Industrial Partnering.

During this past fiscal year, the AMST project leader formed a committee whose members represented the divisions and program offices with a manufacturing interest to examine the Laboratory's expertise and needs in manufacturing. From a list of about two hundred interest areas, the committee selected nineteen of the most pressing needs for weapon manufacturing. Based upon Los Alamos' mission requirements and the needs of the weapon manufacturing (Advanced Design and Production Technologies (ADaPT)) program plan and the other tactical goals, the committee selected four of the nineteen areas for strategic planning and possible industrial partnering. The areas selected were Casting Technology, Constitutive Modeling, Non-Destructive Testing and Evaluation, and Polymer Aging and Lifetime Prediction. For each area, the AMST committee formed a team to write a roadmap and serve as a partnering technical consultant.

To date, the roadmaps have been completed for each of the four areas. The Casting Technology and Polymer Aging teams are negotiating with specific potential partners now, at the close of the fiscal year. For each focus area we have created a list of existing collaborations and other ongoing partnering activities. In early Fiscal Year 1996, we will continue to develop partnerships in these four areas.

Los Alamos National Laboratory instituted the tactical goals for industrial partnering to focus our institutional resources on partnerships that enhance core competencies and capabilities required to meet our national security mission of reducing the nuclear danger. The second industry sector targeted by Tactical Goal 6 was the chemical industry. Tactical Goal 6 is championed by the Industrial Partnership Office.

Introduction

In 1994, the Laboratory identified ten tactical goals that would “force ourselves to focus our institutional resources.¹” Six of the tactical goals are technical in nature and four are operational in nature. Tactical Goal 6, Industrial Partnering, is a technical goal to “Couple the Laboratory’s innovative science and technology with selected industrial sectors while concurrently strengthening the Laboratory’s core competencies.¹” In late Fall 1994, the chemical and manufacturing sectors were selected as the first industrial sectors to be targeted. This report concerns the manufacturing sector, Advanced Manufacturing Science and Technology (AMST) project, and the Laboratory’s effort to build alliances with the United States’ manufacturing industry.

To help Los Alamos fulfill its national security mission of reducing the nuclear danger, the AMST project has two primary goals: to improve weapon manufacturing capability and to retain Los Alamos’ core competencies. Our underlying idea was that collaborations between the Laboratory and US industry would lower common research and development costs by reducing duplication of effort and build a living weapon manufacturing knowledge base within Laboratory personnel.

Develop Manufacturing Capability

Los Alamos has cradle-to-grave responsibility for many of the weapons in the stockpile. From a manufacturing viewpoint, this means Los Alamos shares the responsibility with the production plants for the processes used to assemble, disassemble, and maintain weapons designed at Los Alamos. Today, some manufacturing processes can no longer be used because they are too wasteful or too hazardous while others are antiquated or costly; hence the need for new manufacturing capability to satisfy the mission. The Department of Energy (DOE) is addressing future weapon manufacturing with the Advanced Design and Production Technology (ADaPT) program. AMST relies heavily on the Los Alamos ADaPT program office for mission specific guidance.

Los Alamos has extraordinary research capability, but we do not have much manufacturing expertise. In other words, the Laboratory is weak when it comes to actually putting the technology on the shop floor—technology maturation—or in actually integrating the technologies on the shop floor into a system—process flow design. We believe that industrial partnering will bring those capabilities to Los Alamos very quickly and prevent us from reinventing processes that already exist.

One may ask why this is important; after all, the production plants have always developed the capability to make the weapons designed by the laboratories. The answer is

that integrating design and manufacturing will lower costs by improving agility; reducing waste and rework; easing assembly, disassembly, and maintenance; and enhancing overall quality. So, although Los Alamos' manufacturing capability may not be exhibited in an on-site plant, it will be exhibited in a leaner and more efficient design/production/remanufacturing cycle.

Retain Core Competencies

People and their knowledge and skill comprise a core competency. In the absence of new weapon programs, it has been difficult to attract new and retain experienced weaponeers; that is, to preserve our nuclear-weapons-related core competencies. By partnering with US industry, the AMST project can help preserve those core competencies and capabilities critical for the manufacture and stewardship of nuclear weapons. In such partnerships, Laboratory and industry scientists, engineers, and technicians collaborate precompetitively around a technology—not a product. Once a technology is developed, applying that technology to products is each partner's responsibility. Thus, we retain core competency because our people are able to acquire new knowledge that is applicable to mission-specific projects.

Some of Los Alamos' core competencies lie outside the weapons arena. Originally, the AMST project was going to pursue industrial partnerships that would support these core competencies as well. However, because Los Alamos is a weapons laboratory and AMST could support only limited work, we decided to concentrate on core competencies required for weapon manufacturing.

Project Scope

Tactical Goal 6 prescribes a project plan, deliverables, and success indicators.² The milestones identified for FY 1995 were

- January 1995—Divisions and programs submit candidate focus areas to the Industrial Partnership Office.
- January 1995—Candidate focus areas selected and announced.
- February 1995—Divisions identify project leaders for candidate focus areas.
- January through August 1995—Industry interactions within candidate focus areas.
- September 1995—Partnerships in place with Memoranda of Agreement signed.
- December 1995—Each division has targeted 5% of total programmatic funding for industrial partnerships.

The Tactical Goal 6 plan also outlined an important action item—all program offices and divisions were charged to focus their industrial partnership efforts to provide dual (Laboratory and industry) benefit.² The goal stipulated that Institutional Program Development (IPD) funds were to be used to fund the industrial interactions necessary to get these partnerships in place.

Three events occurred in early calendar year 1995 that significantly reduced the scope of the AMST project. First, program funding shortfalls prevented divisions from appointing project leaders. Second, the ADaPT weapons manufacturing technology program was launched. And third, the IPO's allocations of IPD and Laboratory Directed Research and Development (LDRD) funds were cut in half.

Results

Despite the reduction in the scope of the AMST project, a lot was accomplished. A committee was formed that reduced a huge technology needs list to nineteen items especially relevant to manufacturing Los Alamos' weapon components. Working with the ADaPT project office, the committee chose four technology areas for manufacturing partnership development.

- Casting Technology—modeling, testing, and process development for casting uranium, plutonium, and their alloys.
- Constitutive Modeling—welding; high- and low-strain-rate behavior of plutonium; failure and damage due to aging; and high explosives.
- Polymer Aging and Lifetime Prediction—initially polyurethanes and silicones.
- Nondestructive Testing and Evaluation—weapon-related defect testing.

IPD funds were used to write roadmaps and fund industrial and interlaboratory partnering activities. The roadmaps were completed (see appendices) and partnering was underway at the end of FY95.

The remainder of this report covers the project in greater detail.

Project Description

This section covers the approach AMST used to satisfy Tactical Goal 6, a description and status of each of the four technologies, and an analysis of the project's success in the form of lessons learned.

Approach

The AMST project's approach was to first—get to know the Laboratory's manufacturing technological needs, select those most important to the Los Alamos mission, and create roadmaps for developing those technologies—and then second—approach industry and develop partnerships that fit those roadmaps. To accomplish this we had IPO IPD funds, some influence over LDRD funds and new and redirected Technology Transfer Initiative funds, and a commitment from the Laboratory's technical organizations to appoint project leaders to lead each technology focus area. We intended to pursue industrial partnering in six to ten focus areas, expecting that attrition and other obstacles would result in only three or four actually obtaining Memoranda of Agreement by the end of FY 1995.

To get to know the Laboratory's interests, the AMST project leader issued a call for white papers and solicited division and program input. We believed that soliciting white papers would involve more of the Laboratory citizenry. By early February 1995, slightly behind schedule, about 200 different interests and needs had been identified.

Because so many technologies were identified, in order to reduce the size of the list the project leader formed a committee representing the Laboratory's manufacturing interests. The committee was able to reduce the original 200-plus technologies to 29. This list was further reduced by comparing each of the remaining 29 interest areas with the requirements of the other Tactical Goals and the ADaPT program. This left 19 technologies in the five broad areas shown in Table I.

The committee quickly realized that the manufacturing technologies were not unique to Los Alamos; industry has the same needs and is generally far more advanced in developing technologies for and applying technologies to manufacturing. What is unique to Los Alamos is that the materials we use—for example, uranium, beryllium, and plutonium—are not commonly used by industry. This is not to say that Los Alamos has nothing to contribute to industry or that partnering around technology is a waste of time. What it does say is that technology maturation will follow a different path at Los Alamos than in industry. Consequently, the opportune technology partnering will be around precompetitive, research oriented, long-term topics.

