Enhanced Surveillance Program

FY1998 Accomplishments

AlliedSignal/Federal Manufacturing & Technologies

Lawrence Livermore National Laboratory

Los Alamos National Laboratory

Mason & Hanger Corporation

Oak Ridge y-12 Plant

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Abstract

This report highlights the accomplishments of the Enhanced Surveillance Program (ESP), the highest-priority research and development effort in stockpile management today. This is volume one of eleven, the unclassified summary of selected program highlights. These highlights fall into the following focus areas: pits, high explosives, organics, dynamics, diagnostics, systems, secondaries, materials-aging models, non-nuclear components, and routine surveillance testing system upgrades. Principal investigators from around the DOE complex contributed to this report.

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Acronyms and Terms

ARIES	Advanced Recovery and Integrated Extraction System		MTS	mechanical threshold stress
			MW	molecular weight
AS/FM&T	AlliedSignal/Federal Manufacturing & Technologies		NDE	nondestructive evaluation
			NDIGA	nondestructive infrared gas analysis
Cap	capacitance		NEP	nuclear explosive package
CCD	charge-coupled-device		NWC	Nuclear Weapons Complex
CDU	capacitive discharge unit		OUAL	Ohio University Accelerator Laboratory
CS	compression set		PBXs	plastic bonded high explosives
CSR	compression stress-relaxation		PD	partial discharge
CT	compact tension		PDA	partial discharge analysis
CT	computed tomography		PDF	pair-distribution function
CVA	Canonical variate analysis		PDF	portable document format
∞D	Bayesian inference engine		PDM	product data management
DADS	dynamic analysis and design system		PETN	pentaerythritol tetranitrate
DARHT	Dual-Axis Radiographic Hydro-Test		PLR	percent load retention
DF	dissipation factor		POC	points of contact
DLO	diffusion-limited oxidation		PSCL	Pit Surface Characterization Laboratory
dpa	displacements per atom		PTW	Preston-Tonks-Wallace
DR	dual revalidation		Pu	plutonium
DRIFT	diffuse reflectance infrared fourier transform		QAM	quadrature amplitude modulation
			QET	quality evaluation tracking
DTM	distributed telemetry		R&D	Research and development
EFI	enhanced-fidelity instrument		rf	radio frequency
EOS	equation of state		RGA	residual gas analyzer
EPDM	ethylene-propylene rubber		RTGs	radioisotope thermoelectric generators
ESD	environmental sensing device		RUS	Resonant ultrasound spectroscopy
ESP	Enhanced Surveillance Program		SCE	subcritical experiment
EXAFS	extended x-ray adsorption spectroscopy		SCG	subcritical crack growth
fcc	face-centered cubic		SFE	slim-loop ferroelectric
Ga	gallium		SIG	Surveillance Information Group
GC/MS	gas chromatograph/mass spectrometer		SNL	Sandia National Laboratory
GPC	gel permeation chromatography		SNM	special nuclear materials
GWIS	Global Weapons Information System		SNMS	sputtered neutrals mass spectroscopy
HEs	high explosive(s)		SPAM	Signal Processing And Modeling
HEAF	High Explosives Application Facility		SPME	solid-phase microextraction
HERT	high explosive radio telemetry		SQUID	superconducting quantum interference device
IC	integrated circuit			
INuMM	integrated nuclear materials monitoring		SRTC	Savannah River Technology Center
JTAs	joint test assemblies		SS/DMS	Stockpile Surveillance/Data Management System
KCP	Kansas City Plant			
LANL	Los Alamos National Laboratory		STM	scanning tunneling microscopy
LDA	Local density approximation		STS	Stockpile-to-target sequence
LDMF	laser-driven miniflyer		VOD	velocity-of-detonation
LINAC	linear accelerator		WR	war reserve
LLNL	Lawrence Livermore National Laboratory		XPS	photoelectron spectroscopy
LTTD	low-temperature thermal decomposition		XPS	x-ray photoelectron spectroscopy
MC	Military characteristics		XSR	x-ray synchrotron radiation

Foreword

One Mission. One Program. One Stockpile.

It is our distinct pleasure to present the accomplishments of the Enhanced Surveillance Program. The Enhanced Surveillance Program is the highest-priority research and development (R&D) effort in stockpile management today. The program provides an understanding of future weapon degradation, essential to maintaining the stockpile indefinitely in the absence of underground nuclear tests. We want to share with you some of its most important characteristics.

1. There is one Enhanced Surveillance Program that spans the entire nuclear weapons complex. Teams of scientists and engineers from all Defense Programs laboratories and plants conduct research in this program. The progress to date and the program's future success relies on this collaboration, requiring the combination of skills and facilities spanning the weapons complex.

2. This is a goal-oriented program. As you review the progress over the last year, you will see that we are systematically addressing specific stockpile concerns through achievement of the program's predefined objectives. The program's documented milestones and deliverables drive and gauge our progress. The program balances the delivery of many low-risk, near-term tools with a few higher-risk tasks potentially offering a big payoff for the stockpile in the long term.

3. It is our intention that this be a genuine expansion of surveillance R&D. All organizations in the weapons complex have conducted surveillance R&D throughout their history. With this program, we are placing additional emphasis on improving our surveillance capability. The Enhanced Surveillance Program Plan acknowledges the ongoing R&D efforts and seeks to demonstrate how those actions support the achievement of enhanced surveillance R&D goals.

We are very pleased with this program's progress. We commend the many investigators for their outstanding contributions, as well as the members of the Enhanced Surveillance Steering Committee for building quality teams of performers. We are confident this program will continue to be executed with vigor and success.

Robin Staffin
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Defense Programs

Gene Ives
Deputy Assistant Secretary
for Military Application
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Defense Programs

Introduction

This Annual Report

You are reading one volume of the Enhanced Surveillance Program (ESP) FY1998 Accomplishments. The complete report of accomplishments consists of eleven volumes. Volume one includes an ESP overview and a summary of selected unclassified FY1998 program highlights. Volume one specifically targets a general audience, reflecting about half of the tasks conducted in FY1998 and emphasizing key program accomplishments and contributions.

The remaining volumes of the accomplishments report are classified, organized by program focus area and present in technical detail the progress achieved in each of the 96 program tasks in FY1998. Focus areas are as follows:
• Pits
• High Explosives
• Organics
• Dynamics
• Diagnostics
• Systems
• Secondaries
• Materials-Aging Models
• Non-nuclear Components
• Surveillance Testing Program Upgrades

ESP in Context

The only thing remaining constant in the Nuclear Weapons Program is its mission: to maintain a safe and reliable nuclear weapons stockpile.

In the past, that mission was accomplished on a large scale with growth. Stockpile systems were periodically replaced with newer and better versions, a robust design and production capacity supported both stockpile modernization and the rapid implementation of stockpile repairs, and confidence was assured with the certainty of an underground nuclear test.

Today, with the challenging constraints of producing no new nuclear weapons and conducting no underground nuclear tests, the mission is founded in science-based stockpile stewardship and management. Current plans require systems to remain in the stockpile indefinitely, and therefore, confidence in the readiness of the stockpile now includes an uncertainty driven principally by aging.

The Enhanced Surveillance Program (ESP) is central to the new strategy, focused on understanding and predicting the effects of aging and ultimately reducing uncertainty.

As you read this report, keep in mind that ESP contributions transcend stockpile management. The new materials and aging information gained from the ESP support much more than just predicting component failures and scheduling repairs. This information extends the knowledge base supporting component design, fabrication, certification, safety analysis, surveillance, and dismantlement. With this new knowledge, our confidence in all aspects of stockpile support can be firmly anchored to a broader and deeper scientific base, making the Enhanced Surveillance Program a key component of science-based stockpile stewardship and management.

Also, remember that the ESP is an important element of stockpile life extension. The Stockpile Life Extension Program, DOE's planning framework for proactive management of system maintenance activities, relies on ESP to provide the technical basis for component reuse decisions during refurbishment and to provide the diagnostics required to detect degradation of components before they fail.

The ESP has implemented a strategic vision, based on requirements and focused on the stockpile. The program exploits resources and capabilities across the nuclear weapons complex. We measure our progress against defined performance expectation as documented in the ESP Program Plan. This report is just one example of how ESP documents the delivery of results.

David V. Feather
Enhanced Surveillance Program Manager
Office of Defense Programs
U.S. Department of Energy

Overview

The objective of the ESP is to develop tools, techniques, and procedures to advance the capabilities of the Department of Energy (DOE) to measure, analyze, calculate, and predict the effect of aging on weapons materials, components, and systems and to determine if and/or when these effects will impact weapon reliability, safety, or performance. These tools, techniques, and procedures are elements of two major ESP deliverables: augmentation of the department's surveillance program with age-focused diagnostics and prediction of service lives of safety and reliability components.

The ESP is an essential element of the United States' strategy for efficiently maintaining a safe and reliable nuclear deterrent. Over the last decade, the nuclear weapons program has changed in two significant ways: a policy of extending the lifetime of existing stockpile weapons (hence, no new weapon production) has been adopted, and the nuclear weapons complex has been streamlined, drastically reducing both capacity and capability. The weapons complex now relies on careful planning and scheduling to conduct the required component production, surveillance, and maintenance with diminished resources.

The tools provided by the ESP alleviate the uncertainty of the future. The conclusions of the program serve to validate or dismiss concerns about weapons component failure and to identify previously unknown aging impacts. With early identification of age-related failure mechanisms (through predictive models and age-focused diagnostics) the program enables efficient strategic planning, minimizing the demands for infrastructure and other resources and ultimately reducing the threat to national security. Finally, investments in ESP are recovered when conclusions indicate components or materials do not require replacement.

The activities under this program are carried out at the DOE weapon production plants and design laboratories: the Kansas City Plant (KC), Y-12 Plant (termed "OR" for Oak Ridge), Savannah River Site (SR), Pantex Plant (PX), Los Alamos National Laboratory (LA), Lawrence Livermore National Laboratory (LL), and Sandia National Laboratories (SN). There is strong coordination and teaming among the laboratories and production sites for the planning, selection, and conduct of research projects for this program.

Enhanced Surveillance Program Funding Profile

FY96	FY97	FY98	FY99	FY00
$28.8M	$75M	$60M	$68M	$84.5M

The ESP represents a bridge between the Defense Programs Office's current core R&D and stockpile surveillance programs and provides the necessary predictive models and age-focused diagnostics required to anticipate weapon refurbishment. The program is a necessary precursor of Stockpile Life Extension Program planning. The materials and component service-life predictive capabilities resulting from ESP are focused on anticipating stockpile defects, allowing timely remedial action and refurbishment planning.

The ESP sponsors applied research and development related to the effects of material and component aging. The program leverages work conducted through core R&D and other initiatives such as Advanced Design and Production Technologies and the Advanced Strategic Computing Initiative program. Examples of capabilities ESP is enabling include new age-focused system, component and materials performance tests, new flight test configurations, material characterization and modeling, nondestructive evaluation, and modeling of the weapon aging process to the extent practicable.

Program Tactics

During the conception phase of the ESP, a committee composed of nuclear weapon design and production subject matter experts reviewed each major subsystem within a generic weapon system (i.e. primaries, secondaries, and non-nuclear components) to determine where surveillance capabilities and technologies required enhancement. This assessment is validated annually. Within the three focus areas (primaries, secondaries, and non-nuclear components), the results of the assessment fell into six categories.

- Material characterization and surveillance
- Materials-aging model development
- Component performance models
- System performance models
- Component surveillance and diagnostics
- Enhanced system testing

The figure depicts the DOE's surveillance program. Enhanced surveillance provides age-focused diagnostics and age-aware models as an augmentation to traditional surveillance testing and performance prediction.

Those areas covered by the traditional surveillance program are shown on the right side of the diagram. The ESP is shown on the left of the dashed line. The ESP, as integrated with the traditional surveillance program, forms a coherent approach toward the goal of maintaining a reliable and safe stockpile.

The ESP was constructed to be a short-term (5–7 year), rapidly evolving R&D effort directed by an ESP steering committee. The ESP Program Manager reviews and authorizes all projects. Less fruitful projects are terminated, and new advanced research concepts are added to the program through the steering committee review and authorization process. A program plan is published annually. Full-scale implementation of ESP technologies into the traditional surveillance program occurs when those technologies are demonstrated and determined essential.

There are many examples of the products the ESP delivers. These products range from performance forecasts on critical stockpile components and assemblies, the demonstrated early identification of life-limiting developments, to the identification of the key signatures of aging and the deployment of new surveillance and assessment tools. In summary, the program provides the technical basis for risk-management decision making.
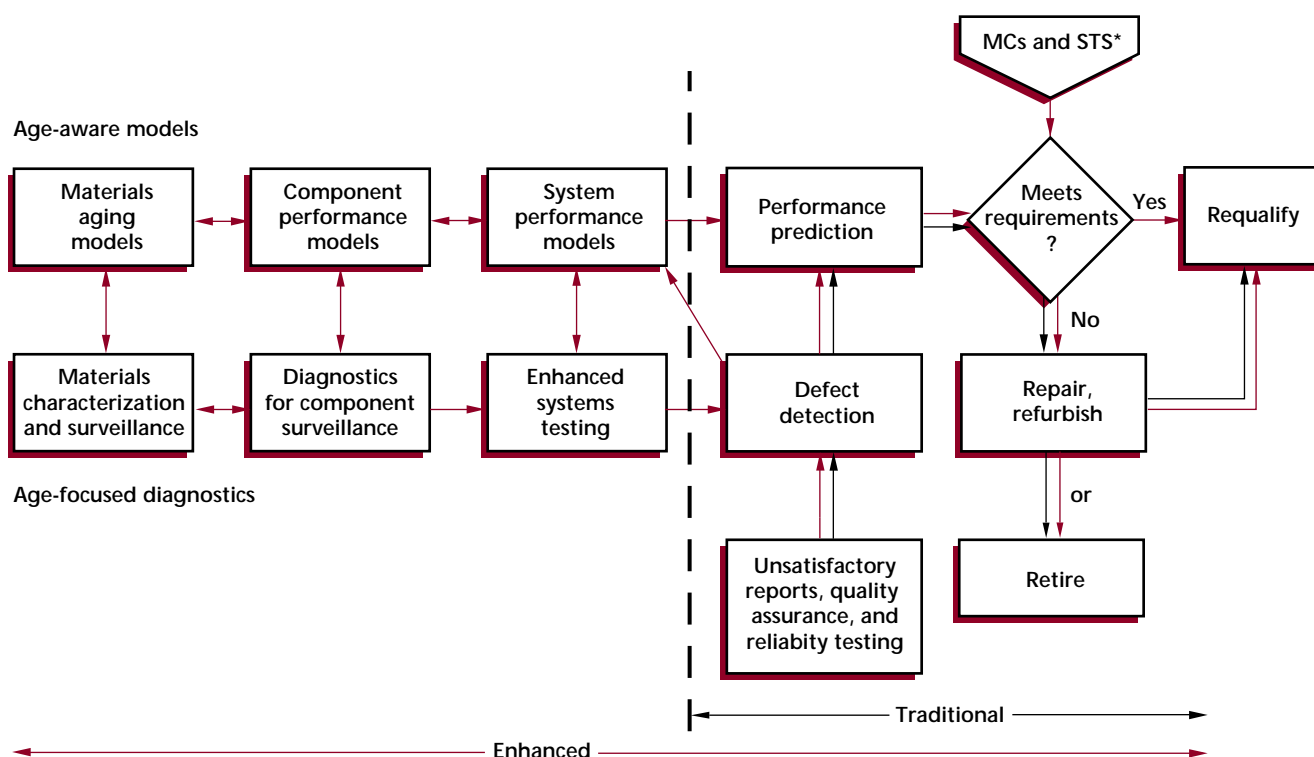
*Military characteristics (MCs) and stockpile-to-target sequence (STS)

Pits
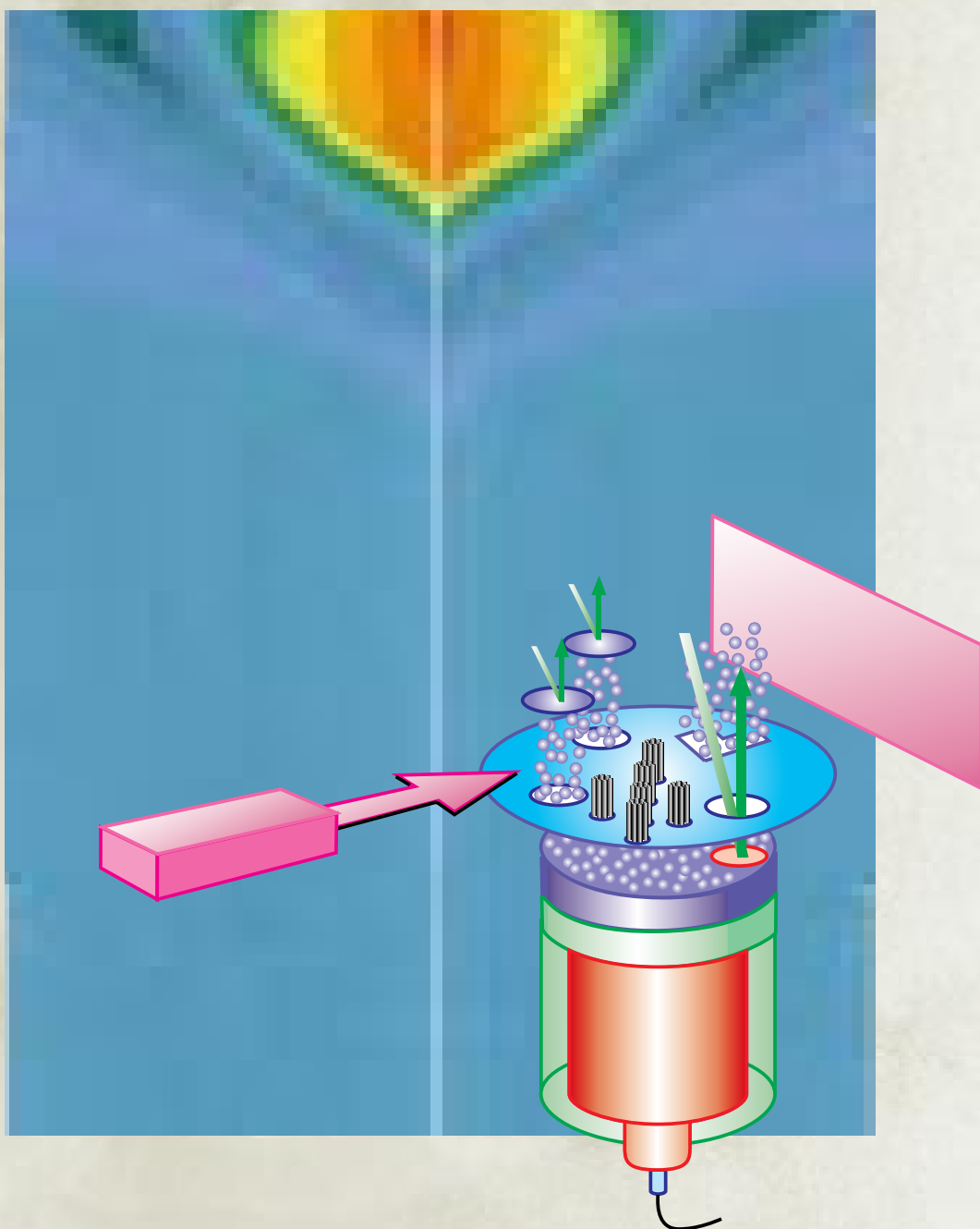
PITS

Focus Area

The Pit Focus Area assesses the effects of aging on the safety and reliability of pits. Tasks in this area include material studies, theoretical models, and system-level performance assessments. Material studies investigate the effects of aging on static and dynamic properties of pit materials in both engineering and nuclear applications. Physical measurements of material properties combined with experiments are used to assess effects on aspects of physics performance. New theoretical models provide a basic understanding of aging that will lead lifetime predictions for pits. System-level experiments are being conducted to assure the validity of predictions and the safety and reliability of the pits in the stockpile.

Analysis, prediction, and mitigation of aging effects in pits, specifically in plutonium, are key to enduring safety and reliability. Changes resulting from aging are expected to occur first in fundamental properties such as composition, crystal structure, and chemical potential. These changes may affect engineering and physics performance characteristics such as equation of state, spall and ejecta formation, strength, density, geometry, corrosion resistance, and nuclear reactivity. Aging mechanisms that cause these potential changes include the in-growth of decay products, uranium recoil damage and associated void formation, phase stability concerns, changes in surface chemistry, and a variety of environmental changes including thermal cycling. Development of advanced characterization tools to measure changes in these properties is essential. The resulting data analysis will expand our nuclear materials knowledge base and form the basis for computational models necessary for predictive assessment. New methods for evaluating the chemistry of external and internal pit surfaces are also an area of emphasis. These capabilities permit the collection of data on the potential reactions of other chemical species in the weapon environment.

Pertinent Tasks

LA09	The Miniflyer (Plutonium and Uranium): High-Strain-Rate Measurements of Pit Materials
LA11	Investigation of Aging in Pu Using ^{238}Pu-Enriched Metal
LA12	Dynamic Behavior of Plutonium and Uranium at Intermediate Strain Rates
LA29	Modeling Stability of Aged Pu
LA32	X-Ray Synchrotron Radiation Measurements of Residual Stress
LA34	Resonant Ultrasound Study of Pu Aging
LA40	Advanced Recovery and Integrated Extraction System (ARIES) Sampling and Analysis
LA41	Pu Microstructural and Surface Characterization
LA50	Pu Sample Preparation
LL01	Modeling of Void Formation and Other Aging Mechanisms
LL03	Experimental Studies of Ejecta and Debris
LL30	Positron Annihilation Study of Age-Induced Defect Structures
LL33	Accelerated Aging of Plutonium: A Joint study with Los Alamos National Laboratory
LL34	Pu Transmission Electron Microscopy
LL37	Gas Gun Experiments: Pu Spallation and Surface Dynamics
LL42	Sensitivity Analysis
PX01	Pit Characterization Laboratory

Deliverables

1. Measure and characterize the products and nature of corrosion processes occurring during weapon lifetimes.

2. Define the chemistry and stability of the gas phase and its relationship to corrosion kinetics.

3. Identify important aging phenomena (e.g., helium in-growth) and develop procedures to monitor and evaluate those changes.

4. Obtain stress-strain mechanical property data at intermediate- and high-strain rates on baseline weapons materials and stockpile-returned plutonium and uranium to understand the compressive deformation response of these materials as a function of aging.

5. Measure the x-ray absorption fine structure spectra, synchrotron radiation-based x-ray diffraction/scattering patterns, and neutron scattering patterns of baseline plutonium alloys, aged plutonium samples, and other plutonium. Prepare a ^{238}Pu-spiked plutonium alloy for accelerated aging experiments. Calibrate and compare the spiked alloy against known, aged samples. Accelerate age to extended lifetimes and measure key material properties to elucidate aging effects.

6. Develop models of plutonium metal aging process with the goal of predicting changes to key material properties. In conjunction with the Accelerated Strategic Computing Initiative and other programs, assess the impact of these changes on pit safety and performance with the final goal of determining useful pit lifetimes.

7. Use high-flux x-ray synchrotron radiation microdiffraction to nondestructively measure residual stress with micrometer-sized spatial resolutions within pit materials.

8. Measure elastic moduli in a broad temperature range for new and aged polycrystalline and single-crystal samples of plutonium, and correlate structural and mechanical properties with age.

9. Predict and measure directly the dimensional changes occurring in aged plutonium as a result of helium accumulation, radiation damage, and resultant void formation.

10. Determine the nature of irradiation-aging-induced defects (distribution of voids, vacancies, and other microstructural characteristics) in the microstructure of plutonium using positron annihilation spectroscopy defect analysis.