Table I. Manufacturing Topics and AMST Focus Areas

Manufacturing Topic	AMST Focus Areas
Materials Synthesis	Plastics and Composite Materials Long-term Aging (Materials Research) ¹ Materials Substitution ¹
Materials Forming	Powdered Materials Processing ¹ Metal Forming Casting Technology ¹ Waste Management ²
Removal and Surfacing	Machine Tool Controls On-Machine Part Certification Plasma Treatments (Coatings, Cleaning, Decontamination, Surface Enhancement) Waste Management ² Machining ¹
Component Assembly	Long-Term Aging (Component Interaction) Welding and Joining Weapon Systems Engineering and Integration ¹
Overarching Technology	Constitutive Modeling & Engineering Analysis ¹ Automation and Robotics (including Virtual Reality) Advanced Sensors Nondestructive Examination (including Nuclear Interrogation) ¹ Hydrogen, Deuterium, and Tritium Science and Engineering
<p>¹Indicates areas with strongest ties to the ADaPT program and the other Tactical Goals.</p> <p>²Waste management was deemed important enough to place it into two categories, but not important enough to consider an "overarching" technology.</p>	

Early in the third quarter of FY95, we learned that funding shortfalls would prevent the divisions from appointing project leaders and that the AMST project would receive only half of the IPD funds that were expected. In this same time period, the DOE ADaPT and ASCI (Accelerated Strategic Computing Initiative) programs became the designated beneficiaries of the Technology Transfer Initiative funds, which further reduced the AMST project's resources. This left AMST with direct control over \$150,000 in IPD funds and influence over the sharply reduced LDRD funds. In response, the AMST project leader conceived a reduced scope plan in May 1995. The essential changes to the program were

- The AMST project leader would be the project leader for all focus areas.
- Given the diminished funding, we decided that the program could support only four focus areas in which the Laboratory had the highest programmatic commitment and where we expected industry to have the highest interest.
- We decided that the technology roadmap for each focus area would be the principal product of AMST, rather than Memoranda of Agreement as specified in the original project plan.
- After the roadmaps were developed, the AMST project leader would initiate partnering in an opportunistic, rather than strategic, manner. That is, we would seek to develop partnerships where there was the best match between on-going technical work and industry interest.

Comparing the remaining 19 technologies to the DOE's ADaPT priorities and to Los Alamos' unique ADaPT priorities and tactical goals reduced the list to the eight technology areas with the highest need. The AMST project leader then consulted with the ADaPT project leader; together they identified four technology focus areas for roadmap development and possible partnering activities.

- Casting Technology,
- Constitutive Modeling,
- Nondestructive Testing and Examination, and
- Long-Term Aging and Lifetime Prediction of Polymers.

Personnel were selected to develop each focus area's roadmap and to serve as technical contacts during industrial partnering activities. Each focus area received about \$30,000 of IPO IPD funds.

Description and Year-End Status of the Four Focus Areas

Each of the four focus areas is discussed briefly below. The full roadmap and partnering information, such as relevant CRADAs for each, is found in the appendices.

Casting Technology

The Casting Technology focus area's principal participants are the Materials Science and Technology (MST) and the Nuclear Materials and Technology (NMT) divisions. These divisions are interested in casting uranium and plutonium, respectively. This focus area's goal is to numerically predict the outcome of the casting process. The roadmap identifies new casting techniques that should be developed, including ambient temperature molds and squeeze casting. Because both are concerned with molten metal, the Casting and Constitutive Modeling roadmapping efforts have much in common and are mutually supportive.

For two reasons, we believed that casting technology had the greatest chance of attracting industrial partners. First, both MST's and NMT's casting efforts are central to their missions and programmatically funded, which means the Laboratory has made a long-term commitment to developing technology in this area. Second, casting is a widely used process in industry. Our belief proved out when the Casting Technology focus area team committed to join the Fastcast Consortium on 7 September 1995.

Casting is an integral part of other Laboratory efforts, and the focus area team has forged links to the Solidification, Continuum Modeling, and Constitutive Modeling working groups of the Los Alamos Center for Materials Process Modeling and to the Advanced Manufacturing Industrial Partnership program, which is sponsoring four casting-related projects.

Constitutive Modeling

The Constitutive Modeling focus area's principal participants are the Applied Theoretical Physics (X), Theoretical (T), MST, and Engineering Science and Applications (ESA) divisions. There are four interests with this focus area: modeling welding; modeling plutonium strain-rate phenomena; modeling high explosive performance; and modeling failure and damage due to materials aging. The interest areas were chosen by the participants for their relevance to the weapons program and the likelihood of programmatic funding next year.

This focus area's goal is to reach a better understanding of material behavior at a fundamental, sometimes near molecular, level and to convert that understanding to better macroscopic models for hydrodynamic and finite element modeling. The computing

power to do such modeling only has recently become available. So the approach is new but full of promise because, if material properties can be derived from modeling the behavior of fundamental particles, then in theory, one could find the material properties for any material in any condition, including mixtures, composites, and new materials. Perhaps even the inverse could be accomplished—given certain required material properties, a material could be selected with or custom made to have the required properties. Because material modeling accuracy must be verified, the roadmap includes testing and verification tasks.

No industrial partners have been found to date. However there are existing CRADAs and inter-laboratory and internal collaborations that support the activities of this focus area. For example, fundamental material modeling and testing is the central part of Los Alamos' participation in the CRADA with the Semiconductor Research Corporation. The technical groups participating in the Los Alamos Center for Materials Process Modeling are involved in CRADAs in which constitutive modeling is important, and Advanced Manufacturing Industrial Partnership funds support three constitutive-modeling-related projects.

Nondestructive Testing and Evaluation

The need for Nondestructive Testing and Evaluation (NDT&E) methods is compelling—we need to know the internal well being of an object, such as a nuclear weapon, without having to take it apart. Or, if it is taken apart, we need to determine the health of the components without destroying them. The ESA-Materials Technology group is the principal participant in the NDT&E focus area. However, NDT&E is used by technical groups Laboratory-wide and is an important technology for industry. Indeed, the other focus areas will use some of the techniques developed within this focus area.

Although we expect industry interest in the roadmap, to date no partners have been identified.

Polymer Aging and Lifetime Prediction

The Dynamic Experimentation (DX), ESA, and MST divisions are the chief participants in the polymer aging focus area. Because weapons will remain in the stockpile for longer periods of time, polymer aging has become a critical concern. Polyurethanes are probably of most concern because they are used as a binder for high explosives and they are known to break down over time.

Partnering activities have centered around redirecting and continuing the 3M CRADA (CRADA No. LA92C10058). Additional partnering opportunities exist with many of the weapon material suppliers and we have begun discussions with Dow Chemical.

Conclusions and Recommendations

The AMST project has accomplished a great deal despite reduced participation and funding. We have developed roadmaps for four technologies; these roadmaps will serve as a strategic plan for technology development. In addition, we have established an industrial partnership in one focus area and have initiated discussions with industry in one other focus area.

In the course of the AMST project, we learned a few lessons about the importance of developing a technology roadmap.

- A roadmaps is a thinking tool. When the roadmap is expressed as a Gantt chart (or any other project planning method) one can see a timeline and determine its reasonableness, one can see the level of effort needed, one can see the relationship between tasks, and if sufficient detail is supplied, one can even plan a realistic budget.
- The roadmaps make our Laboratory's technology needs self evident—they plot a course to acquiring and maintaining the competencies that we need to fulfill our mission.
- There are many opportunities for internal collaborations between the Laboratory's technical groups and we should take advantage of these opportunities. The roadmaps make these collaborative opportunities clear because groups can see where they can contribute to an overall plan, not just a project.
- The link to special programs, such as ADaPT, becomes evident and can be factored into the roadmap as it is developed. Once again, it stimulates a disciplined way of thinking about the goal we are trying to achieve.
- The roadmaps point out where industrial partnering would be useful and where it supports the Laboratory's mission.
- Long-term planning and long-term partnering go hand in hand. Because we have a goal and a way to get there, we are more attractive to industry.
- The roadmaps help plan intellectual property protection.
- By making the Laboratory's purpose clear, the roadmaps encourage other DOE laboratories to work with us. Intersections between their roadmaps and our roadmaps are areas for collaboration.

Our efforts to attract and formalize agreements with industrial partners had its own list of lessons learned.

- It is unlikely that there will be any funds-in agreements in the manufacturing sector. There is a gap between Los Alamos R&D and production capabilities. Our production capabilities are limited and certainly not exceptional. However, our R&D capability makes us good collaborators in a precompetitive, long-term development activity.
- To attract industrial partners, it is necessary to have a substantial up-front commitment by the Laboratory. As a minimum, this means a full-time principal investigator must be assigned to a project. Otherwise, companies do not believe the Laboratory is committed to a project and are hesitant or unwilling to join in any collaboration. Conversely, a demonstrable Laboratory commitment generally invokes an enthusiastic response from industry to those projects with common interests and needs.
- The IPD vehicle is invaluable. We could increase Laboratory participation immensely, thereby gaining technical expertise, by using IPD funds to offset expenses that are not normally incurred by a program. For example, travel to meet with potential partners and roadmap development.

For the future of AMST, we make the following recommendations.

- The AMST project should be continued. For the roadmaps alone, if no other reason.
- Since the AMST project leader is the project leader for each focus area, each quarter one new technology should be selected for roadmap development and industrial partnering. That way the partnering, roadmap development, and other activities would be paced and each would get more attention.
- AMST should pursue a mixed portfolio of weapons and non-weapons partnering.
- In each focus area, AMST should continue to align with the Laboratory mission and important programs like ADaPT.

References

1. "Tactical Planning for the Los Alamos of Today: An Overview," Los Alamos National Laboratory internal document, Rev. 1/20/94.
2. "Tactical Goals for Los Alamos National Laboratory FY95," Los Alamos National Laboratory internal document, Rev. 1/20/94.