11. Experimentally assess effects of aging on ejecta, spall, and equation of state, and assess impacts on primary performance for stockpile weapons. Gather material property data from pits dismantled in the ARIES process in order to expand the age-correlated database of applied plutonium properties.

12. Instrumentation for direct examination of the external surface chemistry of the clad metal on pits.

13. Expanded monitoring program to provide real-time aging data on pits stored at Pantex.

Accelerated Aging of Plutonium

The Accelerated Aging of Plutonium program formally began in October 1997 by Livermore and Los Alamos national laboratories to develop the enrichment technique and to characterize aging behavior as a function of time in a manner that makes best use of the facilities and resources available at each laboratory. We have made steady progress addressing theoretical aging issues, devising plans for fabricating and testing the enriched material, and resolving plutonium facility issues.

Compared with ^{239}Pu, ^{238}Pu has a lifetime shorter by a factor of 280. Therefore, it is possible to increase the rate of self-irradiation damage and accelerate the aging processes. The premise is that by enriching ^{239}Pu with ^{238}Pu, the much faster decay from the ^{238}Pu will create damage in the plutonium at a much faster rate than would normally occur (half lives are 86.4 and 24,360 years for ^{238}Pu and ^{239}Pu, respectively). More importantly, we will be able to measure the properties of the plutonium both in the new condition and periodically as it ages. Once we know how aging manifests itself, we can look for similar behavior in aged stockpile material. By identifying and characterizing the changes (or lack of them), we will provide the information necessary to make recommendations for the future.

Specific tasks are to:
• Fabricate and characterize enriched material and specimens made from it.
• Design and construct storage equipment for accelerated aging of specimens.
• Design, develop, and procure equipment for experiments on aged specimens.
• Develop a database of fundamental parameters for analyzing experiments.
• Develop computational models to translate aging phenomena and effects from the enriched to the weapons-grade materials.

The measure of accelerations (shown in Figure 1) is defined as the number of years required to reach a radiation dose of 10 displacements per atom (dpa). Weapons-grade material will take 100 years to reach this dose, or about 10 years if 5% of ^{238}Pu is added. While it is possible to enrich the material even more, handling and storing the enriched material become limiting factors. All these considerations led to the selection of 5% enriched material.

We have selected experimental tests (see table) that are capable of measuring changes induced by aging, most of which are already in place at the laboratories. Approvals, processes, and equipment must be in place before we make the first batch of enriched material because aging of the enriched plutonium begins immediately. We expect to make the first batch in FY1999.

Radiation-induced void swelling occurs in a specific temperature window determined by dose rate and by vacancy diffusion. As the dose rate increases, the window shifts to higher temperatures. As a result, the specimens enriched with ^{238}Pu must be aged at an appropriately higher temperature. In order to evaluate this temperature shift, theoretical estimates had to be made on the diffusion coefficient for vacancy migration in delta-Pu because no measured value is available. The theoretical value for the activation energy for vacancy migration was found to be 0.69 eV. Using a well-established model for radiation-induced void growth, we calculated the temperature shift as a function of the dose rate or the enrichment (Figure 2). For the 5% enriched material, the temperature shift is 15°C, and this value was adopted for the design of the heater incubators used for aging the enriched specimens.

Accelerated aging of plutonium test program.

Test	Technique	Information
Analytical chemistry	Atomic absorption, emission spectroscopy, radiochemistry	Impurity content, alloying elements, ingrowth of decay products
Density	Archimedes immersion	Swelling, phase composition
Dilatometry	Laser triangulation, linear variable displacement transducers	Swelling
Helium effusion	Gas pressure determination	Helium diffusivity
Mechanical testing	Tensile testing, compression testing	Yield strength, ultimate tensile strength, strain hardening
	Kolsky bar, 40-mm gas gun	Equation of state, shock-loading behavior
Microscopy	Light microscopy	Grain size, phase content, morphology of inclusions
	Transmission electron microscopy	Bubbles, dislocation structure
	Oriented image microscopy	Texture
Positron annihilation	Gamma radiation spectroscopy	Types of atomic defects, Location of helium atoms
X-Ray diffraction	Diffractometry	Interatomic lattice spacing, texture, phase composition
	Low temperature	Self-annealing effects

A roadblock for computing the properties of defects created by self-irradiation in Pu has been the lack of an adequate electronic structure for this material. Some of the valence electrons in Pu change from itinerant to localized when density changes because of temperature or pressure. A new method has been developed and applied to Pu and its dilute alloys that gives a correct physical description of these valence electrons and their role in the properties of weapons-grade Pu.

This method, referred to as LDA+U, is a modified model of the traditional LDA (local density approximation) method. It has been implemented and tested by computing the lattice parameters in Pu–Ga alloys. The results and predictions obtained from the LDA method are shown in Figure 3. The agreement of the LDA+U predictions with the published experimental data is very good, while the old LDA method fails completely.

A similar improvement was noticed for the heat of mixing (Figure 4). Whereas the old theory predicts that the two elements Pu and Ga are essentially immiscible, the new theory gives the correct values and shape for the heat of mixing as inferred from the Pu–Ga phase diagram.

The new electronic structure method will enable us to generate effective interatomic interaction potentials needed for radiation damage simulations. In the meantime, we are performing radiation damage simulations on a surrogate material, Pb, to study the defects generated as a function of increasing recoil energy and of temperature. We found that in high-Z materials, a dramatic change occurs in the structure of the damage at high recoil energies (>30 keV). Most of the self-interstitial defects are retained as small dislocation loops, in contrast to the damage produced by neutrons in fission reactors that consists predominantly of isolated vacancies and interstitial clusters. We anticipate that this trend will continue and that the 85 keV recoil damage in Pu will be very different from the fast neutron damage in stainless steels.

The microscopic defects created as a result of the displacement damage can be observed experimentally with high-resolution electron microscopy techniques (LL33). We expect that radiation-enhanced transport can lead to a redistribution of alloy elements that require a chemical analysis capability. To measure both situations, we are purchasing an analytical microscope with 300-kV electron energy capable of atomic resolution. We expect to obtain this dedicated instrument by the end of 1998 (LL34).
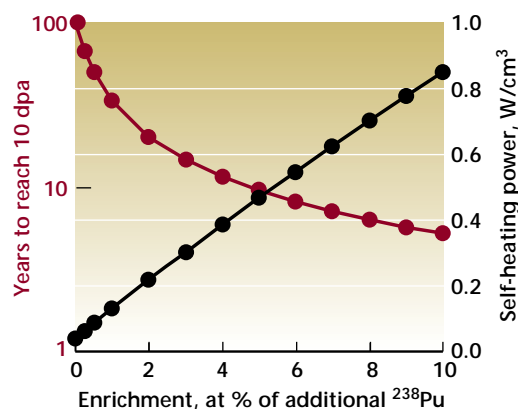

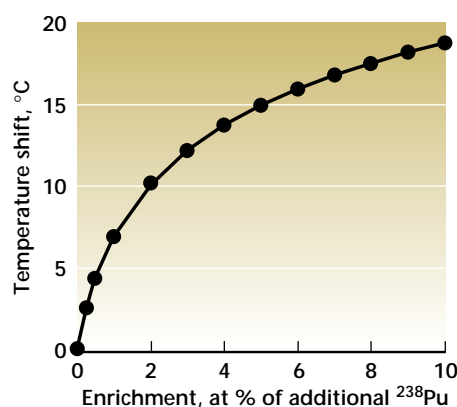Figure 1. Acceleration of aging and associated self-heating of enriched Pu.

Figure 2. The temperature shift determines the appropriate storage temperature for the enriched material relative to the pit temperature.
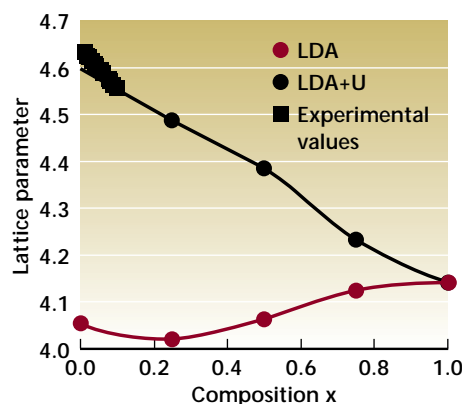

Figure 3. Lattice parameters for Pu–Ga alloys, where x is the Ga atomic fraction.
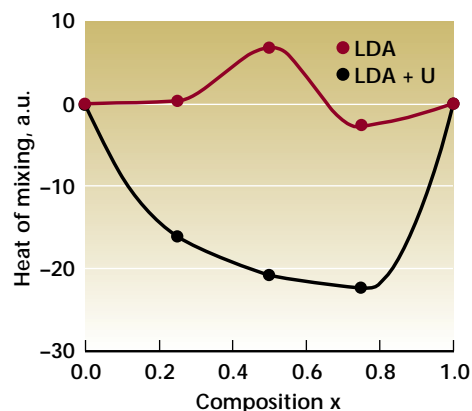
Figure 4. Calculated heat of mixing for binary Pu–Ga alloys.

Experimental Studies of Ejecta and Debris

It is known that material can be ejected from the free surface of some metals when the metals are shocked. Such ejecta from shocked Pu are being characterized in a series of experiments in the U1a complex at the Nevada Test Site. Over time, we will examine ejecta from Pu samples of varying age, surface finish, and manufacturing technique; we will also study the effects of various temporal shock structures and intensities. The experiments are being performed in high-explosive-driven shock systems very similar to that illustrated in the figure, which is the configuration for a Livermore subcritical experiment (SCE) code-named Bagpipe.

The first Livermore SCE, called Holog, was executed in September 1997. All diagnostics fielded on Holog were successful, except for the particle sizing measurement performed by laser holography. The holographic measurement failed because scattered light severely overexposed the film in the detection system. A solution to the overexposure problem was developed and successfully tested in an experiment at Livermore Site 300 on June 26, 1998. The utility of this solution on Pu samples is being verified with the Bagpipe subcritical experiment performed on September 26, 1998. If the overexposure problem has indeed been eliminated, the Bagpipe experiment will provide the particle size data that was lost in the Holog ejecta experiment.

The Bagpipe experiment also measures the Pu surface velocity and Asay foil ejecta data that were collected in Holog. In addition to measuring the ejecta particle size distribution, the Bagpipe experiment is providing information on the reproducibility of experiments and the diagnostic techniques used on Pu samples.

Following Bagpipe is Clarinet, an SCE designed to characterize ejecta differences between new and aged wrought Pu. Two ejecta experiments are included in Clarinet, each of which will be functionally equivalent to the one illustrated in the figure below. One of the Clarinet experiments will use a piece of wrought Pu from an over-30-year-old sample. The second experiment will use a new piece of wrought Pu manufactured with the same specifications as the aged sample. Both experiments will be executed simultaneously and diagnosed with Fabry-Perot velocimetry to measure both the surface velocity and the velocity history of the Asay foils from which ejecta mass/velocity distributions are inferred. Each experiment will also be diagnosed with holographic particle sizing to obtain ejecta particle size distributions. Finally, depending on the quality of the results collected on Bagpipe, piezoelectric probes may be used on Clarinet and could corroborate the Asay foil measurements. Clarinet is scheduled to be executed in the first half of FY99; the date is dependent on the availability and capabilities of LLNL's plutonium facility.

A future SCE will include a third experiment of the exact configuration as the Clarinet, but will use a Pu sample made by the cast pit-rebuild process. This experiment will provide a direct comparison between cast and wrought Pu. Additional future experiments are outlined in the Experimental Studies of Ejecta and Debris plan.
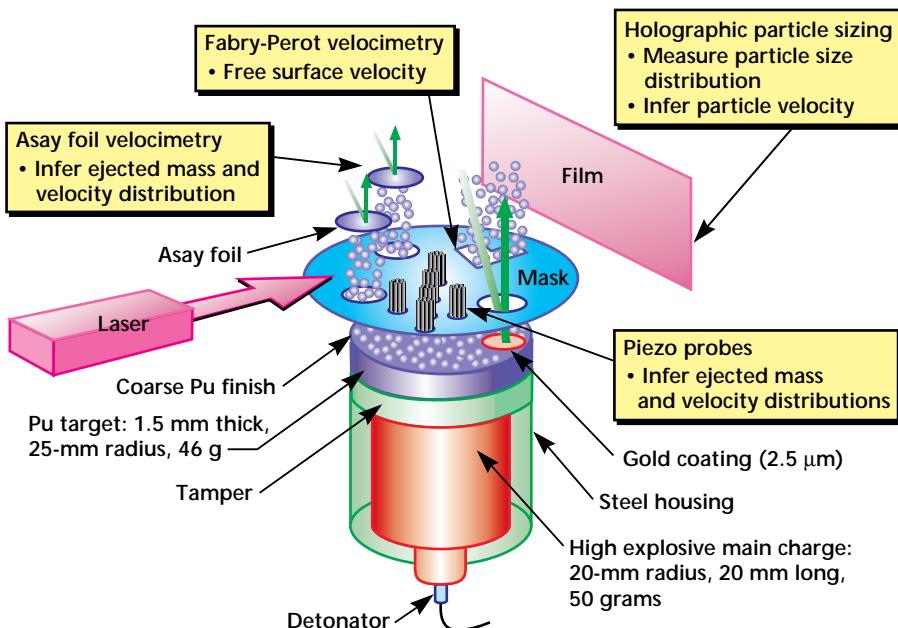
Schematic of the ejecta experimental configuration designed for Bagpipe. Many future ejecta experiments, like Clarinet, will employ qualitatively very similar designs. As appropriate, the experiments will be diagnosed using velocimetry of the Pu free surface to measure the shock arrival time vs the free surface velocity history, holographic particle sizing to measure the ejecta particle size distribution, velocimetry of Asay foils to infer the ejecta mass/velocity distribution, and piezoelectric probes to obtain a second measure of the ejecta mass/velocity distribution.

The Miniflyer (Pu and U): High-Strain-Rate Measurements of Pit Materials

The laser-driven miniflyer (LDMF) experimental method provides the unique capability of evaluating small samples (<500 mg) and obtaining performance data that simulate special nuclear material dynamics. In particular, the LDMF will quantify the effects of self-irradiation on the dynamic spall strength. Delta-phase Pu surrogates were tested this year, and additional tests are planned. These data assist in the basic understanding of radiation-induced defects and will be used in determining the useful life of a weapon pit. The preparation for the first Pu dynamic spall strength measurement is in progress.

During the first half of FY1998, equipment was installed in the ESP Miniflyer Laboratory, located at Los Alamos National Laboratory. The Nd:YAG laser-beam profile was measured, and related diagnostic equipment was installed. Optical and electrical signals and timing circuits were synchronized. The streak camera with optical fiber input and charge-coupled device readout to a microcomputer was interfaced for velocity interferometry signals. The 90/10 optical splitters fabricated by the Kansas City Plant were incorporated for electrical and optical recording of velocity interferometry signals. The electrical recording provides long (>3-µs) recording at 2-ns resolution. The streak camera has shorter record lengths at <200-ps temporal resolution. The small flyers and targets used in miniflyer experiments require the improved temporal resolution of the streak camera.

Experimental Results with non-Pu materials

Initial high-strain-rate spall experiments have been conducted with copper, gold, 316SS, other special alloys, and metal–polymer interfaces. These experiments used laser-launched flyer plates (miniflyers) 25–100 µm thick by 3-mm diameter at velocities from 150 to 700 m/s. Each target's thickness was twice the flyer's thickness. The experimental results were correlated with spall experiments by traditional experimental methods using much larger flyer plates and targets. The extrapolation of traditional data to our miniflyer data yielded expected results.

Experimental Results with δ-Pu surrogate

A surrogate δ-Pu (Sδ-Pu) was prepared for use in the LDMF to evaluate the dynamic spall strength effects of

self-irradiation damage. Two important material properties affecting radiation damage of metals were studied: crystal structure and mass density. Different populations and types of radiation-induced defects can occur in different crystal systems. Because a material's mass density affects the distance that an energetic particle travels through a solid, the concentrations of radiation defects differ. Delta-Pu has a mass density of 15.8 g/cc and a face-centered cubic structure. Surrogate δ-Pu samples were spalled using the miniflyer technique. Surrogate δ-Pu flyer plates 20 µm thick were impacted into Sδ-Pu targets 40 µm thick. The spall strengths of nonirradiated δ-Pu targets and Sδ-Pu targets irradiated to an equivalent 20-year He concentration were tested. Four shots were conducted: three with nonirradiated targets and one with an irradiated Sδ-Pu target. In preliminary tests, the spall strength was lower by approximately 30% for the irradiated sample. Additional tests of surrogate Pu will be performed over the next few months. Below, a spall plane in a target and a recovered flyer plate are shown. The spall plane is approximately 20 µm deep in a 40-µm target, as expected with a 20-µm-thick flyer plate of the same surrogate δ-Pu. The connected voids in the plane are typical of the spall process.
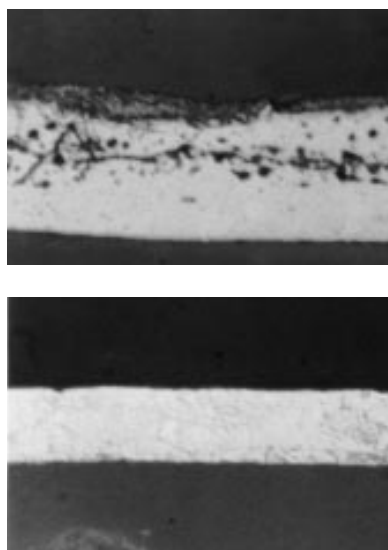
A cross section (top) of a 40-µm-thick surrogate δ-Pu target after impact of a 20-µm-thick surrogate δ-Pu flyer plate (bottom). The connected voids form a spall plane (plane of maximum tensile stress). Irradiation lowers spall strength.

Dynamic Behavior of Plutonium and Uranium (Intermediate Strain Rates)

The Kolsky-Hopkinson pressure bar is designed to measure the uniaxial compression stress-strain characteristics of special nuclear materials (SNM) in a glovebox environment at high strain rates and over a wide temperature range (cryogenic up to near-melting temperatures). To date, plutonium samples have been tested at strain rates of 800 to 10,000 per second at room temperature.

Experimental data from SNM are used to construct and validate constitutive material models. These models are designed to provide predictive capabilities for simulating the high-rate deformation response of weapon materials to meet weapons performance and safeguard program milestones. In addition, experiments provide a quantitative characterization technique for evaluating the influence of aging, processing, microstructure, and composition on the mechanical behavior of plutonium-based and enriched-uranium alloys. This data cannot be accurately extrapolated from either quasi-static or equation-of-state (EOS) measurements and must be measured directly.

Los Alamos National Laboratory's Kolsky-Hopkinson Bar Dynamic Test Facility became operational in December 1997, and the first series of plutonium samples were successfully tested immediately thereafter. The Enhanced Surveillance Program provided the critical support needed to initiate this unique operation, the only one of its kind in the U.S.

Cylindrical SNM samples, typically 5 mm in diameter by 5 mm long, are "sandwiched" between two 10-mm-diameter by 1.3-meter-long, high-strength steel pressure bars instrumented with strain gauges, as illustrated in the figure. To perform a test, a low-pressure gas breech drives a short "striker" bar of variable length into one end of the "incident" pressure bar. The striker impact generates a well-defined, 50- to 150-microsecond-long elastic compression pulse that propagates through the incident bar, the sample, and finally the "transmitter" bar before its momentum is trapped. A dynamic test is considered successful when the stress pulse uniformly deforms the entire sample at a constant strain rate.

This facility is unique because SNM samples, along with short sections of the two pressure bars, are contained within a glovebox to contain radiation and any potential safety hazards. Flexible glovebox seals isolate and separate the remainder of the bar-breech system and the room environment from the test area within the glovebox.

The uniaxial deformation behavior of SNM samples is quantified using stress-strain strain-rate curves calculated from waveform signals acquired by strain gauges fixed midway along the two long pressure bars. Experiments at a given temperature are performed using different striker velocities (controlled by the breech pressure) and striker bar lengths that yield a series of stress-strain curves at different applied strain rates and total strains, respectively.

The compressive stress-strain mechanical behavior of a number of weapons-relevant SNM (both "baseline" and stockpile-aged plutonium and enriched uranium) are being measured over a wide range of intermediate strain rates and temperatures to support the development of predictive constitutive models and to allow assessment of the mechanical response of SNM as a function of age. Tests can be performed at temperatures down to –196°C (77°K) by placing the sample in a bath of liquid nitrogen or at temperatures up to near the melting point by using a resistance-heated furnace placed around the specimen.

Thermally activated dislocation kinetics form the physical basis for material constitutive models, such as PTW (Preston-Tonks-Wallace) and MTS (mechanical threshold stress), which are used at LANL in large-scale, finite-element system calculations of weapon performance. Taken collectively, low-strain-rate data, Kolsky-Hopkinson bar results, 40-mm plutonium EOS tests, and experiments at the Nevada Test Site U1a complex form an integrated approach to characterizing the mechanical response of weapons materials needed to support our surveillance, remanufacturing, and recertification missions.

A schematic of the operation of the Kolsky-Hopkinson bar and the three bar strain waveforms used in the analysis of sample stress, strain, and strain rate.
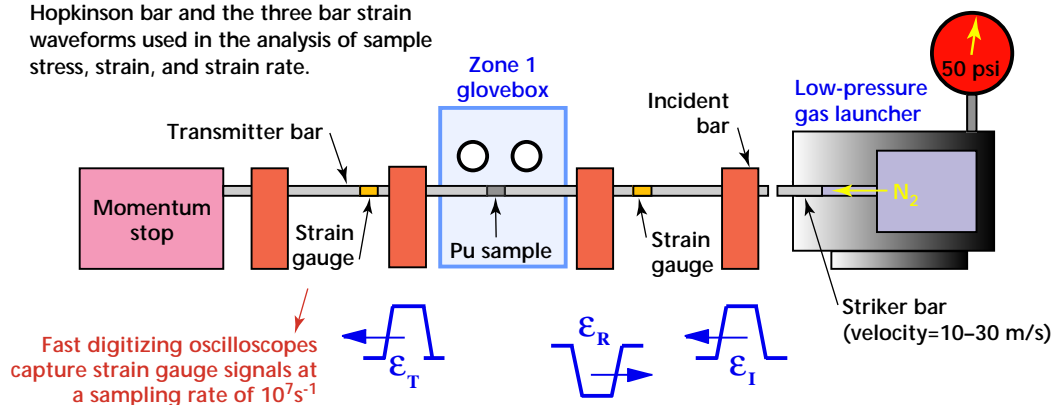
Local-Structure Analysis of Gallium-Stabilized δ-Phase Plutonium

We are developing and applying new methods for analyzing extended x-ray absorption spectroscopy (EXAFS) and x-ray and neutron pair-distribution function (PDF) to more accurately and reliably extract local structural information about aging in δ-stabilized Pu. We have focused on possible local structural defects and/or additional phases in the total model structure. We are analyzing gallium (Ga)-edge EXAFS and the plutonium (Pu) EXAFS edge. The latter is more difficult to analyze because of weaker and noisier data. At low Ga concentrations, there appears to be an additional peak at about 3.8 Å, which we have shown cannot be attributed to the face-centered cubic (fcc) structure nor to the atomic distortions around the Ga atoms. The most likely explanation for this peak is small domains of a second Pu phase and additional disorder. We have introduced these domains into our data analysis and are looking at their influence on the EXAFS (and PDF) spectra.

We are in the process of developing a new method to more reliably extract all of the information available in EXAFS experimental data and to reduce effects of noise on the interpretation. Pu-edge data show that the peak at 3.8 Å in low-Ga samples is a true structural feature.

The fit to the Ga edge data [(a) in figure] in both new and aged samples shows that its local structure is fcc, but with the first three shells of Pu atoms contracted around the Ga atom. Multiple-scattering calculations indicate that the distortions are radial contractions of these shells towards the Ga atom. The fit gives a 0.14-Å contraction of the first shell and about 0.05 Å for the second and third shells. At 1 wt% Ga and above the three shells of Pu, atoms around different Ga atoms should start to overlap each other.

The Pu edge data for both old and new samples [(b) and (c) in figure] show fcc peaks, but for low-Ga-concentration samples the degree of disorder in the different shells cannot be explained by thermal disorder alone. The data also show an additional

well-formed peak in the Fourier-transformed moduli of the EXAFS χ function. We performed simulations of the Pu edge including the distortions around the Ga atoms. As expected, the results show increased disorder in the fcc shells but cannot account for the additional peak. A body-centered cubic (bcc) or body-centered tetragonal (bct) structure with a similar density as the fcc one can produce a second-shell peak at this distance with its first-shell bond length approximately equal to that of the first-shell of the fcc structure. We are currently studying the possibility of an fcc structure with a distribution of small bcc or bct domains included in a model consistent with the presence of the distortions around the Ga atoms. Because the α phase has 3.6-Å bond lengths and is expected to be partially present, we are also modeling this possibility. The most difficult aspect of these simulations is studying the disorder associated with the domain boundaries from one phase to another. The existence of anomalous bond lengths can also come from regions involving slips, stacking faults, or internal twins.

Experimental Ga K-edge XAFS data (a) and a fit to it with a radially collapsed local fcc Pu structure around the Ga atoms. The region that was fit is in between the black vertical lines. Experimental Pu L_{III}-edge XAFS data (b) and a fit to it with an fcc structure. Experimental Pu L_{III}-edge XAFS data (c) and fcc fits with the three-shell Pu distortion around the Ga atoms. Fits for a bcc structure are also given for comparison.
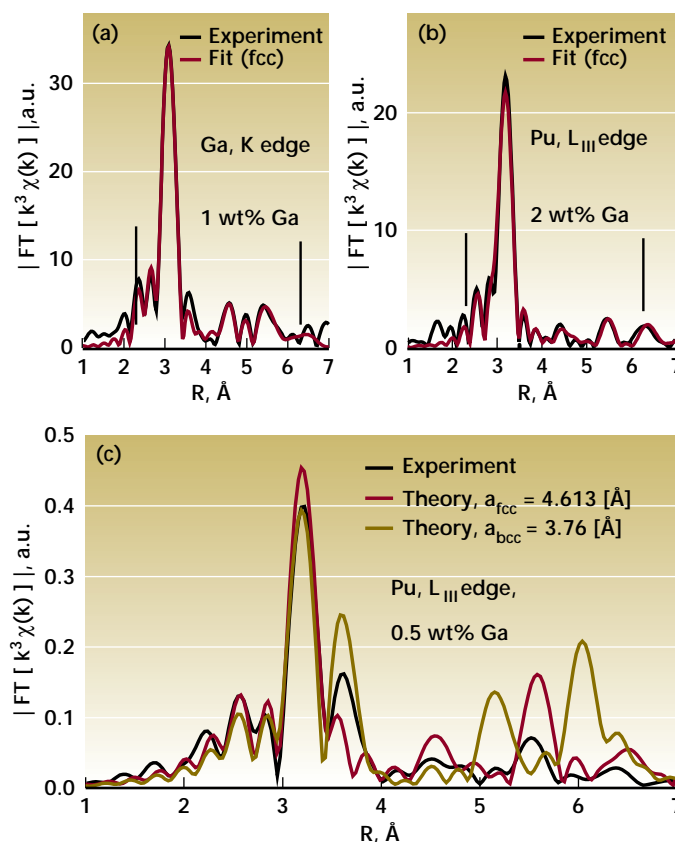
Measurements by X-Ray Synchrotron Radiation

We are developing capabilities that will yield reliable benchmarks for evaluation of aging weapon-component materials in beryllium, steel, and uranium. The spatial and the in-gauge volume resolutions of the x-ray synchrotron radiation (XSR) diagnostic technique in bulk material can be micrometers and cubic micrometers to millimeters, respectively. The penetration depth of XSR in beryllium is comparable to that of neutrons. Using measurable material properties (such as XSR-measured changes in strains and polycrystallinity in beryllium) and an appropriate modeling tool, we may be able to predict the service lives of components.

The purpose of this project is to develop a high-flux, XSR microdiffraction capability, in the energy range of 11 to 80 KeV, for measurement of strain and stress, elastic and plastic deformation, and polycrystallinity in the materials of interest with an extremely high degree of resolution and precision. The technical feasibility of measuring residual strain and stress in thick specimens of beryllium under load and no load conditions has been demonstrated.

A specific objective of this work is to conduct studies of micromechanical deformation (elastic and plastic) in the polycrystalline beryllium and steels at the grain level. The

measurements of residual strain and stress as well as polycrystallinity at grain and subgrain levels in polycrystalline bulk beryllium and 304L specimens under load and no load conditions will be of high priority in our task plans for FY1999.

The results from such investigations will be used to develop polycrystal modeling tools for improving or modifying a state-of-the-art finite-element analysis code for predicting the strain and stress profiles in materials and components.

Through mapping of strain and stress and measurement of polycrystallinity in critical regions of beryllium compact tension (CT) specimens of differing textures, the understanding of fracture mechanisms in beryllium near room temperature appears to have been advanced as a result of our FY1998 work.

We have measured the strain field at and around the crack-tip of fatigue precracked and uncracked specimens of 6-mm-thick S-200 D and P31664 beryllium CT-LT and/or CT-TL specimens under load conditions (T and L indicate the grain orientations from texture in polycrystalline beryllium). Analysis of the data is under way. As a result of this work, we have shown that strain fields can be mapped in critical regions of beryllium CT specimens under load with spatial resolution of 0.175 mm and in-gauge volume resolution of ~0.001 mm^3. With an XSR microprobe beam, the spatial resolution can be extended to ~1 mm.

We are able to measure strains over a grain (or subgrains) in polycrystalline beryllium specimen under load. This opens up the possibilities for the micromechanical deformation studies to be conducted in beryllium at the grain level.

Finite-element calculations of the (from top) hoop, radial, and axial strains in a specially-welded 21-6-9-steel part.
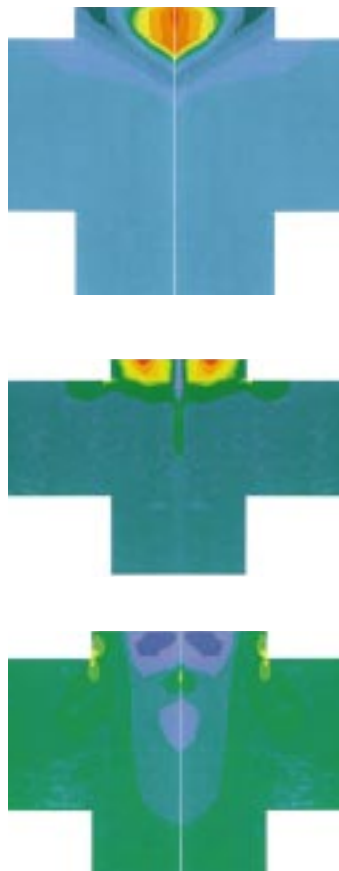
Resonant Ultrasound Study of Pu Aging

Resonant ultrasound spectroscopy (RUS) is a precision probe used to measure elastic properties. It provides both the highest absolute accuracy and the best relative accuracy of any routine elastic modulus measurement technique and can be used on smaller samples in less time than competing techniques. The Los Alamos National Laboratory systems operate from 4°K to 900°K to measure the complete anisotropic elastic tensor of a material over the practical engineering temperature range, as well as the entire range of solid Pu. This technique is being applied to Pu polycrystal samples now; later it will provide the first complete measurement of the elastic tensor of single-crystal Pu over time and temperature.

The elastic tensor of Pu, in both single- and polycrystal samples, is a particularly sensitive test for the effects of aging. It is an input parameter for the modeling of Pu performance in weapons and a crucial first test for microscopic models of Pu.

For the study of aging, the measurement of elastic stiffness is extremely sensitive to such quantities as He ingrowth, defect density, composition, and impurity levels. For example, the elastic stiffness of a system whose specific volume has changed by 0.1% because of various aging effects will exhibit as much as a 3% shift in elastic stiffness, 30 times bigger than the volume effect. Thus, elasticity measurements can provide the first warning of changes. In addition, an RUS measurement is basically a frequency measurement; thus very high precision is achieved, as shown in the figure. It means that in a small sample, where radioactive heating temperature can be controlled accurately, it will be possible to observe, in real time, changes in elastic moduli over the course of a few days as radioactive decay proceeds.

For engineering applications such as evaluating the performance of Pu under forming and casting operations, Pu presents unique problems as it ages or comes under dynamic stress. Because the shear stiffness of single grains varies by a factor of seven with direction—the largest shear anisotropy of any face-centered cubic metal—it is important to understand the variation of this anisotropy with Ga concentration and temperature in poly- and single-crystal samples. The elastic moduli also control the compressional and shear sound speeds, of importance to an understanding of the dynamics of Pu. Results of a recent measurement of Ga-stabilized δ-Pu show values within the range predicted from earlier work.

This experimental work will also provide the calibration and input needed for microscopic modeling of Pu. Something not included in current modeling efforts is how entropy contributes to Pu stability. In contrast to most other materials, the low specific volume of Pu causes a very low Debye temperature. Thus if the free energy, which determines the stable phases, is F=U–TS, where U is the zero-temperature internal energy usually calculated in microscopic models, T is temperature, and S is entropy, then we find that S is very large and dominated by the contribution from the very low elastic moduli of Pu. Coupled with the ease with which Pu can be compressed (the bulk modulus is small) this may be why Pu can contract on warming, and the key to understanding the two highest-temperature phases of pure Pu.
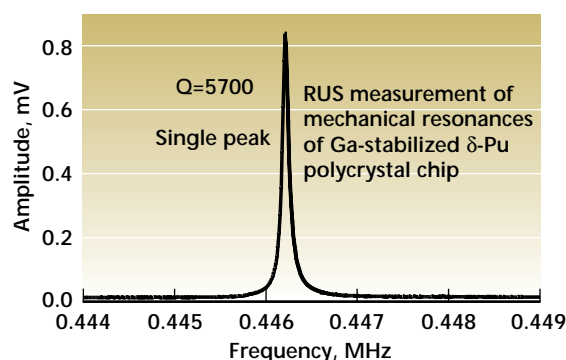
A typical resonance of a polycrystalline sample of Pu. The very sharp resonance and the low noise indicate that part-per-million precision is possible.

Pit Surface Characterization

New diagnostic techniques in the Pit Surface Characterization Laboratory (PSCL) at the Pantex Plant were used in FY1998 to evaluate the chemistry of the external surface of the pit cladding material. During the manufacturing process, while in storage, and during the assembly process, pits are exposed to many environments that can leave residues on the external surface that may not be detected when a weapon is built. The residues could, under certain conditions during the lifetime of the weapon, react with other materials in the weapon environment causing corrosion of the pit cladding.

One example of the application of the new diagnostic capabilities in the PSCL is the determination of the chemical composition of a milky-white, cake-like contaminant on the surface of aged pits from the enduring

Optical micrograph of neoprene imprint (top). XPS spectra from the milky-white material, a zinc stearate mold-release agent employed in the manufacture of neoprene gaskets (bottom).

stockpile. This contaminant resulted from contact of the metal cladding of the pit with a neoprene gasket of the pit fixturing. The analysis revealed the milky substance to be a cake-like material, primarily a mixture of zinc oxide and stearic acid, which is a mold-release agent used in fabricating the neoprene gasket. This contaminant is not corrosive to the pit and has no detrimental effects on the metal cladding of pits for the enduring stockpile; it will not affect the weapon's reliability, safety, or performance.

In some of the fixturings, neoprene rubber gaskets are pressed against the surface of pits. Neoprene is a chloropolymer. It is made by the addition of HCl to vinylacetylene (CH≡CCH-CH_2), producing chloroprene [CH_2=C(Cl)-CH=CH_2], which will subsequently polymerize to neoprene. Residual chlorides will be trapped in the polymer; the amount depends on the conditions in which the polymer is produced (e.g., humidity). The concern is potential corrosion of the pit cladding caused by the presence of the chloride in the neoprene.

This study addressed whether corrosion had, in fact, occurred on pits from the enduring stockpile as a result of aging in the presence of neoprene rubber gaskets. We examined pits that had been in contact with the gaskets for over six years with the surface analytical techniques available in the PSCL. Data from areas on the pit surface that were touched by the neoprene were compared to those of other areas away from the neoprene. In addition, samples lifted from the pit surfaces were analyzed elsewhere by energy dispersive spectroscopy and x-ray photoelectron spectroscopy (XPS). These techniques will be available in the PSCL in the near future.

Pits from three different programs were analyzed. Upon removal of a pit from the fixturing, an imprint was found on the pit surface. The imprint is a ring located approximately halfway between the pole and the equator (or waist) of the pit. The digital optical image of the imprint (left) shows that the band in the impression left by the neoprene ring is approximately 6 mm wide. Analysis of the milky-white, cake-like material revealed the substance to consist of zinc, carbon, and oxygen (zinc stearate). A small amount of silicone was noted. But no corrosion promoters (e.g., chlorides) were detected on the milky-white substance in contact with the pit surface, and no corrosion of the metal cladding was detected following removal of the milky-white substance.
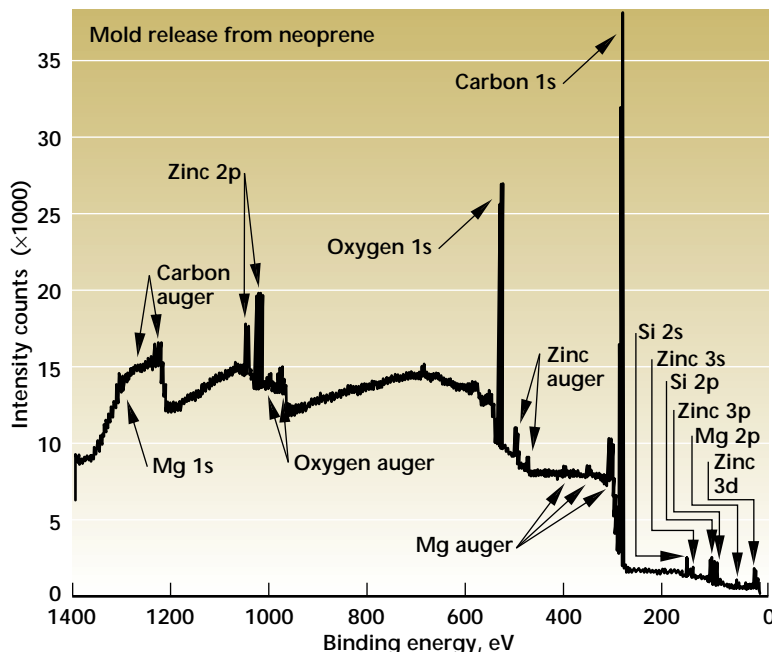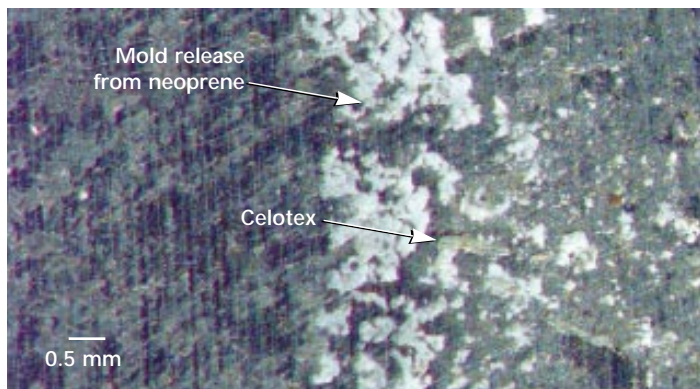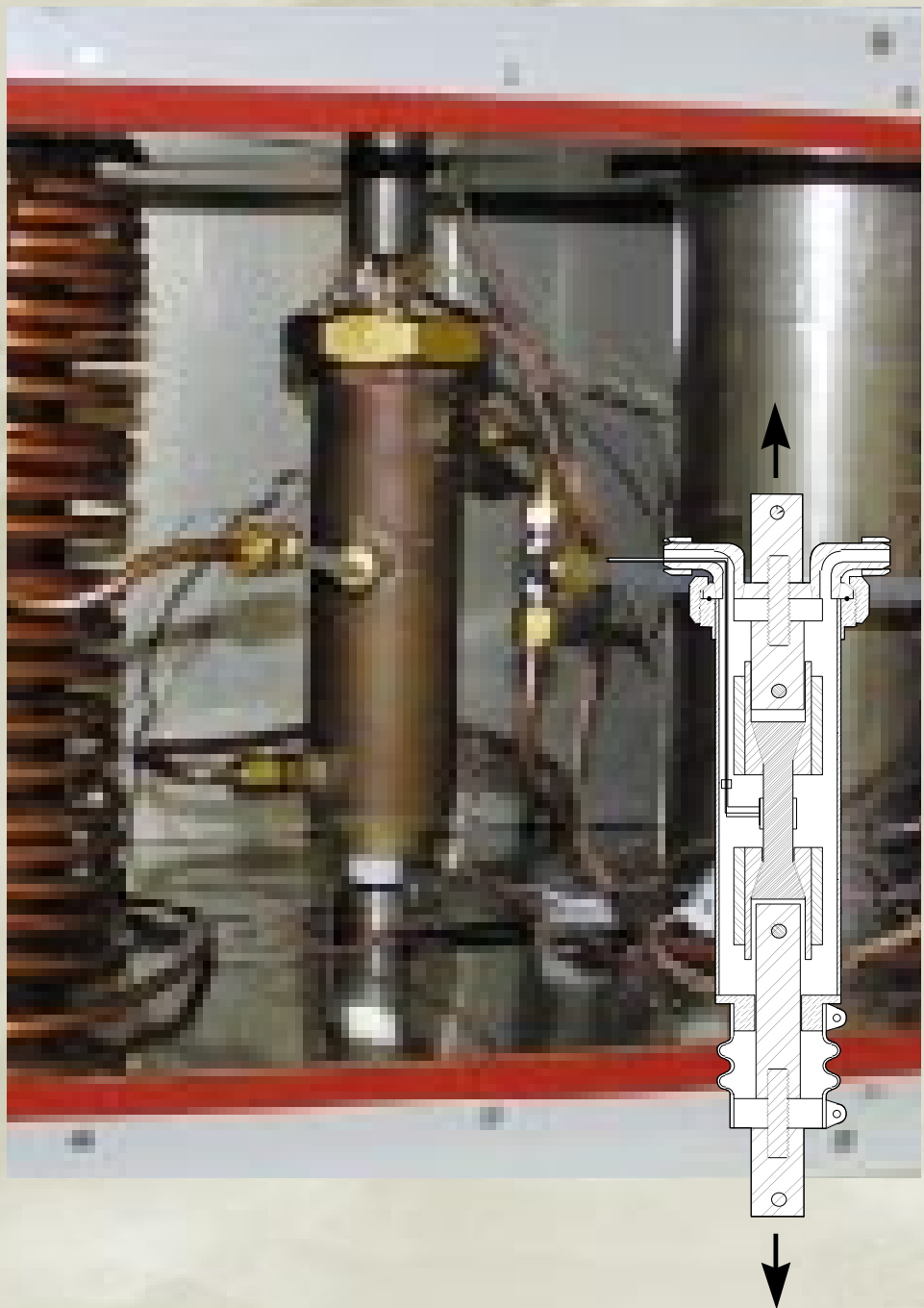
High Explosives

High Explosives

Focus Area

This focus area is intended to assess the effects of aging on the initiation, detonator/booster chain, and main-charge high-explosive components used in nuclear weapons systems in the enduring stockpile. It includes characterization of the physical changes that may occur with aging (including physical, chemical, and mechanical, as well as safety and explosive performance aspects), development of nondestructive examination techniques that allow early and accurate detection of changes that may occur, and the development of models that allow projection of aging and performance behavior into the future. These models will allow estimation of the lifetimes of existing components so that reasonable planning for potential refurbishment or remanufacturing can be made within the Stockpile Life Extension Program.

The work on initiation systems comprises the development of a new nondestructive examination technique used to assess aging of initiation cables. The detonator/booster work consists of an evaluation of the performance aspects of old detonators that remain relevant to those in continuing service. A new test will evaluate divergence between the performance of "retired" detonators and those that will continue to be in the stockpile.

The effort surrounding main charges consists of assessments of the initiability (how promptly and where the detonation reaction begins), energy (how the high explosives move metal), and safety (the change of sensitivity with time). The work also includes necessary assessments of the high explosives as engineering materials.

These tasks were chosen to enhance our ability to predict high-explosive aging phenomena and remaining service lives. As appropriate, results of the work will be transferred to the routine surveillance testing program.

Pertinent Tasks

LA35   High Explosives Initiability and Stability

LA36   High Explosives Mechanical Properties

LA37   High Explosives Lifetime Prediction

LL06   Material Degradation Model Development

LL07   Enhanced Detection of Environment-Driven Changes in Aged High Explosives

LL08   Understanding the Effect of Damage and Aging on Initiation and Performance of High Explosives

LL09   Detonator and Booster Reliability

LL10   Safety and Reliability of Stockpile-Aged Materials

LL11   Enhanced Characterization of Stockpile-Aged Initiation Components

LL12   Mechanical Properties of Aged PBXs and Organics

LL13   Solid-Phase Microextraction

LL18   Changes in Shock Wave Profiles

LL38   Science-Based Modeling of the Gold-Indide Reaction and its Effect on the Performance of Aging Detonators

LL40   Simulated Stockpile-Aged Explosives

LL43   Detonator Safety

LL44   Advanced Analysis of Mechanical Safing and Arming Device Strong-Link Performance

Deliverables

1. Partial discharge analysis test for initiation cables delivered to the routine surveillance program.

2. Analytical and test-fire comparisons of new and aged PETN, LX-16, LX-13, and ultrafine TATB explosives.

3. Models to predict future performance of PETN, LX-16, LX-13, and ultrafine TATB.

4. Development of a new divergence test for stockpile aged HE and the introduction of this new test into the routine surveillance program.

5. Embedded magnetic impulse and velocity comparison of new and aged main-charge high explosives as well as transfer of the test to the routine surveillance program.

6. Skid tests to evaluate aging effects on the safety of main-charge explosives.

7. Three-inch gun tests to evaluate effects of aging on the safety of main-charge explosives; introduction of this compact and analyzable test into practice in the routine surveillance program.

8. Characterization of aging effects on materials-related properties of PBX 9501, PBX 9502, XTX 8004, LX-04, and LX-17. Tests include molecular weight and mechanical properties such as strength and ductility.

9. New nondestructive techniques to allow characterization of aging phenomena and the introduction of these technologies into the routine surveillance program.

10. Characterization of aging effects on the explosive performance of PBX 9501, PBX 9502, LX-04, and LX-17 main-charge high explosives as well as development of models to predict future performance behavior.

Material Degradation Model Development

High explosives (HEs) with slow chemical reactions require a long time to achieve chemical equilibrium, which poses a challenge in developing accurate equations of state. The ideal explosive, LX-14, was studied as a benchmarking case, because it is known to have a short reaction zone and therefore very little kinetic effect. Calculations were performed with no adjustment specific to the bigplate experiment or the individual explosives used. These calculations are therefore predictions of the explosive performance based only on heat of formation and density. We found that we were able to reproduce the time of arrival of the shock wave at the beam positions (0, 2, 4 and 8 cm) very well. We have linked the Cheetah chemistry code to Lawrence Livermore National Laboratory's VHEMP hydrodynamic code. Cheetah linked to the hydrodynamic code calculates the explosive equation of state as a function of elemental composition, heat of formation, and density. This will give us the ability to predict how explosive performance in a warhead is affected by changes in density or chemical composition upon physicochemical aging.