Appendices

Casting Technology Roadmap

Constitutive Modeling Roadmaps

Failure/Damage

High-Explosive

Plutonium

Welding

Nondestructive Testing and Evaluation Roadmap

Polymer Aging and Lifetime Prediction Roadmap

Casting Technology Roadmap

Committee: Rich LeSar, Paul Dunn, Dale Soderquist

Casting 2000—Uranium Casting

This roadmap outlines a unified experimental/modeling program to develop better gravity-fed castings for uranium and uranium alloys. We have broken the overall casting process into seven stages—nozzle/crucible flow, mold filling, nucleation and solidification, cooling, texture development, property assessment, and component manufacture for hydrotests. We describe each stage below and identify key experiments and model development for each.

Nozzle/Crucible Flow

The key features to be determined experimentally are the flotation of particles (carbides), fluid properties, and fluid flow. The modeling must combine fluid and heat flow and possible coupling to external fields. Note that the study of carbide flotation requires the use of multiphase flow. We will iterate between experiment and modeling to first verify the models and then to optimize the crucible/nozzle design.

Mold Filling

The controllable parameters in the mold filling stage are the pour rate and pour characteristics (e.g., bottom tilt and back pressure). These parameters control variables such as heat flow and are dependent on a variety of physical (fluid properties) phenomena, including mold/liquid interface characteristics. The model will use experimentally determined parameters; the output of the model will be compared to the experimental observations to verify its accuracy. After verification, an optimal design of the mold will be determined by combining modeling and experiment. Key parameters to be varied include the design and coatings that affect behaviors such as heat transfer and wetting at the mold surface.

Nucleation and Solidification

The initial microstructure of a cast part depends on the nucleation and solidification of the poured metal, which in turn depends on the cooling rate, second-phase (i.e., carbide) particle content, and other characteristics. This part of the project will focus on determining final-state microstructures, diffusion, and other properties, as well as developing better descriptions of the solidification process. Initially, we will use

deterministic models with microstructure prediction as an empirical model. Later, we will add detailed microscopic models of solidification. Once again, we will iterate modeling with experiment to verify and refine the model. Note that we already have succeeded in accomplishing this task in a limited way through a project funded by the Advanced Manufacturing Industrial Partnership program.

Cooling

Phase transformations that occur during cooling can have an enormous effect on the properties of a final part, especially if they are accompanied by large volume changes. Here, we first will examine such effects experimentally, measuring changes in grain size and morphology as well as final-state residual stresses. The focus of the modeling will be on solid-solid phase transformations and how they effect the grain size and properties.

Texture Development

Texture is the measure of how grains are oriented. The Laboratory has extensive expertise in both measuring and modeling texture effects.

Property Assessment

We will do extensive measurements and modeling to determine the properties of the cast parts. This will require coupling casting modeling with finite-element analysis. Note that this task couples directly to the failure/damage roadmap. At the completion of this task, we will have an integrated casting/properties models that will be used to develop and refine casting processes.

Component Fabrication for Hydrotest

The ultimate test of the cast part will be how it behaves in a hydrotest. We will use the refined model to develop processes and then will make and test them.

Plutonium Casting

This roadmap outlines a combination development/modeling program to improve the efficiency of plutonium casting, heat treating, and forming. The roadmap defines a process that provides a superior product that is nearer to net shape and will reduce the total amount of plutonium metal required (per unit produced) in a production setting. At the same time, exposure of personnel to radiation and waste generation will be reduced. Another objective is to simplify the casting equipment in order to reduce maintenance time and effort.

A computer model must predict fluid flow, mold filling, alloy segregation, cooling rates, and other phenomena of the casting process. In addition, the model should predict and take advantage of alloy movement caused by phase changes and creep that arise during heat treating. These predictive capabilities will enable optimization of mold design and heat treating fixture design and help solve production problems or evaluate process modifications.

Mold and Crucible Coating R&D

Long-life reusable molds and crucibles are desired as a means to reduce both waste and hardware costs. Rocky Flats was successful in making a reusable flat mold that was used for over 100 cycles. Shaped molds used in the Rocky Flats die casting program also were reusable but required a release coating to prevent adhesion to the plutonium; their production lifetime was not established. With coating technology improving substantially in the last 10 years, we believe that reusability can be improved not only for molds but also crucibles.

Facilities Work

The squeeze casting R&D described next requires a new furnace and glovebox. The 18-year-old foundry also used also must be upgraded and modified and the heat-treating furnaces and other equipment used in casting and heat treating also must be replaced.

Squeeze Casting R&D

Squeeze casting has proven to be effective in industry and is a process that appears to not only be compatible with plutonium casting needs, but also offers improvements such as a simultaneous bonding with the pit case and improved cooling rates to help minimize heat treatment. This process parallels die casting capabilities, but with less complicated equipment.

Gravity Casting R&D

New ideas for mold design recently have appeared and heat capacity calculations show that ambient temperature molds can be used without producing cold shuts in the casting. Should these ideas prove practical, casting furnaces may be simplified and cooling rates may be dramatically improved, thus reducing alloy segregation and decreasing heat treatment requirements. Ambient temperature molds might be used with other casting processes such as squeeze casting. These ideas may be of interest to industry as a means of simplifying their casting processes.

Heat Treating & Creep Forming R&D

Because alloy segregation occurs during the cooling period following casting, heat treating is required for alloy homogenization and phase stabilization. Heat treating also is needed for the Lawrence Livermore National Laboratory (LLNL) die casting process. During heat treating, the alloy expands because of phase changes. At the elevated temperatures used, the alloy also can creep and slowly deform under its own weight. By taking advantage of these phenomena, we believe the as-cast dimensional tolerances can be improved.

LLNL's Die Casting Results

A die casting process is being developed at LLNL and the possibility of moving their process to Los Alamos is under consideration. Process efficiency, maintainability, and product quality comparisons should be made for parts fabricated by the LLNL die casting process and those made with Los Alamos processes.

Special Note

The uranium casting roadmap (Casting 2000) addresses much more fundamental issues than the plutonium roadmap. It is possible that some of the modeling codes developed for uranium could be applied to plutonium; this kind of technology sharing would certainly be welcome.

Table II. Industrial Partnerships Investigating Casting

Title or Topic	Company	Lab Contact	Type
Thermal Physical Properties	FastCast Consortium	Paul Dunn, MST-6	Consortium
Phase Transformation	National Center for Manufacturing Science	Terry Lowe, MST-5	CRADA
Fluid Flow	Flow 3D	Deniece Korzekwa, MST-6	AMIP
CRADA—Cooperative Research & Development Agreement AMIP—Advanced Manufacturing Industrial Partnership

Noncritical Progress Milestone Summary Rolled Up

Project: Casting 2000 Roadmap
Date: 4/26/96

Project: Casting 2000 Roadmap
Date: 4/26/98

Noncritical Progress Milestone Summary Rolled Up

Constitutive Modeling Roadmaps

Rather than rely on nuclear testing as an empirical method of measuring the "health" of a weapon and its components, we will rely on computer modeling and non-nuclear testing of components to predict a weapon's health as it ages. Coincidentally, an accurate prediction of a weapon's lifetime will allow us to establish a maintenance plan that might extend the weapon's lifetime. Accurate modeling is essential for predicting changes in a weapon over a long lifetime. The constitutive modeling committee gathered and identified a number of materials and issues that a computer model might address; these concerns are given in Table III.

The constitutive modeling committee chose four high interest areas for roadmap development from this list of concerns—Failure/Damage (overarches several topics), High Explosive, Plutonium, and Welding. Each area's roadmap is discussed below.

Failure/Damage Modeling

Committee: Rich LeSar, Materials Science and Technology Division; John Hopson, Nuclear Weapons Technology Division; Paul Maudlin, Theoretical Division

Weapon components degrade over time. Los Alamos needs to be able to predict failures that may occur in environments described in the Stockpile-to-Target Sequence document and in abnormal environments. Today, we cannot reliably predict failure and damage in virgin material that we can test for material properties. As a weapon ages, the properties of the materials within the weapon change and become increasingly unknown. Consequently, our predictive capability is very limited.

The focus of our effort is to develop a unified set of models for predicting the behavior of metals (except plutonium), ceramics, and composites over time. We can divide this task into several subtasks or elements that must be modeled. First, we need to have a baseline material response, i.e., elastic/plastic behavior. We then need to examine accumulated damage caused by use, work, corrosion, radiolytic decay, and other factors. These damage assessments (e.g., microcracking and porosity) will be incorporated into failure models.

How a material ages will depend critically on its original properties and on how it was manufactured in the first place. Two critical aspects of manufacturing—friction (present in any solid-state process) and particle/powder flow (the essential ingredient in powder metallurgy, a promising near-net-shape manufacturing process)—are included for study in the Failure/Damage Roadmap..

Note that the goal of this roadmap is to create an integrated set of constitutive relations that will enable us to predict lifetime performance of materials. These models will be incorporated into new, advanced continuum codes (under the Accelerated Strategic Computing Initiative, ASCI) to focus on specific manufacturing processes.