For LX-14 and also for stockpile explosives LX-04 and LX-17, we undertook an extensive comparison of the VHEMP-linked hydrodynamic code to results of the bigplate experiment (LL16, which is the experimental analogue of this task). The bigplate experiment is designed to be a sensitive test of the high explosive equation of state. The test measures explosive push at variable angles of incidence. A 20-mm-thick disk of high explosive with a 100-mm radius was initiated with a point detonator at the center. The other side of the explosive was covered with a 0.5-mm-thick copper plate. Several Fabry-Perot laser interferometer beams were aimed at varying radii on the plate.

We compared our calculations to bigplate experimental results on LX-04, which is found in the W62 warhead. In the figure below, we compare the chemistry predictions with the experimental values for the velocity of the copper plate. LX-04 shows significant non-ideal behavior due to the relatively large amount of binder (15% by weight). We see reasonable agreement between the calculations and the experiment. We have obtained similar results for LX-17, which is found in the B83, W84, and W87 warheads. We are now implementing a kinetic capability into the linked code, which will take into account the effects of slow chemical aging reactions. We have performed trial calculations using kinetics in one-dimensional plate push experiments with very good results.

In conclusion, we have established and validated a capability to predict changes in HE performance due to aging-related changes in density or chemical composition. While results are generally promising, we find that the inclusion of chemical kinetics will be necessary for obtaining quantitative accuracy for LX-17 and LX-04. In the next year, we will develop models of observed subtle shifts in chemical composition and/or density. Observed changes of chemistry and density have been very small to date. Density changes will be explored by developing a model of small changes in part size and density due to mechanical loading over time. Chemical changes will be explored by developing models of binder decomposition and high explosive aging chemistry. The aging models will be extrapolated forward in time, then fed into the linked VHEMP/Cheetah code. The result will be an indication of whether explosive performance will change significantly in the foreseeable future.
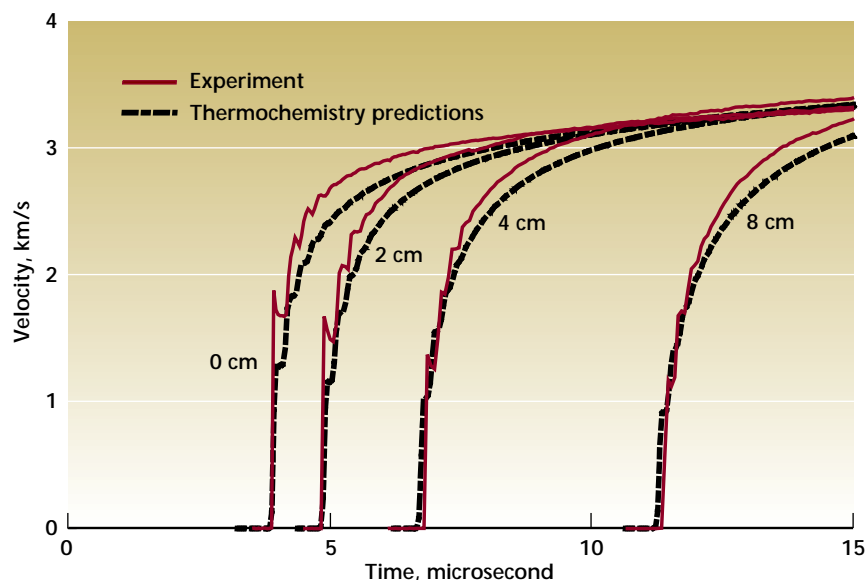
The copper plate velocities for the LX-04 bigplate experiment as measured by Fabry-Perot interferometry at four radii (0, 2, 4, and 8 cm) are compared with the predictions of the linked chemistry/hydro code. Good agreement between calculation and experiment was found, thereby validating the new linked code.

High Explosive Initiability and Stability

We are characterizing the initiability, energy, and equation of state (EOS) of stockpiled high explosives (HEs). First we gather state-of-the-art baseline data for reference and subsequently characterize stockpile-returned samples for aging-related changes that might affect weapon performance, reliability, and safety.

We completed a series of Steven tests (formerly known as spigot-gun experiments) that detect changes in HE sensitivity to low-amplitude mechanical environments. Ongoing activities include: (1) skid tests to detect changes in sensitivity of bare HE charges, (2) development of sandwich test as a potential replacement for cylinder tests measuring HE performance and EOS, (3) embedded electromagnetic gauge experiments to detect subtle changes in HE initiability, (4) hockey-puck experiments using proton radiography to characterize low-temperature (<−55°C) initiability and detonation-wave spreading in PBX 9502 for hydrocode and JTF reactive burn model calibration, and (5) XTX 8004 initiability/energy experiments at the Pantex plant.

The Steven test was originally developed at Lawrence Livermore National Laboratory to characterize the threshold for HE response to a low-amplitude impact (few hundred feet per second) such as might be experienced during a transportation accident. Los Alamos National Laboratory slightly modified this test and added instrumentation to characterize the reaction timing profile and violence. We tested PBX 9501 samples in stainless-steel holding fixtures, which were impacted by mild-steel hemispherical projectiles. Projectile velocity was systematically varied to determine PBX 9501 reaction thresholds. Reaction violence was measured using redundant blast-overpressure gauges and a ballistic pendulum developed for this test. Spigot projectile velocity vs. the average energy release is normalized to a full detonation of PBX 9501. The results indicate no significant difference in the sensitivity of baseline PBX 9501 and W76 samples after 142 and 182 months in the stockpile. The slight difference observed for reaction thresholds has tentatively been attributed to variations in sample densities.

We also developed embedded electromagnetic gauge experiments as an ultra-sensitive measure of the initiability (i.e., ease of inducing a detonation for a given input shock) of HE materials. For this test, a particle velocity/shock-tracker gauge package is installed in the HE sample to minimize shock perturbations. The test sample is located in a magnetic field and each of 11 gauge elements (located at 11 depths) records the local particle velocity. The shock-tracker records the position of the shock front with time. A gas-gun projectile is used to introduce carefully controlled shock conditions (i.e., pressure/duration) into the HE

sample. We characterized the initiation behavior of baseline PBX 9501 at three different densities using three different input-shock pressures. As time permits, we will also test PBX 9501 stockpile samples; the bulk of stockpile testing will be in FY1999. Baseline data will be compared to data obtained using PBX 9501 samples from stockpiled W76 and W78 warheads (which have very different stockpile-to-target sequence environments) to detect age-induced changes in initiation behavior. Thus far, acquisition of baseline data is nearly complete and one W76 sample has been tested. Presently there are insufficient data to determine what effect, if any, age has on the initiation behavior of PBX 9501. Baselining experiments will begin in FY1999 using PBX 9502 samples, and stockpile testing will be completed in FY2000.
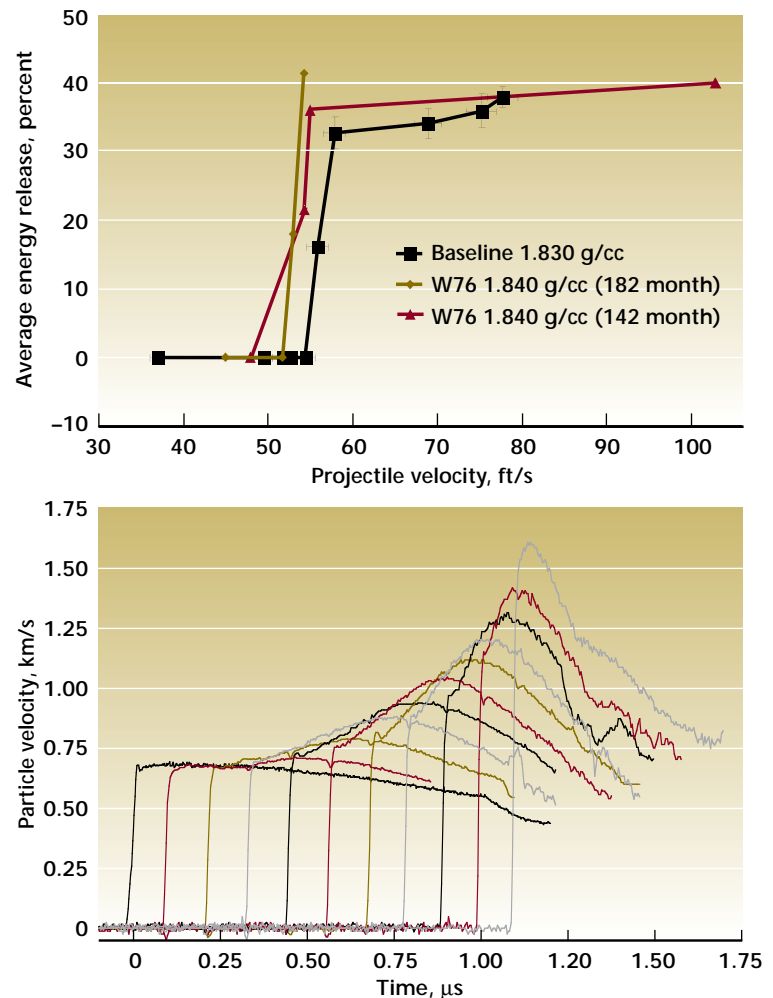
Steven test results (top) indicate no significant difference in the sensitivity of baseline PBX 9501 and two W76 samples in stockpile. Baseline data and results of W76 sample tests (bottom) show that there are insufficient data to determine what effect, if any, age has on the initiation behavior of PBX 9501.

PBX 9501 Lifetime

The work of this task provides information to continuously update and improve the lifetime predictions for PBX 9501 in the W76, W78, and W88 warheads. These activities were completed during FY1998:

• Formulation of nominal PBX 9501 using flaked vs. pelletized Estane for comparisons and certification
• Study of effects of formulation parameters on PBX 9501
• *Study of NP migration mechanism**
• Characterization of NP migration into W78 shields
• Thermal sensitivity study comparing freshly formulated and stockpile samples of PBX 9501*
• *Measurement of glass transition temperature of Estane, Estane with NP and PBX 9501 historical samples*
• *Measurement of affinity of PBX 9501 for H_2O at differing relative humidity*
• *Measurement of radiation effects on PBX 9501 binder**
• *Estane aging study to determine degradation products*
• *Study of the effects of "hot pressing" PBX 9501 on the molecular weight (MW) of Estane**
• *Study of effects of quasi-static compressive loading on Estane MW*
• *Study of inhibitor lifetime in PBX 9501*
• *Characterization of Estane MW in PBX 9501 in stockpile*
• Gathering of historical information regarding PBX 9501 manufacturing

Italicized activities were performed to support development of a PBX 9501 lifetime model. Details on selected activities are presented below.
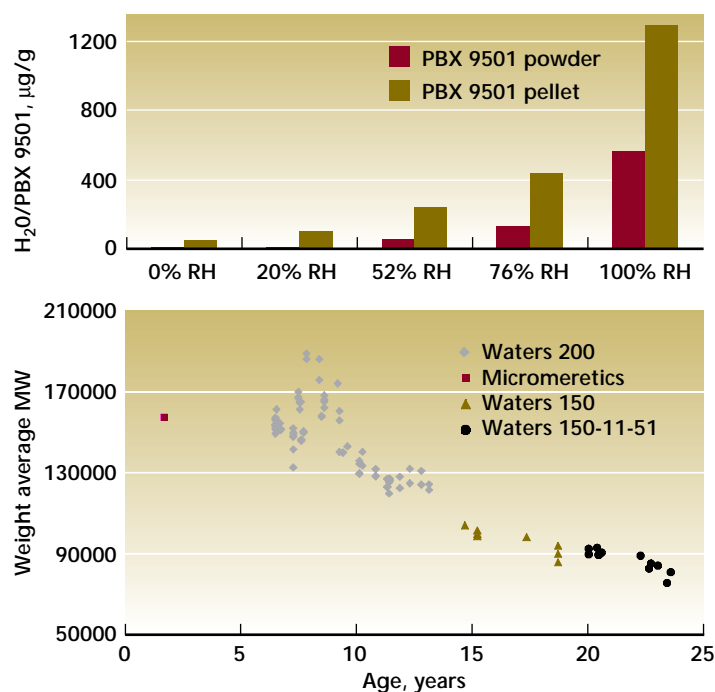
PBX 9501 pellets retain more water than PBX 9501 power, indicating the former may age more quickly (top). Historical Estane molecular weight (MW) data from PBX 9501 lot 622-7 exhibits discontinuities in MW trends associated with instrument changes (bottom).

*ongoing

All 14 lots of stockpiled PBX 9501 were formulated with flaked Estane from B.F. Goodrich. Goodrich now produces a pelletized Estane that meets all specifications for use in PBX 9501, but is slightly different. If it becomes necessary to replace stockpiled PBX 9501, a decision on whether to use reserved flaked Estane (acquired in 1989 and somewhat deteriorated) or newly obtained pelletized Estane will be required. Therefore, Pantex formulated PBX 9501 using both flaked Estane (500 lb) and pelletized Estane (1000 lb) for a direct comparison of properties and war reserve (WR) certification for the W76. Both lots of PBX 9501 have been characterized analytically, and W76 main charges are being manufactured for testing. LANL conducted a parametric study of formulation parameters for PBX 9501 to fully characterize manufacturing techniques.

The primary aging mechanism for pure Estane and PBX 9501 outside (and perhaps inside) weapons is hydrolysis. The affinity of PBX 9501 for water is critical for predicting lifetime. Therefore, pressed pieces and molding powder of PBX 9501 were stored in air at five different humidities and analyzed for water content (see the figure below). Pressed pellets retain more water than molding powder, a surprising result.

One first step in developing an aging model for Estane and PBX 9501 is identifying degradation products to gain insight into reaction mechanisms. A two-year study at Pantex examined Estane samples aged at 50, 75 and 90°C under air or helium, both dry and moist. Estane samples were fractionated and analyzed to qualitatively identify degradation products.

All stockpiled PBX 9501 was characterized for Estane MW by Pantex and Los Alamos National Laboratory. Extensive Pantex investigations revealed correlations between historical reports of Estane MW and specific instruments used at the plant. This correlation is seen by examining the Estane MW of one lot of PBX 9501 used for instrument checkout at Pantex since the early 1970s (lot 622-7) and historical stockpile data (see LA24). Lot 622-7, which is not stabilized and therefore expected to age more quickly than WR PBX 9501, exhibits discontinuities in MW trends associated with instrument changes (see figure, left). These discontinuities lead us to conclude surveillance data alone cannot be used to quantify any age-related increase in Estane MW. Instead, refined analytical techniques must be used to determine if an MW increase occurs and the importance of that aging mechanism.

Detecting and Evaluating Age Effects on Explosives

Two related tasks study the effects of age on high explosive (HE): Task LL07, Enhanced Detection of Environment-Driven Changes in Aged HE, and Task LL40, Simulated Stockpile Aging of Explosives.

Task LL07 deals with enhanced detection of environmentally driven changes in aging HE; it continues to evaluate and develop modern tools to measure the chemical and physical signatures of aging explosives. The observed aging phenomena are beginning to provide the basis for simulating aging stockpile explosives—a focus for the new Task LL40. The following techniques developed in Task LL07 represent promising metrics for the simulated aging of LX-17:

• The increase in the atomic pore volume previously observed in the aging of LX-17 seems to occur when TATB is thermomechanically stressed. When the relative populations of the defect sizes are compared for all the samples measured to date, we observe a power law correlation. This may provide a method for determining the amount of thermomechanical aging that has occurred in a historic stockpile unit, as well as provide metrics for the simulated aged explosives.

• Thermal techniques allow the crystallinity of the binder in LX-17 to be determined; crystallinity influences the stiffness of the overall composite. These techniques can also indicate how long the binder has been above its glass transition temperature and provide a record of the LX-17's thermal history since the last thermal excursion. Other PBX systems with crystalline fluoropolymer binder systems (LX-04 and LX-16) can employ this technique as well.

• Highly charged, ion-based secondary ion mass spectrometry provides a means of making an imaged, solid analysis for trace contaminants in aged PBX. Thermal decomposition products of TATB were quantified for pressed LX-17.

A new task for FY1999 is Task LL40, which is focused on the production of explosives having the same properties as those in the aging stockpile. These explosives will be used for tests in associated tasks to determine age effects on material properties and explosives performance and safety. That data will then be incorporated into aging models, being developed in yet other tasks, to obtain a capability for predicting aging effects and lifetimes of explosives. The lack of adequate aged explosives and the unavailability of aged samples older than 10–20 years have significantly deterred the development of this predictive capability. We plan to fill this void by producing explosives that simulate a variety of ages.

Simulated aged explosives will not be produced by simply accelerating thermal and other processes. The explosives we produce will have the same chemical and physical signature(s) as those detected in stockpile-aged explosives. Efforts are now underway to study the detected signatures and identify the relevant ones. We expect to include some or all of the signatures detected by tools and techniques developed in LL07.

The pathway to simulated aged explosives may be entirely different from the actual aging pathway. For example, to study the effect of observed changes in binder crystallinity, we may formulate explosives with binders having different initial degrees of crystallinity. The ultimate fidelity of the aging simulation will only be as good as the signatures that we select. Within that constraint, however, this task offers the means to extend the understanding of explosives aging far beyond where we now stand.
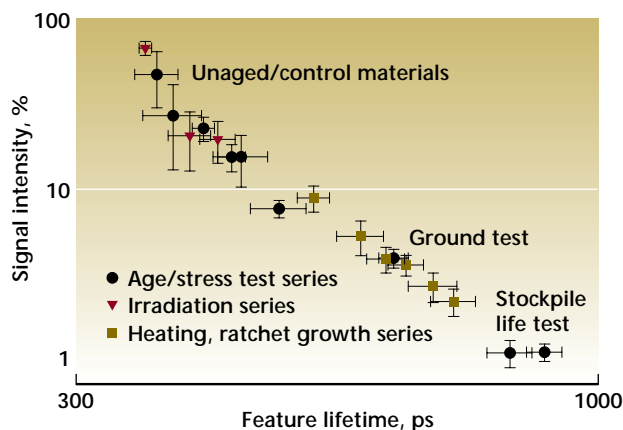
Power law correlation between TATB defect annihilation lifetime values and lifetime intensity. The apparent aging phenomena are unaffected by irradiation and give the impression that under thermomechanical stress, the small defects coalesce into large ones.

Safety and Reliability of Stockpile-Aged Materials

Impact ignition is a common measure of how we assess the safety of explosive materials. Impact ignition generally involves one or more of the mechanical processes of friction, shear, fracture, recompression of damaged or reacting explosive, etc. These processes are extremely difficult to quantify in terms of the work done on the explosive, the amount of explosive on which the mechanical work was done, and the temperatures reached within the heated regions called "hot spots." Previous impact tests, such as the drop hammer test, the skid test, and the Susan test, were developed to test specific hazard scenarios. But the results are not consistent between the various tests, most of which are not amenable to quantitative analysis and computer modeling. In contrast, the Steven impact test was developed to be consistent, instrumentable, and modelable. We completed a 55-experiment test series using this test and determined threshold impact velocities for observable exothermic reaction for aged HMX-based explosives to within a few meters per second. Previous work concentrated on determining threshold impact velocities for pristine and damaged high explosive charges and inert modeling of the mechanical aspects of the test. Concern has been raised that the handling, shipping, and environmental and chemical changes that main-charge high explosives (HEs) undergo during their stockpile lifetime may change their

impact sensitivity. Therefore, new and stockpile-aged charges of four HMX-based conventional HEs and the two TATB-based insensitive HEs were tested in the Steven test configuration. We developed improved instrumentation to yield quantitative data on the energy release rates during reaction. Reactive flow modeling is effective for explaining these experimental measurements and for developing predictive models for other scenarios, most importantly here, aging.

Unlike other impact tests, the Steven test and the Los Alamos version of the Steven test, the spigot gun test, yield distinct critical velocities, below which no reactions are observed. The critical impact velocities increase in the usual order of decreasing impact sensitivity: PBX 9404, LX-10, PBX 9501, and LX-04. Thus far, no important effects of aging on critical impact velocity for LX-04 or the violence of the subsequent reaction have been observed. Embedded manganin, carbon resistance, and carbon foil gauges have yielded pressure histories in the impacted explosive charges lasting for several hundred microseconds. The figure shows typical embedded gauge records in the impact region and at the explosive charge boundary obtained in a Steven test of a 95% HMX explosive impacted near its threshold velocity.

We modeled the ignition of the explosive in the Steven test in several ways. We added a shear ignition mechanism to the ignition and growth reactive flow model in the ALE3D hydrodynamic code, which yielded reactions under the projectile at approximately the correct impact velocities. We also performed quantitative ignition and growth reactive flow modeling for the individual HMX-based explosives in the DYNA2D code using an ignition criterion similar to the 0.37 cal/cm^2 frictional work criterion of Chidester and the growth of reaction parameters determined for low-pressure shock initiation in LX-10 and LX-04. The figure shows excellent agreement between the pressure histories from an ignition and growth calculation and the experimental pressure gauge records in terms of the pressure history in the impact region and the time to violent reaction. We will soon be publishing details of the experimental and modeling results. The ignition and growth reactive flow models for LX-04 and LX-10 are being used to predict hypothetical impact scenarios on aged material that can not be tested experimentally.
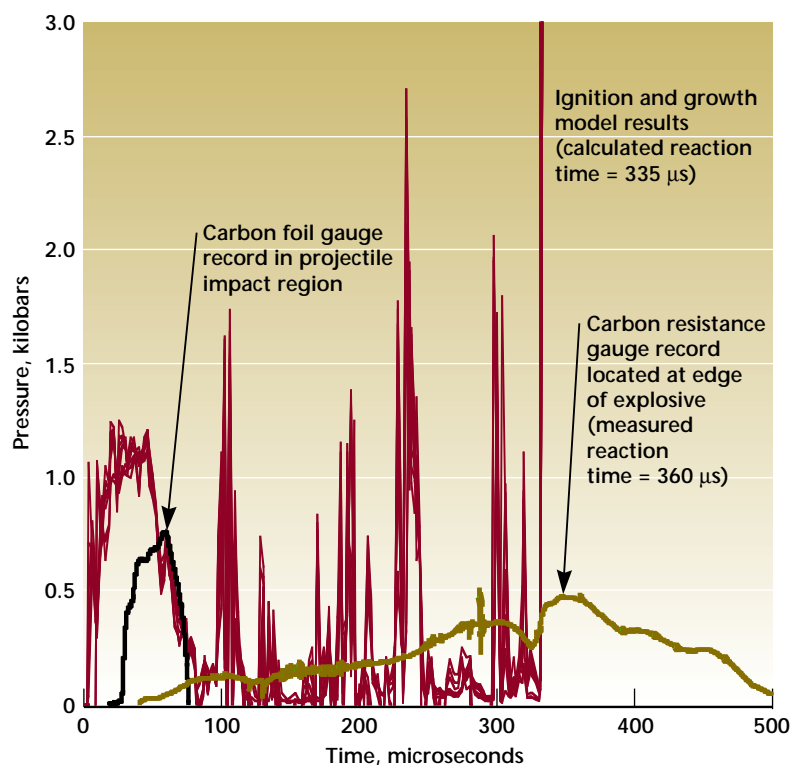
Experimental and calculated pressure histories for the impact ignition of a 95% HMX explosive near its reaction threshold velocity.

Enhanced Characterization of Stockpile-Aged Initiation Components

In the past, the nuclear weapons complex has used a pass/fail detonator cable high-pot test to determine detonator cable electrical integrity. Unfortunately, this test provides no qualitative information. In contrast, partial discharge analysis (PDA) is a qualitative, nondestructive electrical technique for verifying cable integrity and forecasting cable life. This technique applies a voltage to the cable under test and records micro-discharges (partial discharges) in the cable. The charge distribution, frequency, and location of the partial discharge (PD) signatures convey information about the internal structure of the cable. This technique can be used to analyze the structure of a cable and forecast the life of the cable. It can also be used to screen new production and to determine if assembly/disassembly operations are damaging the detonator cables. This project is developing the tools and database necessary for technology transfer.