Table III. Constitutive Modeling Concerns

Material, Part or Process	Issues
High Explosive	Creep, Aging, Cracking, Migration of plasticizer and binder, Chemical kinetics
Composites	Creep, Fundamental properties
Foams	Lifetime performance, accident environment, migration of products, Decomposition, Set
Potting	Lifetime performance
Plutonium	Aging
Casting	Predict final shape and internal stresses
Welding	Distortion, Mixing, Black art
Powdered Metals	Net Shape Forming
Ceramics and Ceramic-like materials	Material removal process, Net shape pressing
Stainless Steel	Hydrogen degradation, Helium infusion
Uranium	Long-term properties exposed to water and hydrogen
CSA components	CSA components
Mercury	?
Radiolytic Effects	Component aging
Caps	Aging
Fogbank	(Purposely left blank)
Misc. Components	Combining mechanical creep w/decomposition
Lithium compounds	Material properties
Accelerated aging	What techniques are realistic?
Structural plastics, e.g. DAP	Properties, aging
Dielectrics	Lifetime
Rubber	Fatigue
Heat treated metals	Property change over time
Assemblies	Material compatibility, Mechanical wear
Adhesives	Lifetime
Nickel plating	Adherence
Metals in general	Corrosion
Internal atmospheres	Effect on materials
Thermal cycling	Fatigue
Molding	Internal stress, homogeneity
General	Material properties at different temperatures, Material properties vs time for different environments

Elastic/Plastic Behavior

This subtask combines experiment and modeling, using facilities in the Materials Science and Technology Division to obtain both high-strain-rate and quasistatic behavior. The general plan is to first assess current capabilities and then develop an integrated set of models. The key is to use experiments to develop and validate the models under a stringent set of conditions.

Damage Accumulation

The failure of a material with time depends on how damage accumulates, including increases in porosity and microcracks and work hardening, aging, and corrosive effects. Again, we will couple experiments (including study of materials recovered from the stockpile) with modeling to improve the accuracy of damage accumulation models. We intend to use the same framework (if possible) as the elastic/plastic materials response models so as to more easily couple damage accumulation with materials response.

Failure

In this subtask we will focus on developing a more integrated approach to failure. We will couple damage coalescence with standard models of crack growth. One area of importance is to link this element of the model with microstructure-based models.

Friction

In solid-state processing, friction often plays a major part in determining a material's properties, especially near the surface. Friction models, especially those that are microstructure-based, have not been adequately developed nor incorporated into continuum codes. How microstructure affects friction and how that microstructure changes due to frictional heating are two questions that need to be answered.

Powder Flow

Powder processing offers many advantages in terms of near-net-shape manufacturing of parts. The key features are the powder flow and the resultant microstructural properties. We will incorporate flow and compaction into our model to allow predictions of agglomeration and resultant microstructure.

Implementation of Models

After the various models are developed and refined, they will be implemented into continuum codes for materials response prediction. One key here is to couple these modeling efforts closely with the code development sponsored by ASCI.

Application of Codes

The new codes and models will be applied to materials manufacturing processes and materials aging issues, coupling with the Advanced Design and Production Technologies (ADaPT) and Enhanced Surveillance programs.

Table IV: Industrial Partnerships Investigating Failure/Damage Modeling

Title or Topic	Company	Lab Contact	Type
Modeling and verification of complex problems in metal forming	Alcan International	David Korzekwa, MST-6	CRADA
Predictive modeling and simulation tools	Semiconductor Research Corporation	David Cartwright, DDT	CRADA
Modeling and verification of complex problems in metal forming	Exxon Research and Engineering	David Korzekwa	CRADA
Advanced materials for aircraft engines	GE Aircraft Engines	Mike Stout, MST-5	CRADA
Numerical modeling of the mechanics of machining	General Motors	Paul Maudlin, T-3	CRADA
Materials modeling ¹	Biosym Technologies, Inc.	Shao-Ping Chen, T-11	CRADA
Application of high-performance computing to automotive design and manufacturing	USCAR	T. Daniel Butler	CRADA
Predictive model and methodology for heat treatment distortion	National Center for Manufacturing Sciences	Terry Lowe, MST-5	CRADA
Powder Compaction	USCAR	Hopson/Reed	CRADA
Advanced optical diagnostics for superplastic forming [§]	Barnes Aerospace	Martin Piltch, CST-2	CRADA
Advanced manufacturing/advanced powder metallurgy ²	USCAR-LEP	Phil Berry, ESA-MT	CRADA
Hub Containment			
	Allied Signal Aircraft Engines	Rich Davidson, ESA-EA	CRADA
Beryllium Oxide Fabrication	Quatro Corp.	John Petrovic, MST-4	AMIP
Directed Light Fabrication	3M Co.	Gary Lewis, MST-6	CRADA AMIP
¹ CRADA not signed at time of report. ² Not clearly relevant to failure/damage phenomena, but may be. CRADA—Cooperative Research and Development Agreement AMIP—Advanced Manufacturing Industrial Partnership

Noncritical Progress Milestone Summary Rolled Up

Project: Const Model-Fall/Dam
Date: 4/26/96

High Explosive Modeling

Richard Browning, Engineering Science & Applications Division

Overview

Modeling the mechanical behavior of high explosives (HE) is important because the behavior of the HE determines the response of weapons systems to both normal and abnormal environments. Accurate and predictive engineering models are needed to estimate deformation and cracking of the HE charges under long-term loads; these models are also necessary for understanding ignition and deflagration-to-detonation transition (DDT) of the HE charges in abnormal situations.

For example, PBX-9501 and LX-14 have very similar compositions and detonation characteristics, yet the behavior of the two materials in a drop-skid test, which is used as an indication of impact sensitivity, is very different. Gibbs and Popolato quote a height for PBX-9501 of 26 feet in a 45-degree plane test. For this same test, the LLNL Explosives Handbook quotes values of 10 feet for PBX-9501 and 5 feet for LX-14. Thus, there is a factor of at least two difference in the large-scale sensitivity of the two formulations. The mechanical properties of the materials are largely responsible for this difference. These differences in behavior must be incorporated into our model before we can understand how the system will respond to a bullet impact or crushing blow.

Another example relates to manufacturing and long-term storage problems. When charges are glued together, the mechanical properties must be known before estimating the long-term strength of the joint. When potentially variable joint strength is coupled with heating and cooling cycles, as occur in actual storage environments, the overall shape and size of the charges can be distorted. Understanding, predicting, and controlling these distortions is key to estimating useful lifetime of the system.

The tests needed to characterize materials in storage environments are different in concept and technique from those used to characterize the response to high-level shock loadings. The former category of tests must take into account long-term, lower-strain-rate-loading over a much wider range of temperatures.

Because of cost and technical problems of performing the required tests, there have been few comprehensive tests of HE behavior in storage situations. There are reasonably accurate models for long-term behavior of PBX-9502 up to temperatures around 70 degrees Centigrade. A model for PBX-9501 was developed based on very sketchy test results. Neither material has been tested at strain-rates in the range of 0.1 to 104.0 per second, although there is a project in the Materials Science and Technology Division (MST-5) to study the higher strain rate region. The Dynamic Experimentation Division

(DX-2) has a project to study the deformation processes at the granular level and as a part of that project are doing some characterization tests at the lower strain rates. These studies complete some of the needed testing, but a more comprehensive testing program is required to develop a predictive material model. Because compression tests on HE samples at high temperatures, temperatures where the material is decomposing rapidly, is very challenging, a large part of the needed testing program is creating new testing methods.

Proposed Testing Program

Because of the complexity of the testing program, to minimize costs one of the first needs is to narrow the scope by testing only a few materials. For the HE component, the choice is PBX-9501, because of its large representation in the stockpile. Selecting the binder system is the next step, because of its dominant role in influencing mechanical properties. However, because many binders are used, selecting only a single binder would overly narrow the scope of the testing program. So, the first task is to select two or more binders that provide adequate variety, yet are feasible from a cost and technical difficulty standpoint.

There are several other programs, or virtual programs, that are involved in this general area. On the project Gantt chart, items 2, 15, and 19 are essentially coordination activities with these other programs. When laying out this tasking, I tacitly assumed that other program/projects would fund most of the microstructural work under Task 19. I couldn't estimate the time required for coordination with the techniques studies, Tasks 21-24, so they wound up with the default one-day allocation. Under the materials category, I envisioned some testing would be required on the separate constituent materials and I built in time estimates. These tests include standard mechanical tests and microstructural evaluations done on coupons of the listed constituent materials.

Task 32, the overall macroscopic test program, has components that cover the range of strain rates from very slow to rather fast, just below flyer-plate-type shock loading conditions. The testing program is scheduled to continue to allow tests at many temperatures and several additional HE/binder compositions.

Task 39, on model development, assumes that a state variable model will be the desired numerical description. The results will be obtained somewhat slowly because of the lack of sound experimental data for making the detailed experimental fits. The breakdown in terms of sub-models is somewhat hypothetical, but reasonable. The overall time scale is somewhat accelerated from my experience of working on modeling PBX-9502 and the attendant experimental program for that material. I have assumed that the

previous experience will help in the model building and experimental process, but PBX-9501 is probably a more complex and difficult to model material.

In all honesty, the aging chemistry section, Task 49, is rather speculative. I believe this is technically feasible, but found very few scientists that share my enthusiasm for actually doing the work. The aging chemistry is envisioned as very complex and few experimental tools are available. As a result, I must admit there is a low probability of obtaining a practical understanding of the aging mechanisms and effects on this time scale. Nevertheless the problem is so important that I believe we should have a continuing effort in this area. If we don't start we will certainly never get there.

The last section on modeling aged material, Task 93, will use experimental data from aged samples and whatever information is available from the aging chemistry task to form predictive models of the materials.

Table V: Industrial Partnerships Investigating High Explosives Modeling

Title or Topic	Company	LANL Contact	Type
Ultrasonic Interrogation of HE ¹	Quatro Corp.	Mike Fletcher, DX-16	AMIP
Polymer Aging		Doug Hemphill, ESA-WMA	AMST
Binder Systems	B.F. Goodrich	Mark Smith, MST-7	Supplier
Polymer Aging	3M Company	Jeff Hay, T-12	CRADA
Polymer Chemistry	Allied Signal, Pantex	Doug Hemphill, ESA-WMA	2
¹ Not clearly relevant, but may be. ² Potential Partnerships being investigated. AMIP—Advanced Manufacturing Industrial Partnership AMST—Advanced Manufacturing Science & Technology CRADA—Cooperative Research and Development Agreement			

Plutonium Modeling

Committee: Galen Straub, Theoretical Division; Dean Preston, X Division; Jeff Hill, Engineering Science and Applications Division

Plutonium is a poorly understood material of critical importance to most nuclear weapons. It is chemically reactive and naturally self destructive via helium growth. Plutonium has only existed for fifty-two years, so there is no legacy of accumulated experience and testing.

Plutonium models are divided into thermodynamic and non-thermodynamic, low-strain-rate models. Thermodynamic models generally are aimed at weapon performance when all or part of the high explosive detonates or deflagrates; that is, when the weapon is intentionally detonated or when the high explosive reacts violently, such as might occur in an accident. Typically in these calculations we describe the materials with equations of state (EOS), the simplest EOS models relate pressure to density.

Non-thermodynamic, low-strain-rate models generally are used to model a weapon's behavior in other conditions as described in the Stockpile-to-Target Sequence document. These conditions include extreme vibration, hot and cold temperature extremes, launch and impact forces, internal loads from other components, and transportation loads. The simplest of these models describe material behavior by relating stress to strain. While we have simple models for plutonium, these models were not designed to account for the behavior of aged plutonium.

The roadmap we created is ambitious. It represents a combination of testing and computer modeling. Because it is difficult and expensive to work with plutonium, we use other metals to develop the basic techniques for experimentally or numerically verifying the material properties we need to measure. Once we are quite sure that the technique is valid, we will apply it to plutonium. Consequently, other material property research is of interest to the plutonium modeling effort and we believe that leveraging these efforts is essential to understanding plutonium behavior. This is where industrial partnering makes sense for plutonium modeling.

Material Response During Phase Transformations

The constitutive modeling roadmap for plutonium and related weapon materials is divided into the areas of (1) developing an improved thermodynamic equilibrium EOS, (2) characterizing and modeling of non-thermodynamic equilibrium constitutive behavior, and (3) applying the accumulated experimental data, theoretical analysis, and models to weapons manufacturing, performance, and safety.

Plutonium Non-equilibrium Constitutive Behavior

The development of a non-equilibrium thermodynamic constitutive model for plutonium's behavior should proceed in parallel and be compatible with the equilibrium EOS work. Indeed, part of the challenge is to experimentally determine the material response in equilibrium conditions and non-equilibrium conditions. In this respect, progress on modeling the non-equilibrium constitutive behavior of plutonium is driven by the availability of experimental data; more specifically, by time-resolved data for high-strain-rate properties.

Tasks for determining aging effects fall under of category of non-equilibrium behavior and also are driven by the availability of experimental data. From the point of view of asking how does a material's properties change with time, it is essential that each property be characterized for its initial time state. This requires an extremely close coupling with the other tasks in this section.

Technology Transfer for Weapons Manufacturing, Performance and Safety

The successful transfer of the technology developed under the Constitutive Modeling Roadmap will require specific attention and resources beyond the model development effort. The models developed within the context of this roadmap must be integrated with finite-difference, finite-element codes. This will not be accomplished unless additional resources are committed to the project.

The Semiconductor Research Corporation (SRC) Cooperative Research and Development Agreement (CRADA) provides many opportunities to study the behavior of small-scale, close-to-grain-size materials; information that can be used by Los Alamos scientists to develop the plutonium behavior model. For example

- Our current effort in the SRC CRADA can be extended to address grain growth evolution during the casting process. The grain structure evolution in thin metal films (the SRC problem) and in the casting process have much in common and compliment one another for model development.
- The success of the modeling (i.e., a reliable predictive capability) in the SRC effort and for plutonium casting are both dependent upon the availability of experimental data.
- In addition to pursuing experiments on plutonium, a parallel effort in a non-fissile material (the materials SRC is interested in) would avoid ES&H problems and expedite both the experimental and simulation efforts. Materials that overlap the semiconductor CRADA work and that might be candidates for such a parallel approach include aluminum and its alloys, copper and its alloys, tungsten, and titanium; these materials have their own importance in the weapons program.

- Solute segregation to grain boundaries is a common feature of aluminum, copper, and plutonium alloys.
- The model of the solidification of a cast metal part will be able to handle complicated boundary conditions (at a computational cost) resulting from geometries or spatially and time varying cooling rates.
- Success in modeling the grain structure evolution in SRC's thin metal films (and its experimental validation) will provide much needed conceptual guidance for the modeling of plutonium casting.

**Table VI: Industrial Partnerships Investigating (Plutonium)
Casting Modeling**

Title or Topic	Company	LANL Contact	Type
Predictive modeling and simulation tools	Semiconductor Research Corporation	David Cartwright, DDT	CRADA
Advanced Modeling of Coating Uniformity and Microstructure Simulation ¹	Alberta Microelectronic Centre	Bob Springer, MST-7	AMIP
Engineering Modeling for Pit Life Prediction ¹	Draper Laboratory	Mike Garcia, ESA-EA	AMIP
¹ Not clearly relevant, but may be. CRADA—Cooperative Research and Development Agreement AMIP—Advanced Manufacturing Industrial Partnership

Project: Const. Model—Pu
Date: 4/26/96

Noncritical Progress Milestone Summary Rolled Up

ID	Name	Year 1				Year 2				Year 3				Year 4				Year 5				Year 6				Year 7				Year 8		
		Qtr 1	Qtr 2	Qtr 3	Qtr 4	Qtr 1	Qtr 2	Qtr 3	Qtr 4	Qtr 1	Qtr 2	Qtr 3	Qtr 4	Qtr 1	Qtr 2	Qtr 3	Qtr 4	Qtr 1	Qtr 2	Qtr 3	Qtr 4	Qtr 1	Qtr 2	Qtr 3	Qtr 4	Qtr 1	Qtr 2	Qtr 3	Qtr 4	Qtr 1	Qtr 2	Qtr 3
95	Extend SESAME Library to Include advanced consti																															
96	Develop object oriented software interface for advan																															
97	Manufacturing processing effects																															
98	Evaluate as needed the effects of process changes																															
99	Develop new models incorporating process specific																															
100	Implementation in full-system, full-physics 3D simulation																															
101	Provide material models, SESAME++ software, and																															

Welding Modeling

Don Rabern, Engineering Sciences and Applications Division

Welds are found throughout nuclear weapons. They are used in high- and low-pressure applications and are subjected to different environments. The process of welding causes distortion of the base material with the potential of changing the fit of mating parts. In addition, the material properties of the base material are sometimes changed within the weld zone. Welds are traditional initiation sites of failures in metals, particularly failure due to fatigue. This is equally true in nuclear weapons and in commercial products. The problems faced in welding have much in common with problems in heat distortion and casting. Therefore, the Welding, Heat Distortion, and Casting initiatives have much in common.

Introduction

The welding roadmap describes technologies and research required to develop a capability to simulate, predict, and assess distortion, weld integrity, and residual stresses in welded joints in nuclear weapon components. Developing the constitutive models and simulation capabilities will enable analysts to predict distortions and stresses caused by welding and to assess the integrity of the weld under mechanical and thermal insult. These predictions can be used as initial conditions to assess a weapon's Stockpile-to-Target-Sequence performance, its reliability after aging, and its performance in accident scenarios. The roadmap is broken into several interdependent areas; each area is discussed briefly below.

Assess the Current State of the Art

Before developing new technologies for the program, we will assess the current state of the art in welding simulation, heat distortion, and phase change. Existing models will be used to assess designs now in the stockpile and simplified tests that are in the literature. Much of the work associated with the Technology Transfer Initiative CRADA (LA9210043-001), "Heat Distortion of Gears," can be applied to modeling welds, especially that part of the project dealing with phase change and residual stresses.

Simulate Residual Stress Due to Assembly

Early in the program we will use existing computational means to simulate a weapon's residual stress state. This will be done to determine the stress state due to assembly and welding. We will numerically simulate a pit and weldment assembly to determine changes in geometry during heating and cooling and to determine the residual

stress, strain, and displacement in the system. This will enable us to apply information and technology from the heat distortion project to weapons component welding. As a benchmark for simulation tools, we will begin an experimental program to measure residual stresses at some location, and we will assess the thermal environment during storage. We will then correlate the residual stress data and thermal data to gain some insight into component aging. We suspect that pits with residual stress will probably age differently than stress-free pits.

Incorporate Phase Change Issues

During welding, a phase change occurs in the parent and welding materials as they heat and melt and then cool and solidify. During the process, the properties of both materials also may change as may the failure modes. We will develop a capability to predict the phase change, material response, and material performance following thermal insult during fabrication. This constitutive model also will have to predict changes in mechanical properties in a variety of weapon materials.