PDA can be conducted between the two conductors of the cable or from one or both conductors to ground. Through FY1998, we demonstrated the viability of conductor-to-conductor measurements, including dielectric degradation of material through electrical aging and stockpile weapon aging.

The figure shows three snapshots of PD signatures while a cable has voltage applied for an extended period. This figure clearly shows that the signatures tend toward higher charge and smaller peak counts as the component ages. Testing also identified the weakest points of existing designs and quantified degradation with time in cables aged in storage and in weapon environments.

Conductor-to-ground measurements are inherently more difficult because metal parts are attached after the assembly is manufactured, leaving voids and PD sites even when the cable assembly is pristine. In FY1999, we will eliminate sources of extraneous PD signatures by performing the test in a vacuum that is below the corona region.

The requirement to compare signatures of cables at various stages of life is pivotal to the PDA project. As a result, it is crucial to have signatures of new and aged cables available. Based on FY1998 results, AlliedSignal/Federal Manufacturing and Technology has incorporated PDA into their manufacturing quality assurance process and is acquiring the necessary database of new cable signatures.

Analysis of aged cables is also essential to an effective forecasting capability. In addition to surveillance returns, a large number of cables made available from the Life Extension Program will be tested in FY1999. Analyses will include mechanical damage testing representative of possible weapon assembly/disassembly mishandling, as well as material degradation testing.

Partial discharge analysis is a powerful tool that has many potential applications in the weapons complex, including forecasting of minimum cable life, identification of design weaknesses (points to improve future designs), improvement of quality assurance of new cables, and quantification of age- and damage-related changes to the cable insulation.
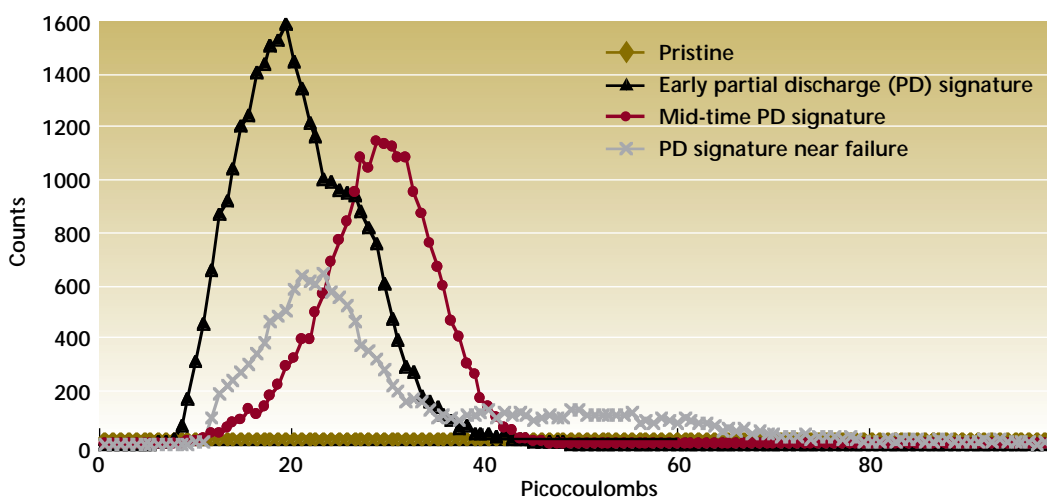
This shows the progression of the partial discharge signatures as a cable is aged electronically. Note that the signatures contain counts of higher charge but lower peak counts as the cable ages. There are no counts for a typical pristine cable.

Mechanical Properties of Aged PBXs and Organics

We are establishing the capability to conduct mechanical testing required for characterizing advanced material aging constitutive models for plastic bonded high explosives (PBXs) and other organic materials used in the stockpile. Our objective is to compile a database of time-dependent changes in the mechanical properties of PBXs as a function of their respective stockpile aging conditions. The mechanical properties of interest include stress/strain to failure as a function of strain rate and temperature, short-term creep tests as a function of temperature and stress, long-term creep tests in weapon environments, stockpile-to-target sequence thermal-mechanical simulation and acceleration; biaxial shear/compression, and fracture.

Although present surveillance testing was not designed to generate such a database, we have made excellent progress toward this goal.

In FY1997, we began building a mechanical testing facility within Lawrence Livermore National Laboratory's High Explosives Application Facility (HEAF). We also developed the PBX environmental test unit, which permits controlled environmental exposures to the mechanical test specimen during loading.

In FY1998, we also began an extensive program to generate the advanced materials database. Because only small amounts of material are available, we continue to perform most development work using the conventional high explosive LX-14

(95/5 HMX to urethane binder) and mock high explosive (HE). Some mechanical data have been generated on LX-04 (85/15 HMX to Viton A), and a very limited amount of data have been genera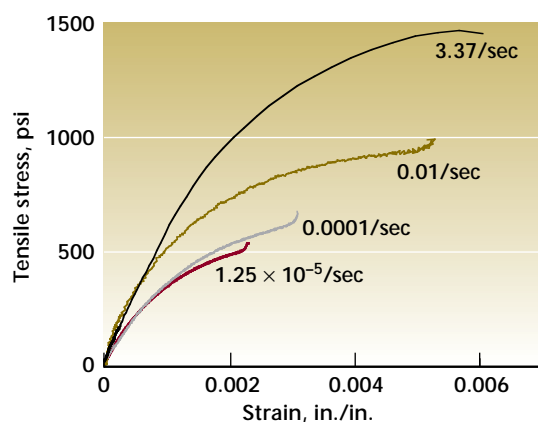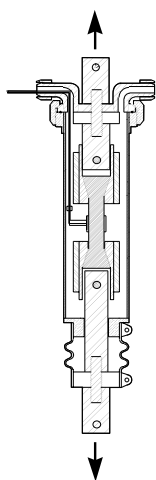ted on LX-17 (92.5/7.5 TATB to Kel-F 800) at Pantex. A thermal strain rate testing matrix has been developed and is being systematically generated for each PBX critical to LLNL programs. We presently have the capability to test in the strain rate ranges of $10^{-5} \le \varepsilon/\text{sec} \le 10^{0}$ and temperatures from $-50 \le T \le 120°C$. Mechanical data for LX-04 are shown in the figure.

Compression testing of PBX has proven to be extremely difficult to do well. We are working to improve specimen alignment because we believe alignment and machining tolerance errors associated with this test have been principal sources of scatter in the compression data in the historical stockpile data. We are helping the Pantex Plant, Los Alamos, and the U.K. Atomic Weapons Establishment minimize the sources of data scatter. We now use three strain gauges arranged 120° apart and average their results, as opposed to using a single extensometer. Minimizing data scatter will result in the need to use fewer test specimens.

To maximize the use of stockpile material, we have been developing reduced-sized test specimens for tension and compression tests and two new specimens for fracture and biaxial shear/compression tests. We believe the reduced-sized specimens are successful; however, we have yet to determine the overall improvements from actual warhead components. We have recently secured the first W62/LX-04 part that will be cored for optimization.

We have successfully demonstrated the use of the biaxial shear/compression specimen with mock HE. To perform biaxial testing of PBX in LLNL's HEAF, it will be necessary to develop a torsional actuator cell for one of the existing axial test machines.

A schematic of the new test unit, the new mechanical test cell, and a plot of change in the tensile stress/strain response of LX-04 at 22°C for increasing strain rates. The higher strain to failure as the strain rate increases is an unusual material response, one we hope to explain and ultimately model.

Organic Materials
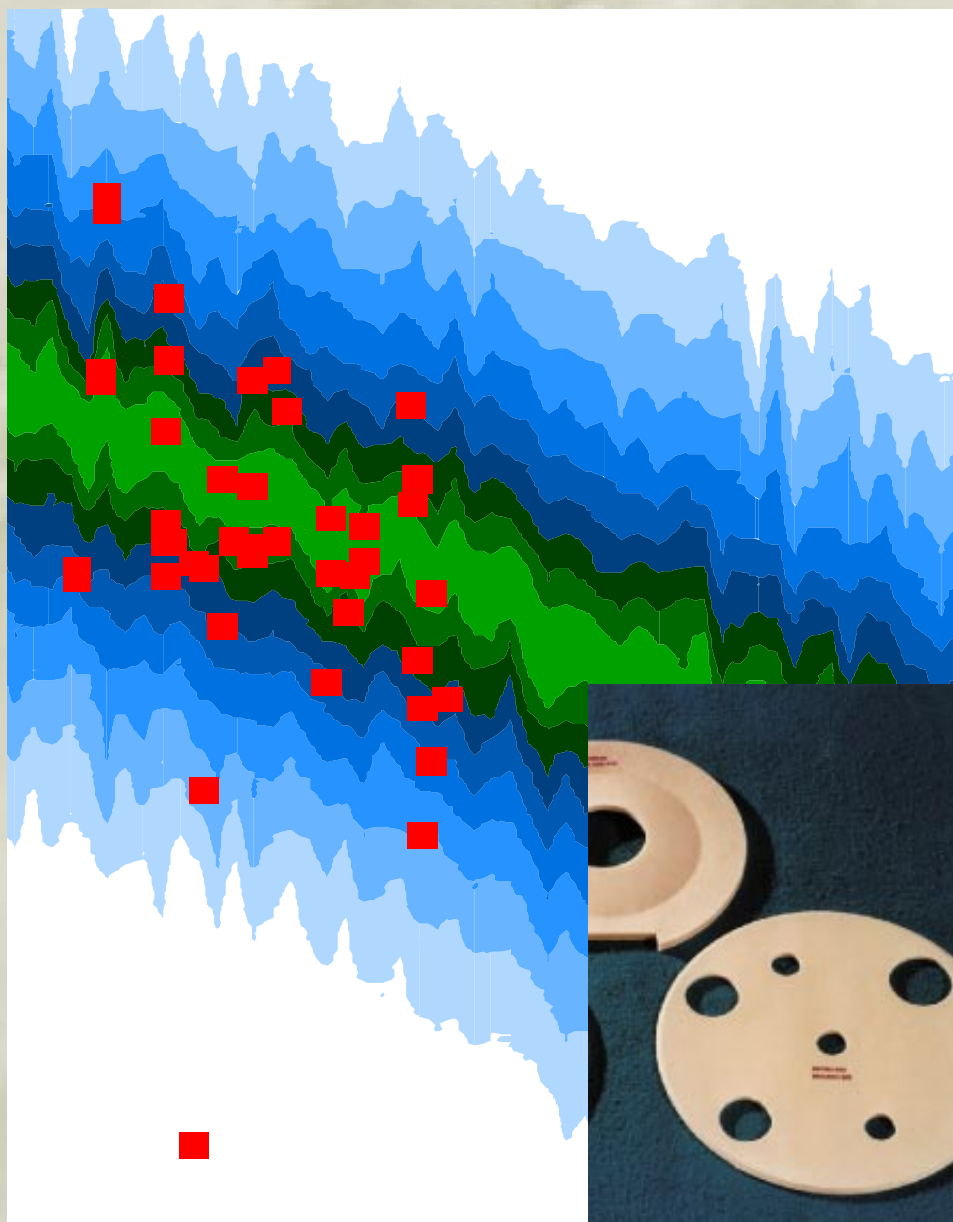
Organic Materials

Focus Area

This focus area addresses the assessment of materials that are both nonenergetic and nonmetallic in character. The various elements that compose the Organic Materials Focus Area provide for the development of baseline materials properties and characterization of stockpile-aged and accelerated-aged materials to support the development of predictive aging models. While the family of organic materials slated to remain in the enduring stockpile is quite broad in scope, emphasis in this focus area is on a limited number of polymers or polymer composites that dominate organic material concerns and have been assessed to have a significant impact on weapon safety or reliability.

Pertinent Tasks

LA06   Polymeric Materials Aging Program
LA24   Theory and Simulation of Polymer Aging
KC07   Foams, Cushions, and Seals
LL35   Compatibility and Predictive Modeling of Weapon Organics and Polymers

Deliverables

1. Complete parts retrieval from dismantled systems; expand parts acquisition to all extended stockpile systems.

2. Run stress-relaxation tests for M-9750, S-5445, and S-5455 cushion materials.

3. Quantify thermal dependence of stress relaxation in silicone foams and elastomers and compare to surveillance data.

4. Continue aging mechanism identification and characterization studies for additional prioritized materials.

5. Produce a report describing the mechanical behavior of PBX-type explosives and other weapon system organic materials and how they are affected by stockpile aging.

6. Apply nonlinear computational analysis to master kinetic equations in PBX 9501 systems and refine those master equations to include the new body of Estane aging data as they become available.

7. Incorporate both diffusion of small species and spatial inhomogeneity into the above computational analysis.

8. Produce a description of an accelerated-aging methodology for stockpile organics.

9. Perform quantum chemistry, molecular dynamics, and other more detailed calculations to answer otherwise unanswerable questions about Estane chemistry.

Polymeric Materials Aging Program

The aging of polymers and high explosives may well be the limiting factor for the extension of the stockpile's lifetime. This task is looking at the 60 types of polymeric materials and 200 polymeric components in the stockpile. The primary objective of our Polymeric Materials Aging Program is to enhance the surveillance of polymeric weapon materials such that the viability of the stockpile can continue to be assessed with confidence. In order to meet this objective, we must understand how materials age and the impact these changes have on the safety, performance, and reliability of the stockpile. Accomplishments in FY1998 include experimental and theoretical efforts directed at the aging behavior of flexible polymeric foam. Some of this work has relevance to a broad variety of materials including other polymers.

Two foam aging models were developed in FY1998. The first model is derived from the statistical analysis of a nine-year aging study conducted at Los Alamos National Laboratory early in the 1970s. Silicone foam was compressed in fixtures and maintained at a constant temperature. The foam samples were removed from the compression fixtures every year and compression load-deflection tests conducted. The sequence of aging under compression, unload, and recovery followed by compression testing is similar to some aged parts in the stockpile that are tested in the existing surveillance program. A model has been developed based on data from the historical study that predicts the load-deflection response of the silicone foam material as a function of material thickness, temperature, stored compression, and time. The model also predicts the unrecovered thickness or compression set the material will experience as it ages, which may be a life-limiting feature for some parts. Predictions from the silicone foam aging model are being compared to surveillance data to indicate long-term trends and identify inconsistent data. As shown in the figure, the model predictions agree well with the data taken from stockpile aged parts.

The second foam aging model was derived from stress relaxation studies conducted on similar material. When polymeric materials are strained or forced into a different shape, the resistive forces within the material decay with time. The constitutive properties of a polymeric material are likely to be different during and after compression even when very short recovery times are allowed. Stress relaxation studies are being conducted to improve the understanding of how constitutive properties change while under compression. Preliminary results indicate that data collected over short time periods can be very accurate in predicting behavior over much longer periods of time. Stress relaxation data collected over a 10-second period accurately predicted stress relaxation data generated by an independent study conducted over a two-year period. The methodology being developed has been applied to a variety of materials in the open literature and therefore may be applicable to other polymeric materials that experience mechanical loading.

Although these two aging models are versatile and can be applied under a broad set of conditions, they are only of value if the material can be quantitatively linked to the safety, reliability, and performance of the stockpile. To explore this connection, an ABAQUS-based constitutive model is being developed to represent the material in a weapon configuration.

A variety of efforts are underway at AlliedSignal/ Federal Manufacturing & Technology (AS/FM&T), Pantex, and Y-12 including material testing and accrual of production process information. AS/FM&T personnel assembled crucial production information on filled vinyl copolymer elastomer, or VCE, and are performing solvent swell experiments on filled silicone materials. Efforts at Pantex include time-staged compression tests on stockpile aged parts. These tests will help establish a rational for time limits on surveillance tests. Personnel at Y-12 identified all canned subassembly polymeric materials, are conducting tests to characterize constitutive properties, and supplied production process information.

All of the information and data generated from these efforts are being compiled into material-specific handbooks to aid future users.
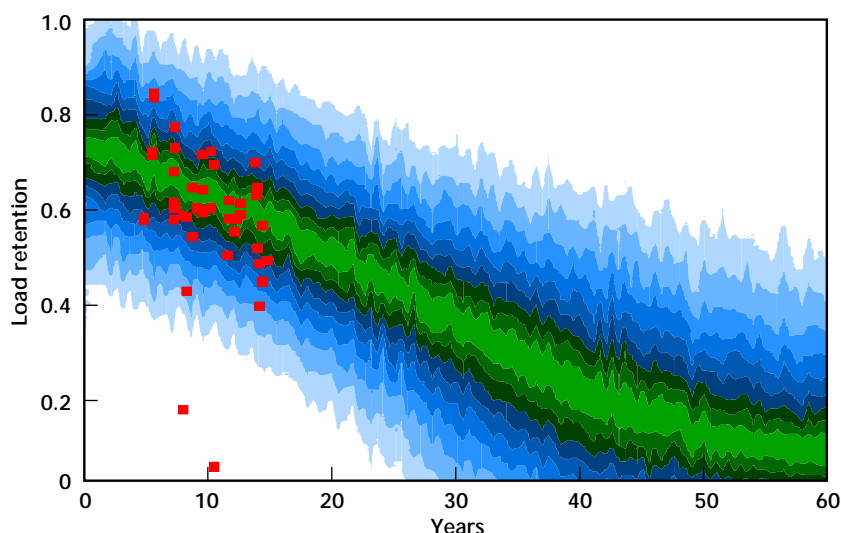
Load retention inference region calculated from the foam aging model. The light green region represents the average change in load retent expected. Surveillance data is shown in red.

Theory and Simulation of Polymer Aging

A detailed chemical model is being developed for the aging kinetics of Estane 5703, which is used in the binder of the plastic bonded explosive (PBX) 9501. When complete, the model will be able to reliably predict the chemical composition and molecular weight of Estane to times longer than the current ages of any of the weapons. Its output will be used in other models being developed to calculate and predict the changes in mechanical properties of the PBX with time.

Estane can degrade by hydrolysis, oxidation, free radical attack, and thermal degradation. In accelerated-aging experiments, any of these mechanisms can be made to dominate. Our objective is to determine which dominates in the mild conditions of weapon storage, and much progress has been made in FY1998.

We have observed that the stabilizer concentration in PBX 9501 appears to be slowly decreasing with time in samples stored in air but to show no net change with time in the stockpile. The differences between the stabilizer concentration in the stockpile and its initial nominal value appear to arise during initial processing. With the model and the fact that no other component is present in small concentration, this implies the important conclusion that there is no catastrophe looming ahead; Estane in the stockpile will continue to age gracefully.

The acidities and the molecular weights of aging Estane library samples have been measured at Pantex. Modeling them shows that the rise in acidity is enough to account for all the molecular weight loss. That implies that hydrolysis is the dominant mechanism for the degradation of Estane in air, even for conditions as mild as room temperature and ambient humidity. The treatment of water sorption and hydrolysis of Estane in the kinetics model have been improved, and a single model now describes the aging of Estane in air under a wide range of temperature and humidity conditions.

Spectroscopic data of aged Estane were obtained and analyzed by our collaborators at Pantex, the University of Alabama, Los Alamos National Laboratory, and Lawrence Livermore National Laboratory. These definitely identify the oligomeric (small fragment) products of the aging of Estane in moist air and also give the ratio of the absolute molecular weights of the oligomers to their polystyrene equivalent molecular weights obtained from gel permeation chromatography (GPC).

We have measured the sorption of water by PBX 9501 and have found that, in the form of molding powder, it absorbs a factor of two to three times less water per gram than it does as a pressed pellet and than neat Estane does (see LA37). With the model, this lower sorption accounts for the fact that, when stored in air under ambient conditions, Estane in PBX molding powder degrades much more slowly than neat Estane.

Finally, Pantex has analyzed Estane molecular weight (MW) data from surveillance samples to see the effects of changes in GPC instrumentation over time. Their results are plotted in the figure. The Waters 200 gave higher values for the molecular weight for both new and aged Estane than do all the newer instruments. Also, the MW of new Estane has been remeasured and found to be higher than previously thought. No instrument showed any initial rise in MW. Additional analysis indicates that some cross-linking can occur, but likely it is not enough to make the weight average MW increase. The calculated line in the figure shows our best current estimate for the actual behavior.
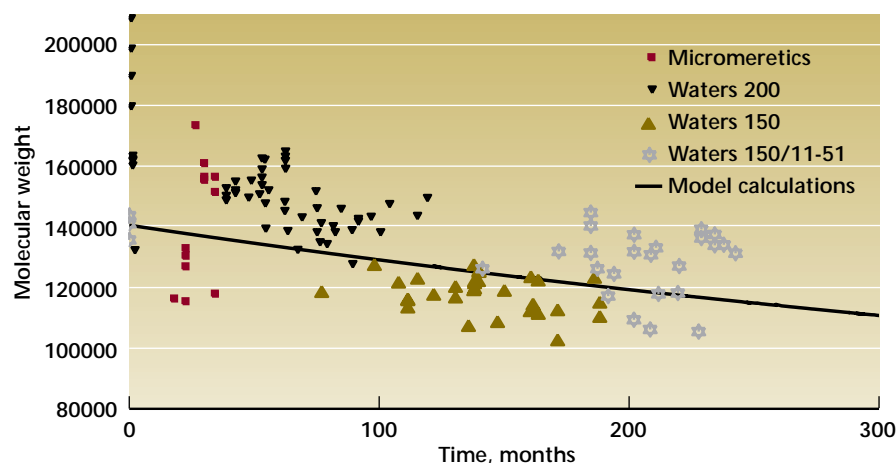
Estane molecular weight of surveillance samples versus time. The differences between measurements with different instruments should be noted, especially for new samples.

Cellular Silicone Cushion Aging Study

Cellular silicone cushions, such as those shown below, serve several functions. They fill gaps between components, compensate for manufacturing tolerances of adjacent components, and allow for thermal expansion. For the cushions to perform these jobs successfully, they are required to exert a specific compressive force at predetermined maximum and minimum gaps. Because the cellular silicone cushions must fill these gaps for the life of the weapon, the long-term stress behavior of the cushion under load is an ongoing concern.

AlliedSignal/Federal Manufacturing & Technologies has conducted studies of various cushion materials in the past. At the end of those tests, the samples were left in the test configuration at specific compression and storage temperatures. This task resumes testing of these existing aged parts, which are now up to 16 years old.

Nine different materials have been retested at least once during FY1998. These samples are representative of materials in all weapons in the enduring stockpile and in several development formulations.

When the cushions were originally placed into the testing fixtures, the force loads required to close the fixtures were recorded. At selected later time periods, these force loads were remeasured to determine how much they had reduced over time. The difference is reported as a percentage of the original fixture closure force, or percent load retention (PLR). High PLR indicates that nearly the same amount of force was required to close the aged fixture as was initially required. In practical terms, high PLR indicates that there is little compression set in the cushion, and that its properties have not significantly degraded during fixture aging.

The results of tests on S-54 material show a continuation of the slow decline in load retention. The material had been stored for 3,521 days (9.6 years) since last testing, for 15.6 years of total aging time, and still exhibited PLR that followed the previous trend. Testing on M97-based materials also showed a slight decrease in load retention, at a lower rate than observed on S-54 materials. The material had been stored for 3,609 days (9.9 years) since last testing, for 15.3 years of total aging time, and still exhibited PLR that followed the previous trend. The other materials included in this study have all been tested within shorter time periods, and all have PLR that are basically following anticipated trends.

The data were reported as plots in a topical report. Copies of the report have been shared with interested technical staff throughout the weapons complex.
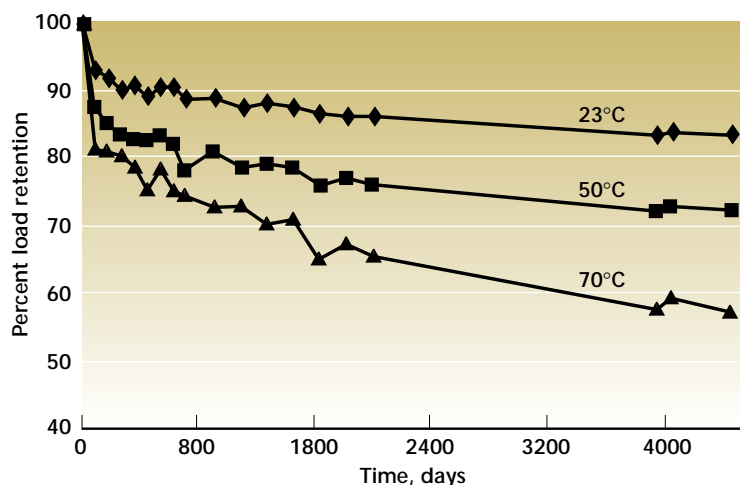
Example of aging study results (left) and representative cellular silicone cushions.

Compatibility and Predictive Modeling of Weapon Organics and Polymers

The goal of this new project, which began mid-year FY1998, is to develop a complete and predictive understanding of the long-term compatibility and aging phenomenology of nonenergetic organic components that affect weapon performance. Our strategy is threefold:
• We identify material properties that affect performance and determine the sensitivity of performance to changes in these materials. Based on this assessment, we develop material-unique roadmaps to identify, characterize, and model key aging signatures by characterizing stockpile-aged components of known pedigree.
• We use knowledge gained in the above strategy to establish appropriate experimental protocols to simulate and accelerate the aging of organics for validating models.
• We address the long-term component performance issues by collecting, analyzing, and preserving corporate knowledge of weapon organics; refining our understanding of each material's unique aging environment; and developing an effective strategy to retain and preserve organic weapon components for future study.

We believe this strategy provides a focus on materials issues important to weapons and a path for developing appropriate new surveillance tests that will provide much earlier detection of changes in critical material properties. The strategy also improves understanding of the material science and chemistry of weapon organics as related to aging and compatibility phenomenology.
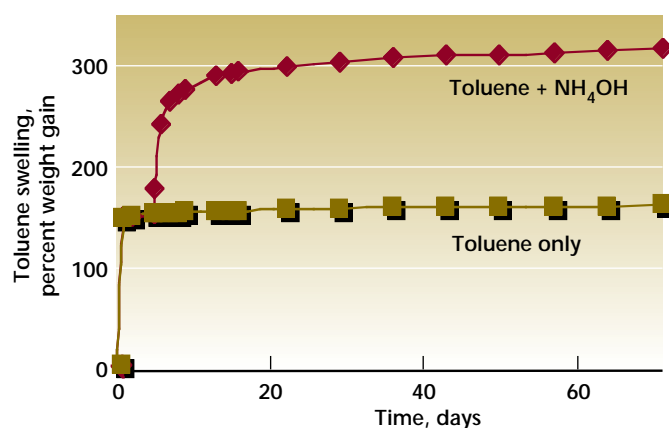
Traditional methods to evaluate the service life of organic weapon components are based on the measurement of physical or mechanical properties of these materials over time or under accelerated aging. This project develops a systematic methodology for identifying the underlying chemical signature changes that accompany stockpile-aged materials and is based on the correlation of molecular chemical alterations to the corresponding physical and mechanical property changes that can be detected before gross mechanical changes have occurred. This approach addresses the short-term question of how a material is aging and the longer-term issue of identifying predictive modeling tools to determine when chemical alterations in a material become substantial enough that macroscopic performance is in question. We are also addressing the potential effects of materials interactions that may occur over long times in the stockpile.

The techniques we use include: solid-phase microextraction and gas chromatography/mass spectrometry to determine volatilization during decomposition or chemical structure rearrangement, positron annihilation spectroscopy to determine atomic free volume or defect size distribution in the bulk material, infrared spectroscopy to determine changes in molecular functionalities, electron spin resonance to characterize free-radicals that might be associated with long-term radiation damage, and scanning electron microscopy and atomic force microscopy to determine any morphological changes. AlliedSignal and Y-12 will supply aged samples of materials and conduct selected complementary experiments on these materials.

FY1998 progress included retrieving stockpile-aged organics from surveillance units, identifying complex-wide expertise to preserve corporate knowledge, identifying design engineers who can identify material properties affecting performance, defining plant and lab tasks for future work, and evaluating experimental techniques. Techniques evaluated include low-level oxidation, solid state cross polarization nuclear magnetic resonance, and material-specific solvent swelling.

Characterization of the degradation of cellular silicone is confounded by the effects of the reinforcing filler fumed silica. The exposure of swollen polymer to ammonia eliminates the reinforcing effect (disrupts hydrogen bonds) and thus allows characterization of the polymer for evidence of degradation.
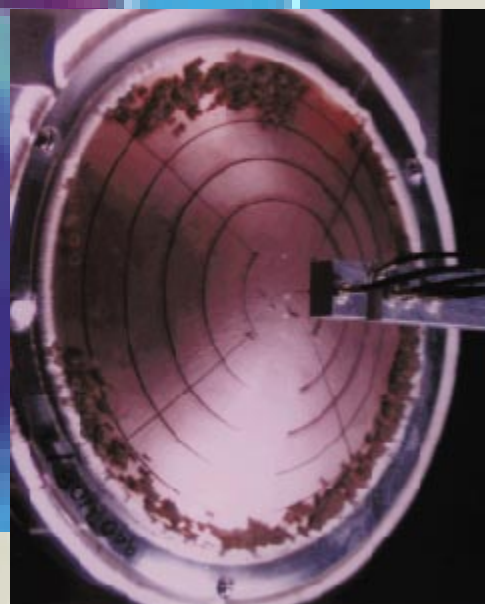
Dynamics

Dynamics

Focus Area

This focus area assesses the effects of aging on the integrated hydrodynamic performance of nuclear weapon components. The work consists of the development of new diagnostic techniques to better assess test results, precision characterization of explosive performance in high-explosive components, and improved utilization of hydrodynamic testing. The new diagnostic techniques and improved methods for hydrodynamic testing will be introduced into the routine surveillance testing program, while the precision characterization is part of the assessment of component lifetimes.

Work on new instrumentation techniques includes development of fiber-optic velocity sensors (pin domes) to better characterize the shock-front velocity and shape, multibeam Fabry-Perot velocimetry to better characterize behavior of large high-explosive components, and picosecond microscopy to better characterize behavior of small components. This advanced instrumentation will be utilized in performance tests of both new and aged high-explosive components, varying widely in size. Methods that allow hydrodynamic testing using the maximum possible number of aged components will be developed, demonstrated, and introduced into the routine surveillance testing program.

Deliverables

1. Fiber-optic velocity sensors.

2. Picosecond microscopy.

3. Laser holography.

4. A screening test to rapidly and inexpensively assess aging effects on high-explosive performance, and introduction of this test into the routine surveillance program.

5. Bigplate and smallplate tests on new and aged main-charge high explosives.

6. Hydrodynamic tests using improved diagnostics for used, stockpile-aged components obtained during disassembly.

Pertinent Tasks

KC02   Fiber-Optic Velocity Sensors
LL15   Development of New Hydrodynamic Measurement and Diagnostic Tools
LL16   Aging Effects on Explosive Performance

Fiber-Optic Velocity Sensors

We are developing a diagnostic tool using Doppler-shifted light in optical fibers to measure the velocity and location-versus-time of high-velocity objects and shock fronts. The fiber-optic velocity sensor and recording system will augment diagnostics currently used to assess the performance of explosively driven, imploding spherical systems in experiments conducted by Los Alamos and Lawrence Livermore national laboratories. This sensor system will provide continuous velocity and location measurements of a point on the imploding surface (instead of the location at one instant in time as given by the electrical pin currently used). The sensor does not rely on the finish or reflectivity of the imploding surface, so it can be used with materials known to provide poor light return under experimental conditions.

The system consists of two components: a velocity interferometer and a fiber-optic sensor. The velocity interferometer is constructed with optical fibers and micro-optics. We completed a prototype unit and are using it to collect data on explosive experiments at Los Alamos' DX explosive facilities. The micro-optics components are being replaced with fiber components as they become commercially available. The fiber components will improve sensitivity and permit the use of smaller lasers. An alpha version of the analysis software was written using IDL language. The GUI-based software is customized for data from the interferometer and fiber sensor.

Numerous sensor geometries and optical fibers have been tested. The most promising geometry is achieved by encasing the fiber in a thin metal tube. Repeatable signals are obtained from this geometry; however, the signals are very complex and difficult to separate because they originate from different locations within and outside the fiber. Current research focuses on improving signal return from the end of the fiber and eliminating or reducing the sources of the unwanted signals. To do this, we are modifying the index of refraction profile of the fibers and material used in construction of the fibers. Computer calculations, as shown in the figure, are used to assist in understanding the data and guide future experiments.

The contour map (left half of the figure) illustrates the pressure profiles in a fiber 300 ns after it is struck with an aluminum plate at a velocity of 1,200 m/s. The fiber begins to "mushroom" on the end as it penetrates the plate at 570 m/s. The end of the fiber is crushing at 630 m/s. A high-pressure pulse is launched down the fiber at about 4,100 m/s. Both the unwanted pressure pulses and the crushing surface return Doppler-shifted light. The illustration (right half of figure) shows how the crushing of the fiber affects its properties as a dielectric waveguide. As the fiber diameter expands, more transmission modes are created that dissipate the laser light, reducing the return signal. Modifying the core profile, changing the fiber material, and encasing the fiber in metal tubes improve the light return and reduce interference from unwanted signals.

This task is a collaboration between Los Alamos National Laboratory and AlliedSignal/Federal Manufacturing & Technologies. The fabrication facilities at the Kansas City Plant and the explosive experimental facilities, computational capabilities, and resources at Los Alamos are used to support the research and development of this sensor system.

Pressure profiles (left) and optical modes (above) in deformed optical fibers.
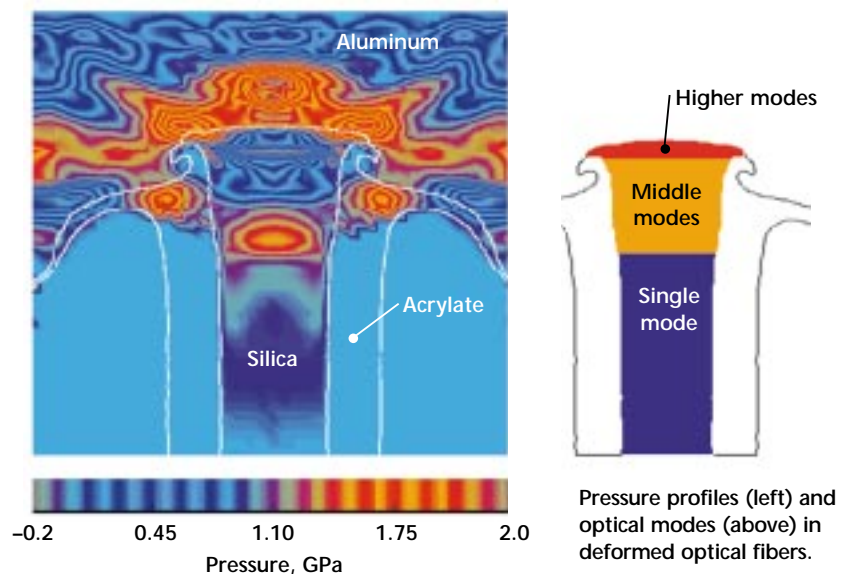
Aging Effects on Explosive Performance

This task uses bigplate experiments to assess the effects of aging on high explosive performance. It is the experimental analogue of LL06, Material Degradation Model Development, which models and predicts the effects of aging; this work is used to calibrate the codes being developed in that task.

A bigplate consists of a disk of pressed high explosive (100-mm radius, 20- to 40-mm thickness) with a 0.5-mm-thick copper or tantalum plate bonded to its front side. A point detonator on axis at its back is fired to create a spherical shock wave that interacts with the copper straight-ahead on the axis and tangentially at the edge. Five Fabry laser beams measure the velocity on the front edge of the copper at different positions. The figure shows a snapshot of bigplate blowing outward 14 μs after commencement of detonation.

Shots with Fabry laser velocimetry were made of two LX-14 and five LX-04 sensitive high explosives and three LX-17 insensitive high explosives. They measured the velocities to an excellent 0.066 mm/μs, or 1%. The explosive causes the metal to suddenly accelerate in velocity, and these jump-offs were measured to 0.01 μs, the smallest number ever achieved.

Our most unusual finding was that out of 10 shots conducted in the series, 7 showed unexplained 0.1-μs lags between the jump-off at 0 mm and at 80 mm. We hypothesized that the detonation wave is slowed down by friction along the inner face of the plate as it moves outward to 80 mm. This effect is not currently represented in our codes.

All samples showed unexpectedly large metal spall (i.e., internal breakage), which extended the on-axis first plateau time by 0.1 μs and created a "rebound" bump on the second plateau (see figure). The spall diminished to near zero at the plate edge. Spall is thought not to affect explosive energy flow; our current codes do not treat it.

The fired explosives span the range of nearly ideal (LX-14 reacts almost instantly) to non-ideal (LX-17 reacts slowly), with LX-04 lying in between. The traditional explosive descriptions used in the codes fit the ideal explosive well and the non-ideal explosive badly. Code runs for LX-17 always show a low initial velocity because of this explosive's long reaction time. The Cheetah Kinetic code, developed in Task LL06, is intended to provide code input to fix this time-dependence problem.

Bigplate is unusual in having fairly simple geometry but with the shock wave crossing zones at various angles on the diagonal. This makes the code runs more sensitive than the better known cylinder, 1D plate and rib tests, where the shock wave always hits parallel to the zone edge. Thus, explosive code packages that calculate well for other experiments fail on bigplate.

The same 22-year-old batch of LX-04 was shot with recently pressed and old samples, and no difference was seen within the 0.05 mm/μs band shown in the figure. Additional cylinder work showed no change in detonation velocity or detonation front curvature between recently pressed and aged LX-04. This suggests that an accelerated aging methodology will be needed before degradation effects can be seen in explosives.
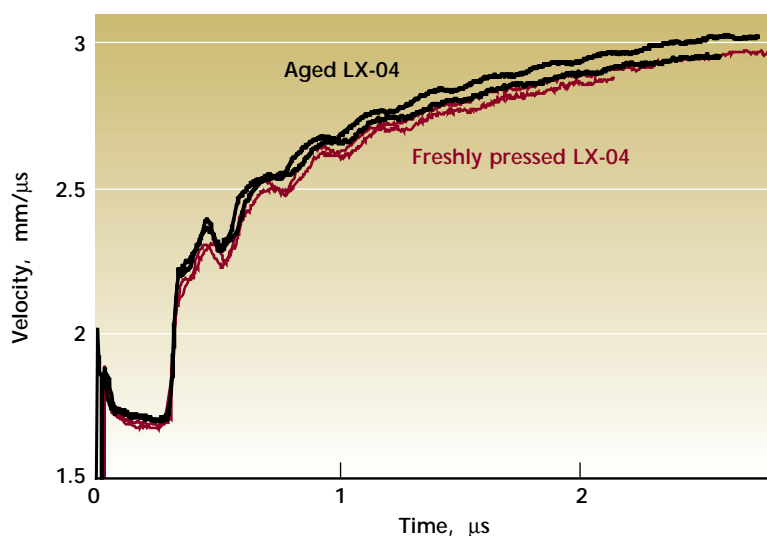
LX-04/Cu bigplate at 14 μs (right). The copper plate is moving outward at 3 mm/μs toward an aluminum bar that will soon be blown away. The center of the copper is bowed because the detonation commenced "on-axis." The explosion has reached the edge and sooty gas from the explosive is creeping to the front. Within error, no difference is seen between the samples from the same batch of LX-04, two samples pressed recently and two pressed 22 years ago.
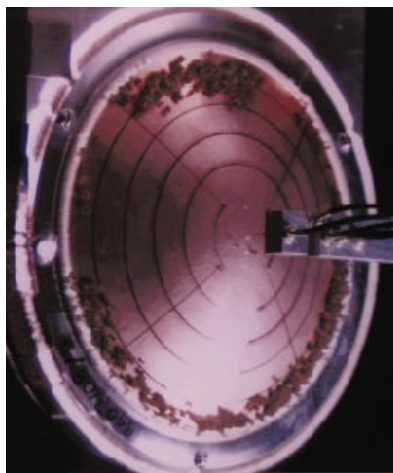
Diagnostics
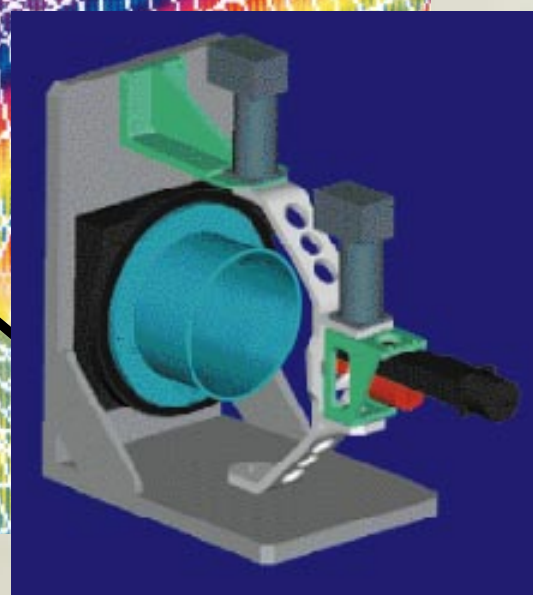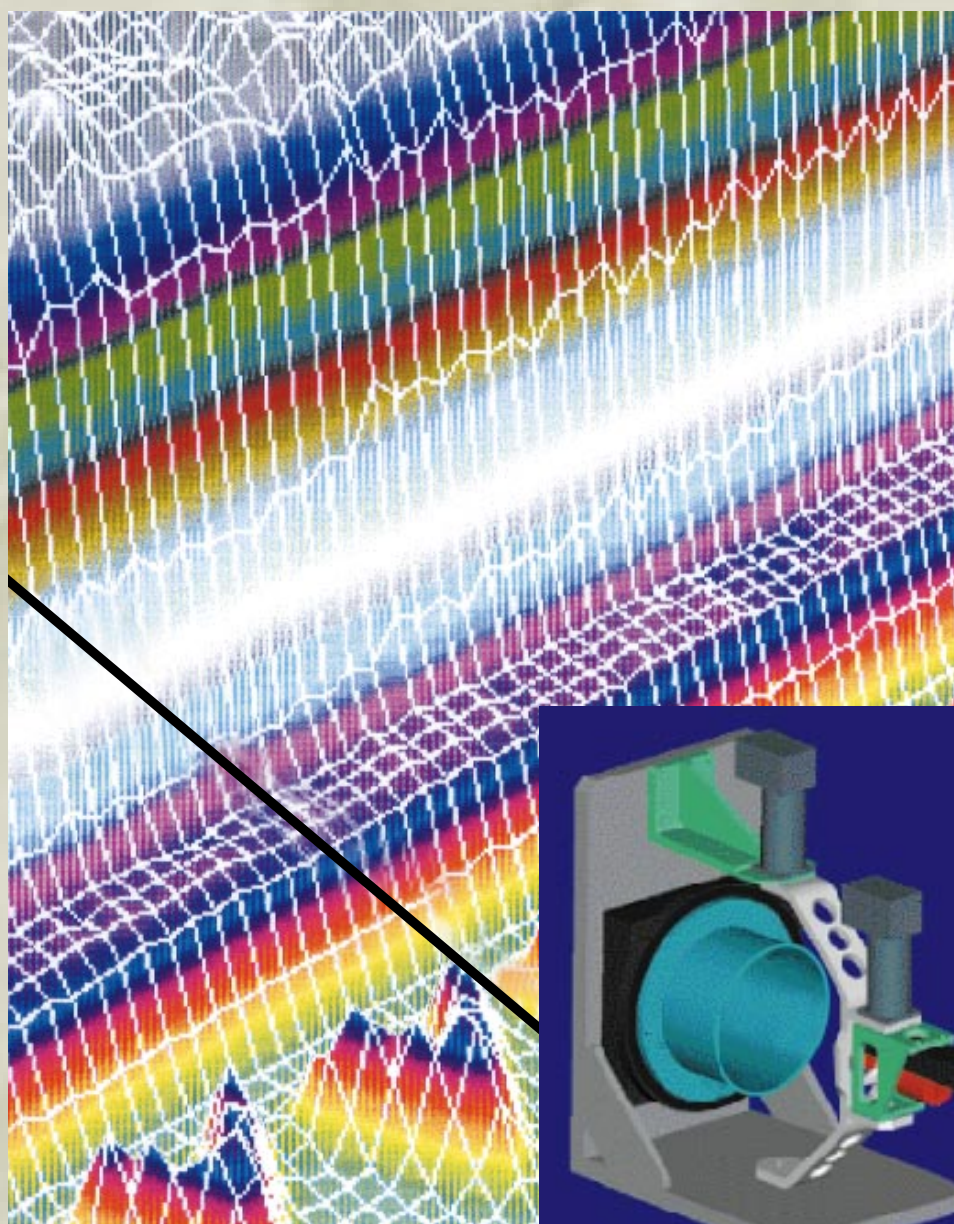
Diagnostics

Focus Area

This focus area includes the development of a new suite of diagnostic methods and instruments that will aid in the early identification of aging problems in weapon system components and materials. New and more sensitive techniques are necessary to measure materials and component properties and the effects of by-products, such as out-gassing of organic materials. The feasibility of real-time monitoring and self-aware system measurements is also being evaluated for incorporation into shelf-life testing programs.

The motivation is to improve the ability to detect potential problems that may require refurbishment or related action. New techniques and methodologies that are developed will be made available to the routine surveillance testing program.

This focus area is divided into the following elements:
- Ultrasonics
- Tomography
- Mechanical testing and sensor development
- *In-situ* diagnostics
- Characterization and analysis
- Pit surface analysis and monitoring

Advanced ultrasonic inspection methods are being developed for assessing the quality of bonds in weapons. These tools provide improved capability to resolve interfacial features for early detection of potential defects such as corrosion and cracking. Neutron radiography and high-definition x-ray tomography inspection tools are being developed for inspecting entire assemblies. These tools will provide much-improved capability to resolve fine features. Vibration and shock testing, as well as other new promising techniques for detecting materials properties, will diagnose damage and structural defects in weapon components.

This focus area also includes in-situ monitoring for shelf-life testing. Engineering feasibility studies of these strategies will determine their practicality, define appropriate detection concepts, develop needed technology, and evaluate prototypes to support an implementation decision.

Characterization tools and analytical methodologies are another element. This set of tools will allow the identification of early signs of degradation of organic components and the potential effect on organic and metallic components. The suite of tools will be applied to nondestructive examination of the gasses within the warhead space of stockpiled weapons and will be applied in a similar fashion to stockpile canned subassemblies (CSAs).

Pertinent Tasks

KC10   Sensor Technology Development

LA16   High-Energy Computed Tomography Detector Array

LA18   Bayesian Inference Tomography

LA19   Advanced Ultrasonic Methods for the Stockpile

LA20   Low-Level Vibration and Advanced Signal Processing

LA21   Development of SQUID Microscope for Surveillance

LA26   Analysis of High-Resolution Vibration for Damage Identification

LA28   Residual Stress Prediction

LL13   Solid-Phase Microextraction

LL19   Enhanced Ultrasonic Characterization of Assemblies

LL26   High-Resolution X-Ray Tomography

Deliverables

1. Ultrasonic inspection tool with better resolution than currently available.

2. Operational neutron imaging system capable of detecting millimeter-sized voids or structural defects in low-Z materials.

3. High-definition x-ray tomography system with at least 1-mil resolution for detection of defects in partial and complete weapon assemblies.

4. Set of vibration and shock test procedures optimal for diagnosing structural defects.

5. Toolbox of signal analysis techniques for determining structural characteristics from test data.

6. Superconducting quantum interference device (SQUID) microscope to measure and map extremely weak magnetic fields associated with defects or corrosion.