Testing

One cannot perform a credible analysis without controlled experiments against which to benchmark developmental code performance. Consequently, we will run simplified welding experiments to verify the constitutive laws we develop. We will run a variety of experiments as well as mechanical tests to determine properties of pre- and post-welded materials. As part of this effort, metallurgical evaluations of the specimens will be done to assess grain structures to support future efforts in micromechanical modeling. After experiments and evaluations are completed the experiment data will be recast into theory suitable for constitutive model development.

Thermal/Mechanical Coupling Modeling

We will assess the gains and advantages of coupled thermomechanical modeling over more conventional methods. We speculate that predictive simulations of welding processes will require a fully coupled approach. We will determine the need for, and if required, we will develop advanced fully coupled simulation methodologies. These simulations will concentrate on the benchmarked experiments on pits and CSAs discussed above and in later sections. As the technology matures we will model the weld pool and the material buildup and solidification during the welding process.

Inverse Method Modeling

Current approaches take the initial conditions into account and simulate the process, heat distortion, and material mechanical behavior. In the inverse method, we start with the heat distortion and residual stresses and determine the initial conditions required to achieve that state. The inverse method will enable analysts to specify the stress state and geometry they wish to achieve after assembly and welding and determine the welding process and thermal environment needed to achieve that end state. Developing this method will greatly enhance our ability to control manufacturing processes to ensure efficiency of manufacturing and reliability of product.

Micromechanical Modeling

The next order of simulation will include micromechanical behavior in the constitutive relationships; current methods only include macromechanical properties. Future methods also will have to consider grain boundaries, slip fields, flaws, and local damage to adequately assess local behavior at high strain rates, large thermal gradients, melting, and solidification. The payoff will be tailored properties in the weld zone, predictive modeling techniques to address manufacturing processes, and reliability in joining technologies. We plan to develop these micromechanical models and use them against the benchmarked experiments on weapon components suggested above and in later sections. Micromechanical modeling will require supercomputers and tailored architectures, including massively parallel computer architectures.

Table VII: Industrial Partnerships Investigating Welding Modeling

Title or Topic	Company	LANL Contact	Type
Directed Light Fabrication	3M	Gary Lewis, MST-6	CRADA AMIP
Super-Plastic Forming	Flameco—Barnes, Jet Die—Barnes	Marty Piltch, MST-6	CRADA
Heat Treatment Gear Distortion	NCMS	Terry Lowe, MST-5	CRADA
Selective Laser Sintering ¹	DTM	Pete Smith, ESA-WMA	AMIP
Ultra-Narrow Gap Laser Welding of BeAl Alloys	OptiCAD Corp.	Milewski, MST-6	AMIP
¹ Related, deals with same issues in plastics CRADA—Cooperative Research and Development Agreement AMIP—Advanced Manufacturing Industrial Partnership

Nondestructive Testing and Evaluation Roadmap

Committee: Nondestructive Test and Evaluation Team, Engineering Sciences and Applications Division, Measurement Technology Group

Scope

This roadmap must be a living document. The directions for capability development represent the combined opinions of the Nondestructive Test and Evaluation (NDT&E) team in September 1995. As time passes, priorities change and technology evolves. Accordingly, to maintain relevance, this roadmap must be revised annually.

This document presents the following:

- background on the Advanced Design and Production Technologies (ADaPT) Initiative and Advanced Manufacturing Science and Technology (AMST) project,
- background on NDT&E at Los Alamos,
- the current status of the NDT&E capability,
- current NDT&E research and development projects,
- the projected future status of NDT&E capabilities (to 2000), and
- a roadmap for getting from where we are now to the projected future.

Background on ADaPT and AMST

The ADaPT Initiative's goal is the identification and demonstration of agile, flexible, and environmentally acceptable technologies needed to produce nuclear weapons in quantities ranging from units per year to 100 or 200 units per year. This new production complex will incorporate state-of-the-art design, materials processing, manufacturing, and quality assurance technology. Here, "production" includes surveillance as weapons age, requalification, full and partial rebuild, and performance prediction.

The AMST project's strategy is to align the Industrial Partnership Office's research and development projects with ADaPT.

NDT&E technologies cut across the entire ADaPT program: surveillance, materials characterization, process development/qualification, and quality assurance. NDT&E will play a vital role in any final ADaPT configuration.

NDT&E Background

The NDT&E team resides within the Laboratory's Engineering Sciences and Applications Division, Measurement Technology Group (ESA-MT). The other teams in ESA-MT—Environmental Testing, Robotics, and Systems and Sensors—contribute to ESA-MT's NDT&E capabilities in many ways. Several of the projects in this roadmap will require participation and even leadership from these other teams.

NDT&E supports Laboratory missions through the application of its techniques in support of internal Lab programs and projects undertaken for outside customers. Also, NDT&E engages in research and development that enhances our ability to support Laboratory missions.

As demonstrated by the following list of selected NDT&E-supported programs, NDT&E is a vital player in programs cutting across the Laboratory's core, industrial partnership, and conventional defense missions.

Science Based Stockpile Stewardship

- Surveillance diagnostics
- Accident response group (ARG)
- Fire resistance pit development
- Advanced materials and process development
- Dynamic test diagnostics
- High explosives and detonator inspection
- Pit rebuild program
- Detection and characterization of aging effects
- Component replacement and certification for reuse

Non- and Counter-proliferation

- Nuclear Emergency Search Team (NEST) diagnostics
- Chemical weapon treaty verification
- Assistance to Former Soviet Union

Environmental Stewardship

- Waste container inspection
- Assistance to Hanford and Rocky Flats

Conventional Defense

- Dynamic test diagnostics (high speed imaging)

Industrial Partnerships

- Automotive research and development (various applications)
- Radiography image detector testing

Current Status

NDT&E currently maintains twelve inspection technique groupings. Most of these techniques use portable instrumentation; thus, we can perform inspections at our customer's location.

- Radiography (film, real-time, microfocus, high-energy, low-energy, digital)
- Ultrasonic inspection
- Acoustic resonance spectroscopy (ARS)
- Eddy current inspection
- Video holography

- High-speed imaging (flash x-ray, high-speed video, high-speed x-ray video, cineradiography)
- Passive infrared imaging
- Fiberscopic inspection
- Dye penetrant inspection
- Magnetic particle inspection
- X-ray fluorescence
- Acoustic emission inspection

Current R&D

NDT&E is conducting funded R&D projects in:

- 450 kilovolt computed tomography system
- Digital radiography
- Digital image enhancement
- Video holography applications
- Integrated inspection station development, and
- Acoustic Resonance Spectroscopy

These projects are discussed in the Future Directions and Roadmap sections. We expect that our progress in these on-going R&D projects will lead to near-term applications of these techniques to new inspection problems.

NDT&E Future Directions

Development of four thrust areas is critical for the future of Los Alamos NDT&E: Integration of Technologies, NDT&E Digital Data Architecture, Enhanced Inspection Methods, and Inverse Methods. These thrust areas are described briefly next, followed by brief descriptions of additional capabilities that must be developed and modernization efforts that must be pursued in order to accomplish the thrust area goals.

Integration of Technologies. Combines existing technologies to create new technology.

- a *Designed or Concurrent Nondestructive Testing (NDT).* By integrating computer-aided design (CAD) and rapid prototyping with NDT simulation software, this project will integrate NDT&E into the design process and give us the capability to evaluate NDT techniques for a given part. Given a part's design file, the NDT engineer could seed flaws into critical areas of the part. The file then would be fed to various NDT simulations such as radiography, ultrasonic inspection, and eddy current inspection. Such simulations would save time by allowing the engineer to evaluate the feasibility of an inspection method before a part is made. The seeded file also could be input to a rapid prototyping system to make test parts, which could be inspected in lieu of the real part.
- b *Sensor Positioning.* Robotics can be used to drive sensors such as ultrasonic and eddy current transducers over a complex part contour by using CAD files of the part or by "teaching" the robot the motions required. Robotic positioning of x-ray sources, detectors, and/or parts under inspection would be beneficial to creating optimal radiographs.

NDT&E Digital Data Architecture. At the present time, much of the NDT&E data that we produce is digital in nature. Digital data is convenient for visualization. Also, some customers for film radiography for weapon surveillance are asking that we digitize radiographic film images for reporting and storage in their databases. While it is improbable that *all* our data will be digital, we can expect the fraction that is digital in nature to increase steadily. Given this trend, it is vital that we implement an NDT&E Digital Data Architecture that will satisfy our digital data processing, imaging, storage, and reporting requirements today, while providing growth potential for tomorrow's needs.

The digital data revolution does more than provide a storage and processing medium. It directs us towards new techniques such as data fusion that promise to create new NDT&E information from the synergistic combination of multimodal inspection data. The Sunrise TeleMed Project is developing a distributed database system for multimedia data that might be suitable for the NDT&E Digital Data Architecture. Using a distributed database architecture would give us the means to avoid the bottleneck that could result from collecting data onto a single, central server. TeleMed allows the data components to be owned and managed at the source, but provides, simultaneously, a unified view of the data between organizations. The TeleMed concept also may provide secure access to NDT&E data by weapon program personnel both inside and outside Los Alamos.