7. Damage-detection system using high-resolution vibration analysis.

8. Extended state-of-the-art welding process models benchmarked against experimental data.

9. Laser-based technique for residual stress measurement in reservoirs.

10. Suite of fiber-optic sensors for monitoring of weapons materials and stockpile weapon systems.

11. Optochemical sensors with neural networks that measure, record, and broadcast the presence of various chemicals.

12. Miniature, nonintrusive gas monitor, which can be incorporated in rebuilds or surgically implanted in existing stockpile units.

13. Solid-phase microextraction sampling method for analysis of organic compound decomposition and resultant effects in weapon headspace atmospheres and CSAs.

14. Fiber-optic-coupled laser for analyzing high-explosive decomposition products.

15. Prototype infrared gas analyzer to supplement residual gas analyzer.

16. Laser drilling and welding process for sampling of CSAs.

OR04	Infrared Surface and Gas Analysis
OR09	Evaluation of Hydrogen Balance Methods
OR10	Materials Interactions
OR18	Laser Penetration and Rewelding for Gas Sampling
OR19	Radiographic Parameter Optimization
SN13	Systems Engineering of an Arming, Firing, and Fuzing Device Testbed
SN14	Weapon State-of-Health Monitor
SR02	Residual Stress Measurement of Reservoirs
SR05	Enhanced Inspection of Reservoir Girth Welds
SR06	Imaging Light Elements by Gamma Resonance Absorption
SR07	Defect Detection by TV Holography and Speckle Interferometry

High-Resolution X-Ray Tomography

Computed tomography (CT) is a method of computationally reconstructing an extensive set of projection (transmission) measurements into a three-dimensional volumetric data set. The so-called CAT scan in diagnostic medicine is one type of CT system. This approach permits inspection and characterization of three-dimensional objects without the confusion from superposition of structures that occurs with simple projection radiography. Once it is developed, CT will provide an important tool for full inspection and characterization of welds in pits.

We are developing an x-ray CT system using a commercial electron linac with 9-MeV electron energy that produces an appropriate x-ray spectrum and gathers data in a reasonably short time. The x rays have a substantial population in the 1–4 MeV range. X rays with this high energy are extremely difficult to image with high efficiency and clarity.

We adopted an approach for using a scintillator to convert the x-ray image into visible light, then using optics to transfer the light to a charge-coupled-device (CCD) camera. A schematic of the system we have developed is shown in the figure. To protect the camera from scattered radiation, we employ two turning mirrors in the optical chain. The large number of pixels in the CCD enables us to simultaneously measure x-ray transmission for more than a million rays through the object. We typically employ a thousand different rotation angles (views of the object).

The second component of this work is to develop computer algorithms that employ prior data to improve the reconstruction. Much is known about each pit from inspection data and other sources. This information can be used to guide the image acquisition strategy and to constrain the reconstruction.

We performed simulations to guide the system design. Some are simple ray-tracing calculations; others are full Monte Carlo transport calculations with secondary-particle following. The simulations show that the spread of secondary radiation in the scintillator limits resolution and the spread increases sharply with scintillator thickness. Image-acquisition time is nearly inversely proportional to scintillator thickness, so a trade-off occurs between scan time and scan resolution. Experimentally, we demonstrated a resolution of 0.005 in., based on the measured full width at half the maximum line-spread function.

Using a prototype system, we demonstrated CT of a complete weapon pit showing features not possible with conventional film radiography. In addition, we are imaging test objects containing welds. The objects have been fabricated to represent small intentional "defects" in the weld, but contain no special nuclear material.

Using simulated and actual data, we have also improved the algorithm for reconstructing an early test object made of depleted uranium and steel but no weld.

This project led to several important innovations. Because focusing the lens using x rays was tedious and imprecise, we devised an insertable focusing camera using visible light. It is cofocal with the main CCD, allowing focus on a resolution chart at the scintillator using visible light. We also introduced an x-ray fiducial that is fixed with respect to the scintillator. Now we can computationally correct for any image position drift that occurs during data acquisition.

We plan to complete the technology demonstrations, optimize the basic design, and then work with a private-sector company to construct a reliable, user-friendly system for use at Pantex.

Turning mirror

Optical path 63–165 cm

Scintillator

Turning mirror

Imaging lens

Axiom AX-2 digital camera
1536 × 1024 pixels
9 μm pixel size

Object

3-m source detector distance

Center line of array

Axis of column array

Axis of rotation

Schematic of the data acquisition system used for computed tomography of weapon pits.
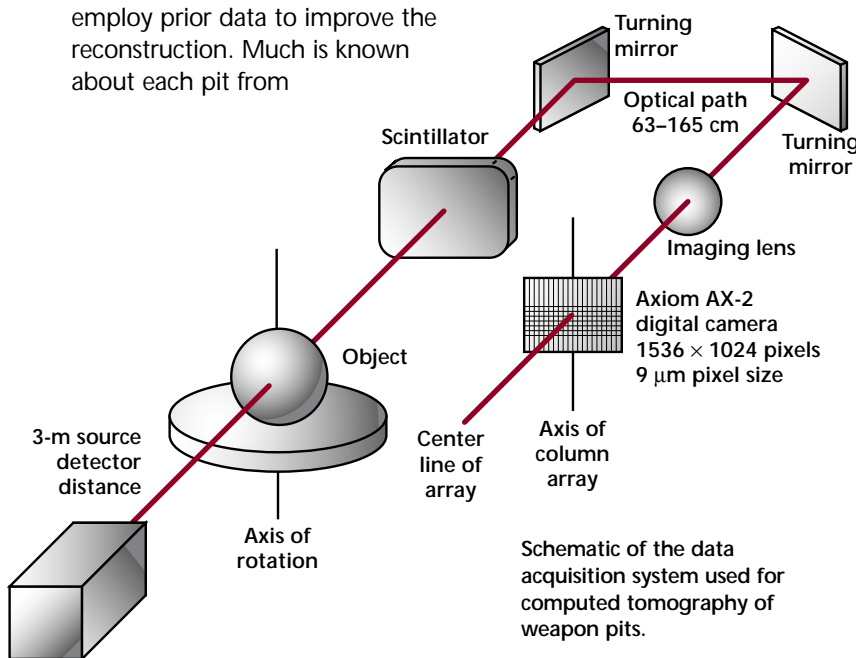
Advanced Ultrasonic Tomography

This project supports research, development, and modeling of novel ultrasonic inspection techniques and enhanced imaging and reconstruction methods to assess stockpile condition. The tools under development are providing important new insights into the analysis and interpretation of complex ultrasonic data and will ultimately prove crucial for nondestructively detecting early manifestations of component deterioration. The work is directly applicable to pits and gas reservoirs.

Ultrasonic imaging offers unparalleled sensitivity to small defects and density variations. For instance, digital radiographic methods are incapable of measuring density variations of less than 0.5%, whereas ultrasonic techniques can detect 0.01% variations. Thus, ultrasonic techniques offer the possibility of both measuring and imaging subtle changes in materials due to aging that cannot be assessed radiographically.

Ultrasonic imaging methods have evolved substantially from the techniques used in the 60's and 70's when the bulk of the stockpile was created. One of the most significant advances has been the ability to automatically acquire vast amounts of data with computerized high-frequency equipment that was not available even a few years ago. Because parameters inherent in the full waveform are often indicators of subtle material conditions, if not of overt flaws, full waveform-capture ultrasonic scanning is an important tool for rapid, inexpensive evaluation of stockpile status.

Our goals are to perfect ultra-sensitive inspection techniques that capitalize on vastly increased hardware capacity and to reconstruct the enormous quantities of multi-dimensional raw data into standardized forms that can be easily interpreted, quantified, and compared against one other. Problems of interest include quantifying residual stress, weld inspections, bond quality assessment, and grain size measurements. Data reduction methods under development—specifically 3D interactive visualization, velocity tomography, and time reversal imaging—have the potential to serve as powerful enhancements to conventional ultrasonic testing.

Significant progress has been made in several areas:
• A new signal processing technique for enhancing signal to noise in highly attenuating media such as polymer potting compounds. The multiple comparative energy loss method identifies difficult-to-detect voids with contrast and resolution far superior to infrared thermograph and other competing methods.
• A unique ultra-sensitive capacitative pressure transducer for measuring third-order elastic constants. Variations in such parameters may provide new insight into polymer bond degradation and aging. The capacitative transducer is also useful for calibrating ultrasonic transducers, superconducting quantum interference devices, and quantum sensors.
• An interactive, 3D visualization and image analysis package for processing ultrasonic inspection data as well as data from other common imaging modalities (e.g., x-ray and neutron computed tomography). The software imports, renders, and manipulates full waveform data from various commercial systems in common use within the nuclear weapons complex. The package includes a variety of signal processing, image enhancement, and display features, including contouring, edge sharpening, data warping, animations, and isosurface rendering. To support multiple imaging modalities, we are moving toward data fusion capabilities for enhanced defect identification and characterization.
• Initial use of newly released ultrasonic modeling codes to simulate data acquisition from otherwise difficult materials and conditions to determine algorithm performance and provide quantitative inverse solutions.

From left to right (scan orientation not aligned with photograph): Phantom test piece with fabricated void defects; typical infrared thermography results; normal ultrasonic tomography scan using interface echo technique; post processing of the same part imaged using comparative multiple energy loss technique to enhance signal-to-noise ratio. The absence of silastic, shown in red, is clearly visible using this method.
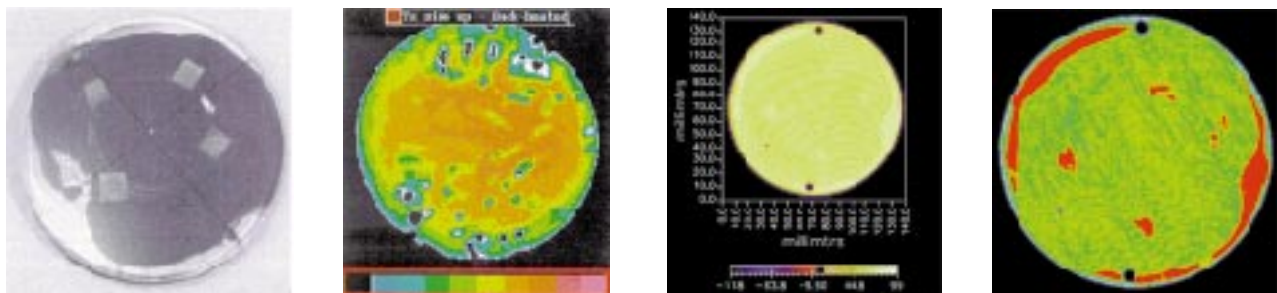
Enhanced Ultrasonic Characterization of Assemblies

A team from Lawrence Livermore National Laboratory (LLNL), Y-12, AlliedSignal, and Savannah River is developing ultrasonic technologies for the nondestructive evaluation of bonds in weapons components. Advanced ultrasonics will allow the quality and strength of autoclave, solid state, and adhesive bond lines to be assessed, thereby contributing information on how a weapon is aging and what remaining life it has. The technology developed for this task includes specialized ultrasonic scanning systems and signal processing and pattern recognition algorithms that advance our capabilities to detect and characterize bond defects. This work will result in a demonstrated measurement capability that provides high-resolution images of bond lines that display quality variations in a weapon component. This capability will be suitable for routine surveillance testing at DOE production sites.

Because there are four participants in this project, the first step was to determine the baseline ultrasonic capabilities existing at the four sites and decide on the standardized hardware and software needed by each participant for cooperating on the work. Each site acquired the necessary standardized ultrasonic instrumentation and data acquisition systems. Next, the team agreed on the characteristics in bond specimens that would be representative of potential problems in the stockpile. Bond specimens with those characteristics are currently being manufactured at LLNL and other sites. These bond

Ultrasonic scanner for assessing bond quality.

specimens will be used for testing and diagnosing new ultrasonic hardware and software.

Lawrence Livermore is developing and implementing classification techniques for correlating information contained in ultrasonic bond line signals with the quality of the bond. Sets of bond specimens with known pedigrees have been acquired, and ultrasonic data acquisition systems are being developed to collect data about the specimens. Signal processing algorithms are being written and implemented to process the ultrasonic data and reject noise. Feature extraction and selection software are also in development to identify the pertinent characteristics of ultrasonic signals for bond quality determination. The classification software is based on statistical pattern recognition and probabilistic neural networks.

During the classification algorithm training phase, the best classification process will be determined by analyzing the ultrasonic signals of specimens with known bond quality; that is, the bonds have been measured by strength testing and microstructural analysis. When this training phase is complete, the selected classification process will be verified by processing a second set of ultrasonic signals from bonds of unknown quality. Once proven, classification procedures will be implemented into ultrasonic inspection systems, along with advanced methods for displaying the results. For instance, variations in bond quality may be displayed as different colors, and the displays could be either two-dimensional or three-dimensional images.

The design and fabrication of an ultrasonic scanning system for weapon components began this year and went through three design iterations. The figure shows a three-dimensional rendering of the system. The ultrasonic instrumentation has been specified and purchased. The control computer has been acquired. Some of the data acquisition and motion control software has been written. The bond classification algorithms developed by this project will be implemented in this scanning system to provide images of bond quality. Production versions of this system will be built and installed at the appropriate sites for surveillance testing.
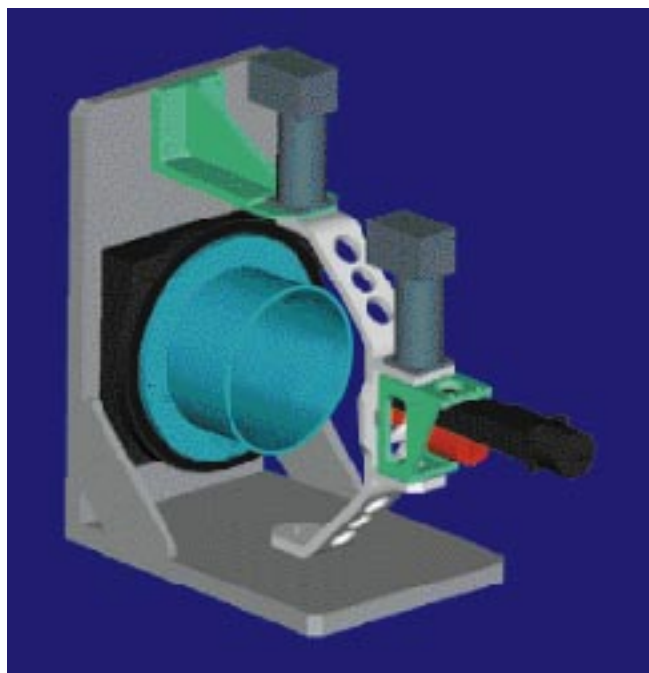
Enhanced Inspection of Reservoir Girth Welds

A unique ultrasonic inspection method has been developed and demonstrated for inspection of tritium reservoir girth welds. This method is capable of detecting intergranular cracks in the weld heat-affected zone as well as weld flaws such as porosity and lack of fusion in the weld bead. We developed a separate type of inspection for two different reservoir configurations. The LF- and M-type reservoirs have a mid-body belly band girth weld, and the K-type reservoirs have a circumferential cap girth weld. Ultrasonic inspection has the potential to monitor in-service degradation in the Shelf Storage and Reservoir Surveillance programs and detect welding defects during fabrication of new reservoirs.
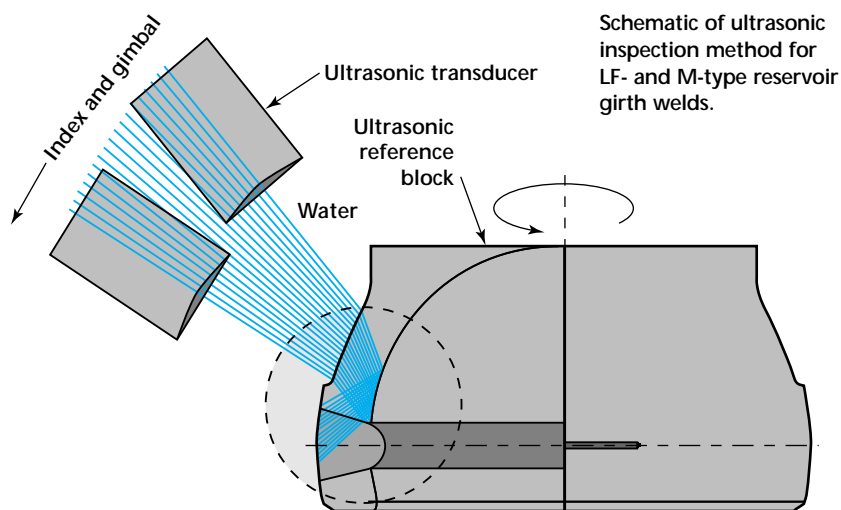
A conceptual drawing of the ultrasonic inspection method for the LF- and M-type reservoir girth weld inspection shows that a water immersion method is used to provide coupling of the ultrasonic signal to the reservoir. A computer-controlled inspection device simultaneously rotates the reservoir around its axis and indexes the ultrasonic transducer in discrete increments to interrogate the weld heat-affected zone. A mechanical gimbal maintains a constant incidence angle of the inspection ultrasound beam to the surface of the reservoir. Ultrasonic signal feedback is collected and correlated to positional information by the computer-controlled inspection device and the data acquisition system. For complete inspection of the girth weld full coverage, scans are conducted above and below the girth weld and in the girth weld bead. A standard 10-MHz ultrasonic transducer is used for inspection of the girth weld. The data acquisition and processing system is capable of rendering color graphic representations of the inspection results.

The inspection method developed for the K-type reservoir cap girth weld is a direct contact method that can be applied manually in the field or laboratory. It employs essentially identical ultrasonic inspection and data acquisition and processing equipment as the immersion method described for the LF- and M-type girth weld, but it does not require a sophisticated mechanical inspection device.

Accomplishments in this program to date include the following: (1) The contact inspection method for the K-type reservoir girth weld has been fully developed and demonstrated in the laboratory on calibration standards. Field inspection procedures have been written and inspection technicians have been trained and certified in the inspection method. Five K-type reservoirs have been sampled from the stockpile for inspection in a field laboratory. (2) Calibration standards for the LF- and M-type reservoirs have been machined, and the immersion inspection method has been successfully demonstrated manually in the laboratory. (3) A programmable immersion inspection device with computer controls has been located at the Savannah River ultrasonic inspection development laboratory, and software and hardware upgrades required to fully automate the inspection system have been identified and cost estimates obtained.

This project is a collaboration with the Los Alamos National Laboratory. Funding is being leveraged with the Reservoir Surveillance Operations and Shelf Storage Program conducted at the Savannah River Technology Center.

Schematic of ultrasonic inspection method for LF- and M-type reservoir girth welds.

Index and gimbal

Ultrasonic transducer

Ultrasonic reference block

Water

High-Energy Computed Tomography Detector Array

This year, much progress has been made in developing a high-energy computed tomography (CT) detector array and capability. Specific accomplishments include:

• Acquisition of components.

• Integration of hardware with prototype control/data acquisition software.

• Design and fabrication of necessary cables, boards, boxes, etc.

• Evaluation of several collimator designs and simulation of their performance.

• Selection of final collimator design and fabrication of a single channel for actual testing.

• Development of data acquisition and control software design and testing of prototype software.

• Development and testing of reconstruction software in concert with other programs. The software was found to be compatible with all our detectors and sources.

The last four items deserve additional comments and explanation.

We carefully considered the design of the collimators to yield the best performance possible. Three basic designs were proposed and individually evaluated. Some of the points considered were the feasibility and cost of manufacture, collimator performance, and ease of use. The "ideal" design, a 0.3-millimeter air bore with a solid

tungsten collimator, was dismissed after several machine shops across the country reported that they could not fabricate the parts required. The selected design is a 0.3-millimeter beryllium bore with a collimator made of both powdered and solid tungsten. Performance simulations on this design show it to be nearly ideal and not a limiting factor in the performance of the detector. This design was fabricated and tested.

Data acquisition and control software has been designed to be interoperative with our reconstruction and rendering software, thus reducing the cost and effort associated with this capability. The user interface for all our CT systems have been unified in this effort. The agreed upon data standard has already proved to be very robust and flexible in that it has accommodated several additions and improvements without the need to redesign the data and file structure.

The reconstruction software necessary to process the data from the detector array has been designed to be common to all of our detectors and sources, and its development has been supported by other programs. This software is PC-based, fast, easily amenable to distributed and/or parallel processing, and can execute in parallel with the data acquisition. It is also available to run, essentially without change, on a variety of platforms. It can easily be executed on workstations, larger computers, and even teraflops machines, as well as on the PCs currently in use. The figure shows the kind of reconstruction possible with this system. The data in this image are from a low-energy source and are of a resolution target developed by AlliedSignal/Federal Manufacturing & Technologies.

In the final analysis, this high-energy detector array shows great promise as an accurate, high-resolution inspection tool for use with pits, canned secondary subassemblies, re-entry vehicles, other weapons parts, and non-weapons parts.

Preliminary reconstruction of a resolution target from AlliedSignal/ Federal Manufacturing & Technology. The small wires are 0.5 mm in diameter. The bend in one of the small wires is real.
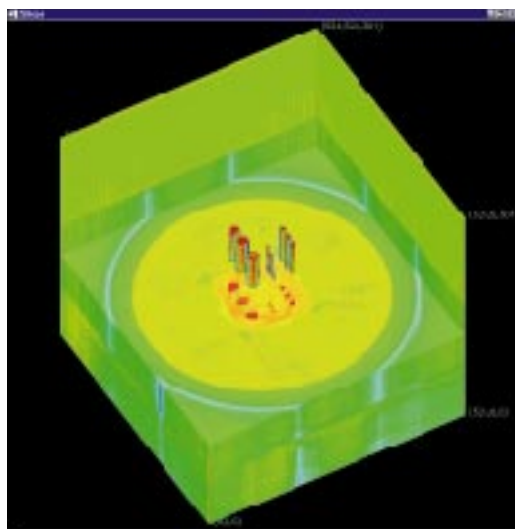
Development of SQUID Microscope for Surveillance

Since the first data was acquired in late August 1997, numerous changes have been made to the superconducting quantum interference device, or SQUID, microscope system to improve induction coil centering and to implement an automated motion control and data acquisition for precise scanning. The SQUID microscope control and data acquisition software package has been written in LABVIEW integrating SQUID device control, motion control, and data acquisition. We confirmed very high sensitivity for both extremely small and deeply buried defects (beneath millimeters to centimeters of intervening materials).

A stress fracture in a Ti-W surrogate was clearly observed, demonstrating the severe lattice defects were not necessarily evidence of a physical separation. A series of measurements were made using aluminum plates with various cracks and holes. The SQUID microscope detected even the smallest cracks beneath several millimeters of intervening conductor. Similar results were obtained using 1-cm-thick plates of titanium (having similar conductivity to U and Pu).

A second induction coil design was tested and found to significantly decrease sample edge effects. This observation led us to initiate the modeling effort using a finite-element electromagnetic code to better understand this and other effects.

A systematic study of seam widths using the titanium plates showed a clear trend in signal amplitude (a similar trend was observed for the phase) as a function of seam width. Seam-width resolution better than 0.005 in. can easily be attained with this algorithm. A computer code to analytically calculate seam width is currently in progress and should enhance the resolution dramatically. The greatest challenge is developing the required sensitivity within our computational capabilities.

We began using plates with a 100-μm copper layer to test sensitivity to scratches and determine spatial resolution. We recently scanned a plate scratched with "P-21" and found we could resolve the image from raw data.

Currently our work focuses on refining the finite-element model to

the required sensitivity and resolution and validating the results. Work continues on the analysis codes to further quantify seam widths in titanium samples. We are designing optimal induction coils to test the ability to target features at specific depths in the sample. We have designed an experiment to identify cracks in a thin layer of conductor buried under other layers of conducting and nonconducting materials. Calibration plates are being fabricated to help quantify the effects of feature width and depth.