- a NDT&E Digital Data Architecture Implementation.* The architecture must be designed and adopted. The required software must be written. Our workstations must then be networked together to provide secure utilization of the data architecture.
- b Data Fusion.* Combines data (e.g., images and signal traces) to more completely describe a part's inspection data and to have all data available from one source. The data would be stored in "patient files" similar to hospital records. The data then could be fused in a number of ways to combine the inspection results from a number of complementary NDT methods; for example, radiography and ultrasonic inspection, x-radiography and neutron radiography, and ultrasonic inspection and eddy current inspection. Other methods that can be combined are computed tomography, infrared imaging, dye penetration, magnetic particle techniques, videography, and photography. Digital video would be used to store and play back dynamic data such as real-time radiography, high-speed video, and infrared video.
- c Enhanced Image Processing.* The NDT&E team currently has work under way to develop 3-D image information from our ultrasonic inspection and eddy current data. This work is crucial to our efforts to bring ultrasonic inspection and eddy current to the high level of acceptance that radiography has long enjoyed.

Enhanced Inspection Methods. There are several NDT&E techniques that we want to add to our tool kit to enable better, faster, and cheaper inspections for production, surveillance, and stockpile stewardship.

- a Integrated Inspection Station.* The Integrated Inspection Station is a computer controlled, "smart" robotic station that conducts NDT&E inspection using any of several techniques. For example, ultrasonic inspection, acoustic resonance spectroscopy, eddy current inspection, SQUID, and infrared inspection of an object could be done with a single station. The station's computer controls the inspection and records the data from each inspection modality. The Integrated Inspection Station maximizes worker productivity and minimizes radiation exposure when inspecting radioactive parts.
- b Embedded Sensors.* Sensor packages, which can be quite small, can be embedded into weapon systems to enable data readout without disassembly. Using ultrasonic inspection sensors to determine aging effects on weapon materials is possible with minimal impact to weapon packages. In the simplest implementation, power and data lines would be connected directly to the sensor. If a direct connection is not possible, ESA-MT has developed technology for active and passive radio-frequency telemetry.
- c 450 kilovolt Computed Tomography (CT) System.* We recently received a new 450 kilovolt x-ray source for our CT system. This new source is the key component for moving the CT system to a fully operational mode by January 1996. This system can image objects 0.25-meter in diameter by 0.5-meter high. Research and development in FY96 will be directed towards improving our density and spatial resolution to 0.25% and 0.5-millimeter respectively.
- d Whole Weapon System Inspection.* It may be possible to gather valuable information about the condition of a weapon system without disassembly. 3-D inspection techniques, such as CT fused with data from other NDT methods, could give useful information on the condition of a system. The goal would be to develop predictive methods that would indicate when aging effects had degraded a weapon system's yield, reliability, or safety.
- e NDT/Destructive Evaluation Correlation.* Correlating the results of whole weapon system NDT with destructive evaluation results would allow weapons engineers to calibrate whole-weapon-system NDT methods; correlate NDT indications with known defects/anomalies; define detection thresholds; and (possibly) eliminate some destructive tests. The Digital Data Architecture Project would provide the ideal methodology for data storage and correlation.
- f Inspection for Manufacturing.* We need technologies to analyze new production methods such as casting, machining, joining, bonding, and near-net-shape processes, and techniques for in-line manufacturing inspection. One example would be to couple improved high-speed video x-ray imaging (used to gather real-time data on metal flow during casting) with computed tomography (used to inspect for flaws in the casting). Another example is to mesh on-line optical inspection for dimensional tolerances (during machining) with on-line ultrasonic and eddy current inspection for flaws (of the finished workpiece). The first order goal would be to improve productivity by eliminating the requirement that parts be taken off-line for inspection. The long-term goal would be the development of a "smart" machining station that minimizes rejected parts by intelligently directing machining operations.

- g Enhanced Inspection Capabilities.* Advances in technology lead to completely new NDT&E techniques and increase the sensitivity and precision of existing techniques. Our NDT&E personnel must work to stay abreast of NDT&E developments so that we can procure or develop equipment and techniques that will extend our surveillance capabilities beyond the current state-of-the-art. Several examples are listed below in the section entitled "Added Capabilities to Support Thrust Areas."

Inverse Methods. This thrust covers research and development of methods to describe part characteristics (e.g., contour, thickness, flaw shapes, sizes, and locations) from NDT data. Clearly, the NDT&E Digital Data Architecture will play an important role in handling and processing the data for our inverse methods thrust.

- a CT to CAD to part.* Commercial software is available to convert 3-D CT data sets into CAD files. This software could be used to produce drawings of parts for which the original drawing are unavailable.
- b Acoustic resonance spectroscopy flaw detection and identification.* We propose combining CAD file data with acoustic resonance spectra from a part to identify flaw shapes, sizes, and locations; to determine part contours and dimensions; to characterize internal material properties; and to monitor aging effects.

Added Capabilities to Support Thrust Areas. In order to supply the inspections and methods proposed in the thrust area projects described above, we recommend that NDT&E acquire the following set of technological capabilities. Given the realities of limited budgets, evolving technology, and changing customer requirements, there will be additions to, and subtractions from, this list in the years ahead.

- a High-Energy Computed Tomography (HECT).* The microtron has replaced the betatron as NDT&E's primary high-energy radiography source. The initial microtron installation includes a positioning stage that is adequate for many CT applications and only the detector and control software are needed to bring HECT on-line. HECT will produce very precise 3-D images of dense weapon components and assemblies that require the penetrating power of very high-energy x-rays.
- b Microfocus Computed Tomography (MicroCT).* MicroCT will make fully 3-D images with very high spatial resolution (10 micrometers) on small (1-cubic-centimeter) parts. With the capability to detect cracks as small as 1 micrometer, MicroCT will be very valuable for analyzing material aging.
- c High-Energy Microfocus X-ray.* A high-energy (1 megavolt or greater) microfocus x-ray source would improve our spatial resolution by an order of magnitude for parts such as pits and CSAs. Our existing microfocus inspections are limited to light materials. The high-energy microfocus x-ray source would be ideal for microCT work as well.
- d Improved High-Speed Video X-Ray.* We will combine state-of-the-art x-ray image intensifiers with an advanced high-speed video system to produce a greatly

enhanced capability for high-speed, real-time radiography. The new capability will give better resolution and faster response. This capability will be helpful in developing advanced manufacturing processes such as metal casting. It will also reveal internal deformations that occur in crash or drop tests.

- e *Holography.* ESA-MT has the video holography capability to detect minute changes in surface properties due to deflection/stress. We are developing methods to apply this capability to stockpile surveillance tasks.
- f *Large, Multiaxis Integrated Inspection Platform.* We need to acquire a large capacity inspection platform that will allow us to inspect full-up weapon systems.
- g *Neutron Radiography using LANSCE.* We propose a facility at LANSCE to perform neutron radiography. With the shutdown of the Omega West reactor, NDT&E and the Laboratory lost its neutron radiography facility. LANSCE would be able to support thermal, cold, fast, and resonance neutron radiography. In addition, real-time neutron radiography could be performed.
- h *Digital Radiography (DR).* There are a variety of digital radiography methods available and under development. The promise of DR is the elimination of x-ray film as the primary means of displaying and storing x-ray images. DR eliminates time consuming chemical film processing and its waste generation, eliminates film archiving, and allows image processing for enhanced interpretation. Eliminating the film development time, makes it possible to view more images. More views plus digital image enhancement promises improved inspections at lower cost.
- i *Miniature High-Energy X-ray.* By miniaturizing high-energy x-ray sources, they become more portable and more easily shielded. This opens new avenues of application as well as makes the ARG/NEST mission and other existing portable high-energy radiography techniques easier.
- j *NDT Simulation Software.* We have tested early versions of radiography, ultrasonic inspection, and eddy-current computer simulation software. This software is being developed at Iowa State University. Presently, these simulations are somewhat simplistic, but they are being upgraded we will acquire the upgraded versions when their capabilities meet our needs.
- k *Ultrasonic Velocity Station.* An ultrasonic velocity measurement station will measure material properties such as sound velocity in aged high explosives.
- l *Miniature Pulsed Neutron Source and Detector.* We propose to use a portable system for neutron backscatter inspections, g-activation thickness measurements, and stress measurements.

Modernization: Maintaining State-of-the-Art. To maintain our existing capabilities at state-of-the-art level continuous effort is required.

- a Modernize X-Ray Bays.* Many of our x-ray facilities are becoming dated. To maintain cost effective operations in the future we need to upgrade the support facilities. Critical needs are for remote precision-positioning and alignment systems, remote monitoring and dosimetry systems, and state-of-the-art real-time radiography detectors. Many of our x-ray generators are many years old and should be replaced within a few years. These upgrades are essential if NDT&E is to continue to satisfy the Laboratory's needs for radiographic inspections.

Table VIII: Industrial Partnerships Investigating NDT&E

Title or Topic	Company	LANL Contact	Type
Designed or Concurrent NDT	Automotive & aerospace industries	Dave Stupin, ESA-MT	1
Data Fusion	Automotive, aerospace, & medical device industries	Dave Stupin, ESA-MT	1
Enhanced Image Processing	Automotive & aerospace industries	D. Alicia Vickoe, ESA-MT	1
3-D CT to CAD	Automotive, aerospace, & medical device industries	Dave Stupin & D. Alicia Vickoe, ESA-MT	1
High-Energy CT	Scientific Measurement Systems; Bio Imaging Research; Aracor	D. Alicia Vickoe, ESA-MT	1
Microfocus CT (MicroCT)	Scientific Measurement Systems; Bio Imaging Research	Dave Stupin, ESA-MT	1
High-Energy Microfocus X-Ray	L&W Research; Northstar; Schonberg Research	David Fry, ESA-MT	supplier
Improved High-Speed Video X-Ray	Kodak; Ford Motor Co.; Eaton Industries	Lawrence Bryant; ESA-MT	supplier 1 CRADA
Neutron Radiography	Industrial Quality; NRE	Thomas Claytor; ESA-MT	1
Digital Radiography	XEROX; US Technologies; Industrial Quality; Molecular Dynamics	Dave Stupin, Karl Mueller, & David Fry; ESA-MT	1
Miniature High-Energy X-Ray	L&W Research; Schonberg Research	David Fry; ESA-MT	supplier
Superconducting Quantum Interference Device (SQUID)	Conductus; UTEX	Thomas Claytor; ESA-MT	supplier AMIP
¹ Potential partnerships being investigated CRADA—Cooperative Research and Development Agreement AMIP—Advanced Manufacturing Industrial Partnership

Project: NDT&E Roadmap
Date: 4/26/96

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Polymer Aging and Lifetime Prediction Roadmap

Committee: Doug Hemphill and Richard Browning, Engineering Science and Applications Division; Phil Howe, Dynamic Experimentation Division; Elliott Douglas, Materials Science and Technology Division

The aging of plastics and high explosives is probably the limiting factor in determining the maximum stockpile life before a weapon must be rebuilt. With more than 60 different types of polymeric materials and over 200 different polymeric-based components in stockpile weapons systems, a wide variety of mechanisms might cause a particular system to fail. Several studies currently are underway or being planned to characterize the aging of polymeric and polymeric-based components. The purpose of this roadmap is

1. to begin to bring the studies mentioned above together,
2. to leverage technical resources within the Laboratory and DOE,
3. to maximize technical effectiveness and probability of success,
4. to identify areas where further study is required, and
5. to identify where collaboration with industrial partners is desirable and could help achieve the Laboratory's goal of extending the lifetime of stockpiled weapons.

Current Status

Several organizations at Los Alamos long have an interest in polymeric aging. The Engineering Sciences and Applications Division, Weapon Material Applications Group (ESA-WMA) developed many of the polymeric components in the nuclear weapons stockpile and has an ongoing program in evaluating the mechanical response of aging polymeric and polymeric-based composite components. The Dynamic Experimentation Division's Explosive Technology Group (DX-16) and ESA have extensive experience in evaluating compatibility of various components and are active in traditional and enhanced surveillance to further evaluate polymeric weapons' components returned from the field.

DX-16 is establishing a nonintrusive, ultrasonic high-explosive (HE) evaluation program for charges returned from the stockpile with the intent of monitoring for polymeric binder degradation. In addition, DX Division has done extensive development and characterization of binders for HE components in the stockpile and is heading up an effort to further characterize degradation of Estane 5307 in certain stockpile systems. Aging studies in the Material Sciences & Technology Division's Polymers and Coatings Group (MST-7) have targeted mechanical properties of glassy polymers and composites and specific chain scission mechanisms in selected polymers. ESA-EA (Engineering Analysis Group) has been involved with modeling long-term viscoelastic response for various polymeric-based components. In addition, molecular dynamic modeling

capabilities in the Theoretical (T) Division and advanced spectroscopic techniques in the Chemical Sciences and Technology (CST) Division are being used to develop mechanics-based models for aging phenomena.

Other organizations in the DOE complex including Allied Signal/ Kansas City Plant; Sandia National Laboratories; and Lockheed Martin (Y-12 Plant) are working with us to characterize aging effects in polymeric and polymeric-based composite materials. Efforts also are underway with the United Kingdom under the Joint Working Group (JOWOG) structure to address aging issues in weapons stockpile components. This brief overview is not complete but gives an idea of the wide scope of existing or planned efforts.

Information available from outside the DOE complex is severely limited. A review of the American Society for Testing and Materials standards illustrates the enormous neglect of polymer aging. There are only 68 test methods or standard practices that address aging. Of these standards, less than one-half have been approved by the agencies of the Defense Department. Many of these tests address the material's weatherability as determined through accelerated testing methods. We also identified five classes of materials that are covered by additional test methods: adhesives and binders, composites, foams, rubbers, and plastics. Nearly all of these tests are intended for measuring material properties for qualification of use, not for evaluating the mechanistic causes and results of aging.

Funding sources at Los Alamos include funds supporting technology development in weapons surveillance, advanced surveillance, weapons materials, and weapons surety; formal programs such as the Advanced Manufacturing Industrial Partnership, Advanced Design and Production Technology, Laboratory Research and Development-Competency Development, and Institutional Program Development programs; various Department of Defense programs, and funds-in from industry.

Future Requirements

A coordinated polymeric aging program should ultimately result in the ability to predict the behavior of polymeric materials and components over an extended lifetime in a variety of environments. In the nuclear weapons arena, this ability will enable weaponeers to confidently certify nuclear weapons in the stockpile. To accomplish this, molecular, component and system modeling coupled with actual fabrication and testing (engineering and hydro/nuclear/hydronuclear) of "aged" systems will need to be done. Considering the scope of this effort, it is likely that a series of functional system tests will be done, with realistically aged components being included in the tests as we better understand aging phenomena. For purposes of a five-year effort, select critical components would be targeted. Further efforts would then build on this standardized methodology.

Roadmap

The following narrative expands on the flowchart given in Figure 2.

All critical components will be evaluated for effects due to aging. Problem areas that have been identified include degrading HE binders, compressed cushions and pads, and migrating plasticizers. This list will be modified as more surveillance and enhanced surveillance data becomes available and select components will be targeted for aging characterization.

Studies of polymer aging historically have used some form of accelerated aging, usually heat. Samples subjected to accelerated aging then were tested to evaluate aging effects. While this method has merit, it introduces additional aging or other change mechanisms so that the end results are not reliable for predictive use. A comprehensive aging methodology needs to be developed that will allow us to confidently predict material changes in terms of mechanical properties, morphology, chemical species, and migration.

What is lacking at Los Alamos, in industry, and in academia is a knowledge of aging mechanisms that weapons designers can use to predict the effects of aging on properties of interest. These mechanisms are diverse and, no doubt, largely dependent on the type of polymer and conditions of exposure. Without this knowledge, any predictive technique is subject to considerable uncertainty. A large part of any polymer aging program should be directed toward establishing aging mechanisms, either through verifiable molecular dynamic models and/or traditional Edisonian techniques.

Several issues of concern have been identified in the aging arena. A predictive capability based on classical viscoelastic theory, i.e., time/temperature superposition or classical spring/dashpot models, needs to be developed, particularly for load-bearing plastic or composite components. Other issues include migration of species and its effects on various components and degradation through hydrolysis, radiation, or spontaneous scission mechanisms. Weapons scientists in the United Kingdom are particularly concerned with lot-to-lot variations in materials and how that variation affects aging mechanisms. These, and other issues, need to be resolved to effectively predict aged material behavior. Industrial interest in resolving these types of problems is thought to be considerable. In fact, initial contacts by the MST Division with plastics producers has indicated a high degree of interest in working cooperatively in addressing these issues.

Because of the wide variety of polymeric materials in nuclear weapons, system modeling of hydrodynamic and engineering responses is needed to help identify which components are most critical to the performance of aged weapons. Several critical issues already have been identified through upfront design requirements or found through surveillance activities. This list is by no means complete and further issues will, no doubt,

be identified through our enhanced surveillance activities. In addition, in order to perform component, subsystem, and full-scale weapon tests a capability to synthesize "aged" polymeric materials and to fabricate "aged" components will need to be developed. Without this capability to verify models and perform final qualification tests, the entire effort will be interesting, but of limited use to the nuclear weapon design community.

Resources

Throughout the Laboratory, the expertise exists to address the issues surrounding aging of polymeric materials in stockpiled weapons systems. ESA Division has capabilities to fabricate and evaluate nearly all polymeric-based components and systems and the modeling capability to develop aged component design parameters. DX Division has several programs underway to evaluate binder degradation in high explosives. They currently oversee many stockpile and stockpile return activities and have developed an extensive knowledge base of weapons compatibility issues. MST Division's polymer science and synthesis capabilities provide further expertise and characterization capability. They actively are studying binder degradation mechanisms and have developed a strong industrial interaction base. T and CST division chemists and physicists are evaluating aging mechanisms through use of molecular dynamic modeling and advanced spectroscopic and other characterization techniques.

A critical strategy in developing a successful program is leveraging off other organizations to accomplish stated goals. In the polymer aging area, these organizations include the rest of the DOE complex, nuclear weapons agencies in the United Kingdom, and industrial partners. The initial ties have been forged, primarily between ESA and DX divisions and the weapons community and between MST Division and industrial collaborators. We must maintain and enhance these ties as this effort matures. JOWOG and other technical exchange groups within the DOE are being guided toward polymeric aging issues.

US industry stands to gain the ability to control and predict the aging of their products, which will result in improved product quality and enhanced competitiveness. Because of this potential benefit, we anticipate that collaborations with both industrial materials suppliers and finished product manufacturers will result from this program. In fact, one supplier of weapons materials has already expressed interest in our studies of polymer aging.

Figure 1. A Proposed Roadmap for Evaluating and Modeling the Effects of Aging on Polymeric Materials

Project: Polymer Aging
Date: 4/26/96

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