AlliedSignal/Federal Manufacturing & Technologies completed a brass-board flux-locked loop electronics package for controlling SQUIDs. The package was integrated with a SQUID, supplied by Los Alamos National Laboratory, similar to that used in the current SQUID microscope. Slew-rate performance was benchmarked at $>3 \times 10^6$ Φ_0/s, exceeding the current published world record ($<2 \times 10^6$ Φ_0/s) for DC SQUID performance. Significant improvements will be realized by optimizing the circuit and HF-packaging techniques. The huge slew rate enables us to use SQUIDs over previously unrealized dynamic range and handle transients that would typically unlock a SQUID. This capability is important for the surveillance programs because it will enable the SQUID microscope to be more easily incorporated into the very noisy electromagnetic environments of the plants.

SQUID microscope prototype (above). Upper plot shows raw data for seams of various widths in a 1-cm-thick titanium plate. An unflawed titanium plate of the same thickness covers the seamed plate. Lower plot shows the width of a fit to the data as a function of seam width.
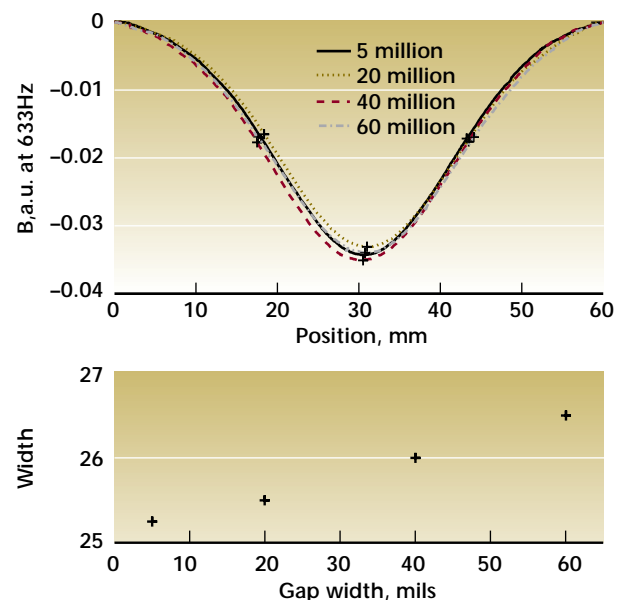
Solid-Phase Microextraction

Using microcollection and analysis of chemicals in the weapon backfill gases, we are developing a simple yet unique method to nonintrusively establish weapon environment and integrity of materials. The targeted chemicals outgas from the high explosives as well as from other organic materials in the weapon assembly. This technique detects changes in these materials because of aging as well as defects. This valuable tool will remotely detect and assess the aging of organics in weapons and will identify potential compatibility issues (materials interactions) that should be more carefully monitored during surveillance teardowns.

Microextraction is implemented within the weapons complex because it is safe, transparent to current surveillance activities, and provides a wealth of chemical information. Collection, which is typically in the low-nanogram range, does not interfere with the weapon headspace either by depletion or contamination. The gas volume collected is limited to the dead volume of the microextraction collection vessel that holds the fiber assembly. The current design, as shown below, has a dead volume of 2.5 ml. This device, tested online with the new moisture sensor, which is part of the Phoenix gas-sampling manifold, has no effect on measurements down to the lowest tested point of 10 ppm.

The collection process uses a fiber, 1 cm long by 100 μm in diameter, coated with an absorbent that accumulates chemicals without bulk collection of the backfill gas. Following collection, the fiber is hermetically sealed and analyzed on a bench-top gas chromatograph/mass spectrometer (GC/MS).

The advantage of this collection technique is its high delivery efficiency for GC analysis. Compounds collected by the fiber absorbent can be desorbed directly at the tip of a GC column with little loss or dilution. This results in high sensitivity, even for polymer fragments. The mass spectrometer provides molecular weight and structure information needed for positive identification in the low- and sub-ppb range. With this approach, we can identify unknown compounds as they exist in a complex mixture at trace levels.

In this application, we have found that microextraction is particularly useful on compounds having high surface activity (sticky) and those that are difficult to collect and transfer to an instrument for analysis. Significant losses of even volatile compounds occur when sampling is done at the gas bottle port through a gas sampling manifold (Blue Goose) that is currently used for collecting permanent gases. When sampling is moved upstream to the purge valve, we can collect and identify for the first time known polymer degradation fragments from silicone and polysulfide materials. This information is being compiled into a living database that will be used to help pinpoint potential problems.

During FY1998, a significant number of weapons and compatibility test assemblies were sampled—nine B83s and 16 aging/compatibility test units from the W68, B83, and W84 programs. The W68 and W84 compatibility test units are relevant because they use materials found in the enduring stockpile weapons. To assist in interpretating the weapon signatures, data from these compatibility test units are combined with signatures obtained from material and chemical standards used in the weapon components and during manufacturing.

With Sandia, we are completing initial evaluations of materials used in the B83 weapon primary and fireset. A survey of materials used in the W87 physics package was completed, and a report was generated on formulation information, which is critical for differentiating decomposition products.

B83 coring tool

Micrometer-sized fiber
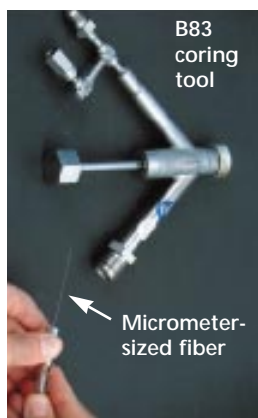
Comparison of chromatogram signatures for the B83 weapon taken at three sampling locations: the weapon purge valve, 50-cm downstream, and the gas bottle port (2-m downstream). At the latter two downstream, less volatile compounds are not detected at elution times of around 20 min. (Note: Those peaks not labeled have been identified as either material synthesis precursors, aids, or byproducts, or manufacturing aids. Most of the signatures seen at 30 min are background from the fiber septum seal).

— In coring tool
— At 50 cm
— At gas bottle port

● Silicon decomposition products
● Polysulfide decomposition products

Time, minutes
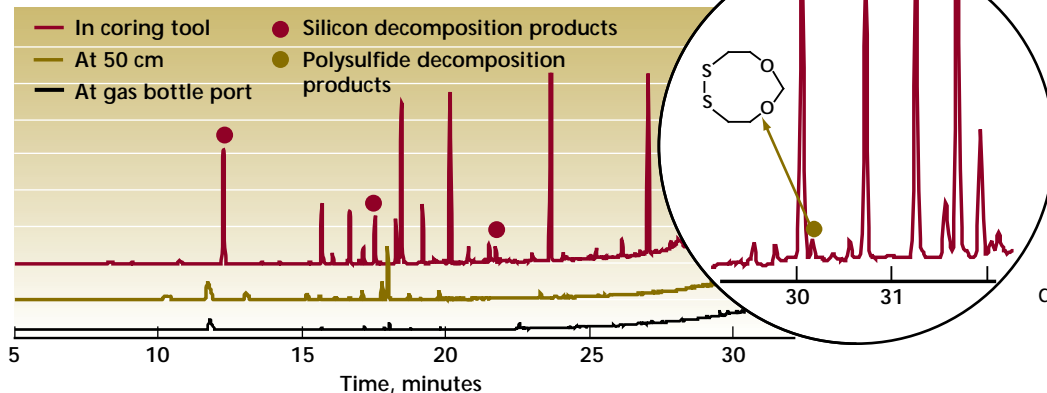
Sensor Technology Development

Fiber optic-based sensors for selected environmental conditions and selected chemical species are being prototyped and evaluated for weapons aging studies. Several different hydrogen sensors have been tested and portable systems for them have been prototyped. Three different hydrogen sensors—palladium, yttrium/palladium and palladium Bragg grating—have been fabricated. They are currently being evaluated in materials aging and component studies.

The palladium fiber optic sensor and spectrometer system fabricated at Savannah River Technology Center (SRTC) has been evaluated by AlliedSignal/Federal Manufacturing & Technologies (AS/FM&T). The first deployment of this environmental hydrogen sensor is anticipated for a materials aging and compatibility test scheduled to begin in FY1999. Aging canister sensor heads utilizing glass-to-metal fiber optic seals (see figure, below left), which were developed in task LL32, were fabricated at the Kansas City Plant and sent to the Y-12 Plant. These sensor heads were equipped with the Savannah River hydrogen sensor lens, Lawrence Livermore National Laboratory (LLNL) hydrogen sensor, and Entran pressure transducer. Core stack kinetic and aging studies utilizing these sensor heads began at Y-12 in June 1998, over a year ahead of schedule.

The AlliedSignal yttrium/palladium fiber optic hydrogen sensor has a potential increase in sensitivity greater than 10 times the palladium sensor. Initial adhesion problems with yttrium to glass have been corrected by adding a thin coating of chromium to the glass before the yttrium/palladium coatings are applied. This new process was used to coat lenses that are interchangeable with the Savannah River sensor lenses. Initial tests of these coated lenses in sensor heads indicate no adhesion problems.

The prototype Bragg grating sensor system (see figure, below right) uses a fiber laser with fiber optic Bragg gratings for hydrogen concentration and temperature measurement. The fiber optic hydrogen sensor is 0.4 mm in diameter and 3.81 cm long. The fiber optic temperature sensor is 1.5 mm in diameter and 3.05 cm long. Both sensors are totally optical and introduce no electrical energy into the test vehicle. The prototype system was built into an aluminum case for portability. A laptop computer provides data acquisition, reduction, and display.

A materials science study to improve the response time of the Bragg grating hydrogen sensor is ongoing. It involves the introduction of porosity into the palladium film by alternative fabrication techniques, such as electroplating and plasma flame spraying. Although the current hydrogen sensor is useful for enhanced surveillance studies, a faster response time would make it more desirable for kinetic studies.

AS/FM&T, SRTC, LLNL, and Oak Ridge National Laboratory are working closely to develop multi-use applications for real-time environmental sensors for aging and materials compatibility tests.
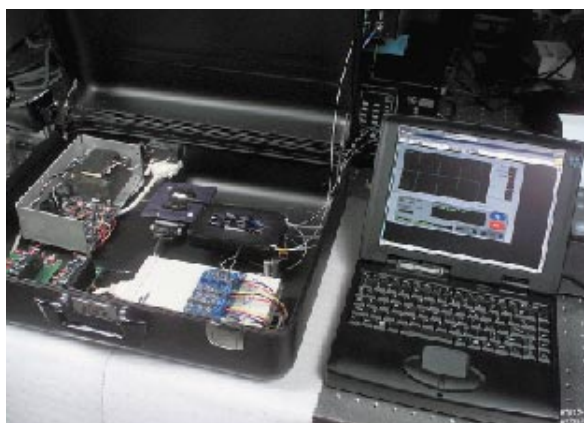
Prototype hydrogen sensor installed in aging canister cover and readout (left) and prototype Bragg grating hydrogen sensor and associated opto-electronics (right).

Microsensors for Evaluation of Materials Degradation and Corrosion in Weapon Systems

This project's long-term objective is to develop a suite of chemical sensors for real-time monitoring of changes in stockpile materials. In the near term, the sensors will provide kinetic data never before accessible from Core Stack Compatibility Tests (a suite of tests that use a stacked array of materials to evaluate materials compatibility and compare various weapon design options). These sensors will provide the capability to verify component and weapon integrity by analyzing their dead volume gases. The presence of certain volatile chemicals in the monitored environment indicates material degradation. These sensors will be incorporated in a protocol for component inspection, refurbishment, and retirement. This year's success is the result of an extremely productive collaboration involving AlliedSignal/Federal Manufacturing & Technology, Savannah River Technology Center (SRTC), Y-12, and Lawrence Livermore National Laboratory.

The most significant accomplishment this year is the successful initial attempts to integrate chemical sensors for hydrogen into Core Stack Compatibility Tests at Y-12. For the first time ever, these sensors offer the potential for obtaining real-time kinetic information. In addition, progress has been made in developing chemical sensors for other gas-phase species.

The photograph shows integrated hydrogen sensors and a schematic of the setup. These tests have been running with no apparent significant deterioration in sensor performance. Simultaneous pressure measurements in the retorts are also being recorded. Three independent test assemblies are being continuously monitored. Using our current system multiplexer, which switches between sensors, monitoring is possible for up to 16 assemblies. Data acquisition and analysis is still in progress by the end of FY1998.

Prior to starting the tests, we determined from calibration curves that the sensors would show response to at least 0.1% H_2 at 760 torr. We are working to improve responses at lower pressures to obtain better sensitivity limits and stability. Improvements in multiplexer and in the sensor design (including adding an internal reference) are underway.

Our current effort focuses on developing fiber-optic sensors. The key element of these sensors is a chemically selective thin-film coating deposited on the end of the fiber. Any gas-phase component that exhibits a high affinity for or reacts with the coating is collected on the end of the fiber and detected spectroscopically.

As a first step, we have chosen to demonstrate a sensor for hydrogen. The hydrogen sensor that has shown the greatest promise was developed at SRTC. The design, shown in the upper schematic, includes a thin palladium alloy film deposited on the end of the quartz lens. Two optical fibers are affixed to the lens. Light from a tungsten halogen lamp is launched down one fiber and collimated by the lens. The light reflected from the metal film surface is transported back to a spectrometer by the second fiber. When hydrogen is present, it is absorbed into the palladium alloy film, changing its optical (reflectivity) properties. Using this sensing concept, we have demonstrated a reversible response to hydrogen in the range of less than 0.1% to several percent. Our sensor is an improvement of an earlier micromirror design, first proposed by Butler and coworkers at the Sandia National Laboratories.
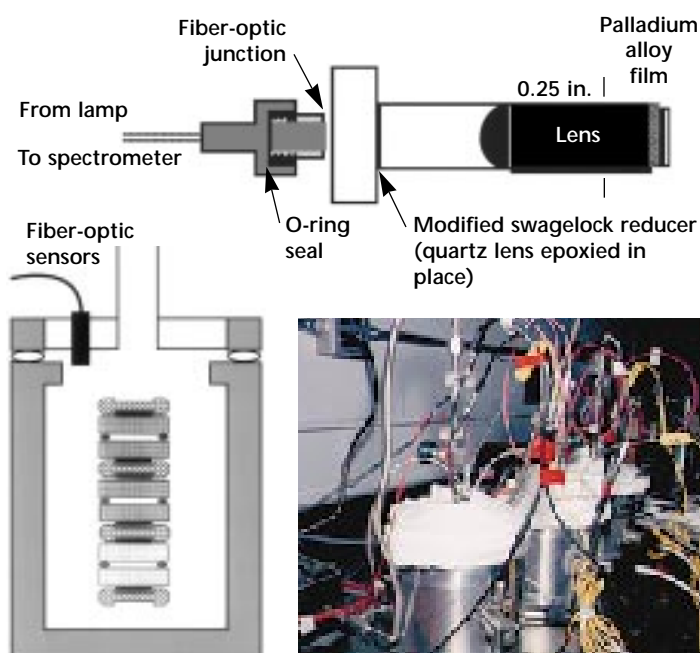

Photo of Core Stack Tests with integrated hydrogen sensors and schematics of hydrogen sensor design and core stack assemblies.

Systems Engineering of an Arming, Firing, and Fuzing Testbed

The purpose of this project is to understand the systems engineering issues associated with incorporating chemical sensors in a weapon subsystem. Systems issues of safety, reliability, volume constraints, sensor accuracy and drift, power demand, and communications are being considered. Our focus at this stage is placing existing instrumentation into an arming, firing, and fuzing (AF&F) unit taken from the stockpile to assess the state of the art and guide the evolution of embedded sensors. Ultimately, chemical sensors will be used in a suite of *in-situ* diagnostics and built-in test features where they will enhance surveillance testability and augment the traditional disassembly and inspection methods of determining subsystem state of health.

Based on past and present investigations, an initial set of sensors for hydrogen, water vapor, pressure, and temperature were selected. The table lists the instrument measurement ranges available for these sensors.

We are using an integrated nuclear materials monitoring (INuMM) electronic sensor package that contains each of these sensors. The INuMM package, which was originally developed to monitor stored pits, will be installed into a W68 AF&F that has been modified to provide the necessary volume for the sensor package. The figure shows a W68 AF&F and hydrogen sensor calibration data.

Two W68 AF&F units, retired from the active stockpile, are currently under modification at the Kansas City Plant (KCP). These units were selected because of their ready

availability and the recently developed database on the composition of the internal atmosphere of the W68 AF&Fs.

Testing will commence early in FY1999. During testing, gas samples will be withdrawn periodically for gas chromatography/mass spectroscopy analysis and compared against the data telemetered from the self-powered INuMM package/hydrogen sensor sealed within the testbed. The data will also be compared with the periodic solid-phase microextraction data recorded for similar W68 AF&F units sampled at KCP.

An improved water-vapor sensor that uses chemiresistor technology and has a measurement range of 200 to 50,000 ppm will be incorporated in the INuMM package in FY1999. This sensor will also detect a number of organic vapors.

Sensor ranges for preliminary testbed	
Sensor	**Measurement range**
Hydrogen	10 to 10,000 ppm
Water vapor	5% to 90% RH
Pressure	0 to 15 psia
Temperature	–15 to 60°C
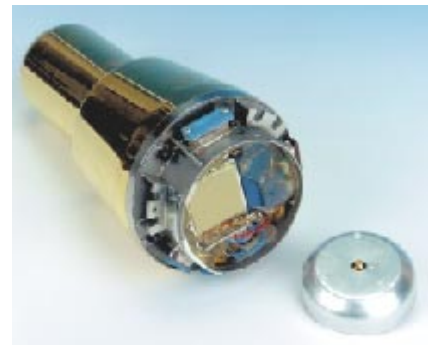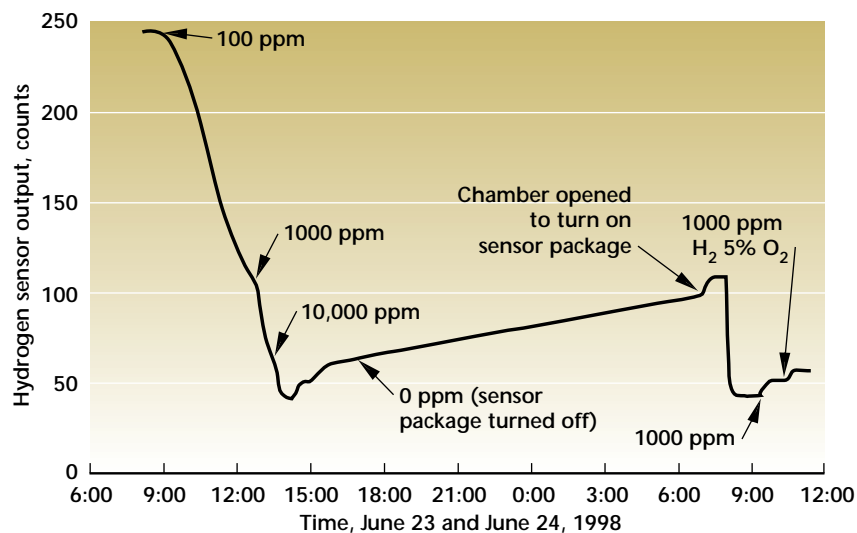
W68 AF&F (above) and calibration data for the hydrogen sensor in the INuMM electronic sensor package.

Weapon State-of-Health Monitoring

We are developing chemometric tools based on advanced statistical analysis and pattern recognition methods to extract time/age information from the gas analysis of weapon internal atmospheres. The fundamental hypothesis underlying this project is that the weapon's integrated time/temperature history is encoded in the composition of its internal atmosphere. Application of the advanced modeling and pattern recognition techniques provide a general indicator of an individual weapon's state of health. Non-intrusive gas sampling coupled with chemometric data analysis extracts more aging information from current surveillance gas samples and data than has previously been available.

Our research shows that each weapon type has a unique gas signature resulting from the outgassing and aging of materials in the weapon. As a weapon ages, its gas signature changes slightly. This change can be detected and modeled using chemometrics. The chemometric model extracts age-related information imbedded in the gas signature, flags peaks (i.e., compounds), and predicts an age for the unit. Discrepancies between the predicted age and the actual age can signal the presence of a unit whose signature is distinctly different than the rest of the weapons of the same type and of the same age. The unit can then be studied further to determine the reason for the discrepancy.

An example of extracting age-related information from a weapon's internal atmosphere is shown in the figure. These data were taken from routine surveillance for the B83 and illustrate how age-related information can be obtained from the analysis of organic gas data. Although the data set is limited, the predictive capability of the model is seen to be very good. A much larger data set has recently become available for the W80 from the field sampling effort (see SN17, Enhanced Gas Analysis for Diagnostics and Surveillance). A cursory analysis of this data set (~100 samples) shows that age-related information is also contained in the W80 data.

The sampling of weapon and component atmospheres has recently been enhanced by orders of magnitude with the introduction of solid-phase microextraction (SPME). The gas sampling station in the figure is used to collect pressure and moisture data, as well as to collect gas samples both with and without the use of the SPME technique.

This technique extends the sensitivity of methods such as gas chromatography/mass spectroscopy so that the number of species detected is an order of magnitude higher (depending on the system) and the signal-to-noise ratio of the chromatograph is more than an order of magnitude higher than that for a gas phase sample. With this richness of data, chemometric techniques of data analysis become all the more important.

This work is a collaborative effort between AlliedSignal/Federal Manufacturing & Technology, Pantex, Lawrence Livermore National Laboratory, and the Sandia National Laboratories.
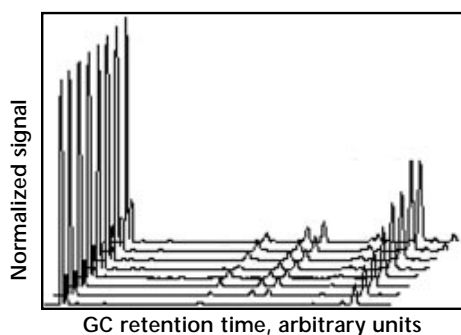
Typical organic signature (gas chromatography raw data) from eight B83s is shown above; results from modeling data obtained from twenty-two B83 units with a prediction for eight more units are shown on the above right, and a gas sampling station (right) for sealed components such as arming, fuzing, and firing systems at the Kansas City Plant.
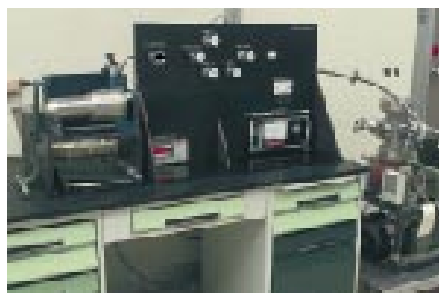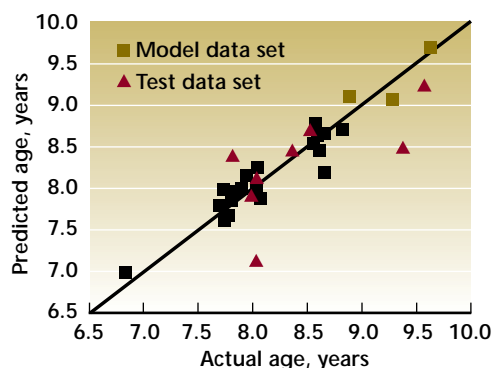
Identifying Damage with High-Resolution Vibration

The goal of this work is to develop a nondestructive weapon monitoring and damage-detection system using high-resolution vibration analysis. The final product will augment existing surveillance tools for enhanced assessment of the stockpile. Detecting damage internal to canned subassemblies (CSAs) is the primary focus.

The basic concept of vibration testing is that dynamic parameters (acceleration time histories, resonant frequencies, mode shapes, and modal damping) are a function of the physical properties (stiffness, mass, damping, and boundary conditions) of the component or system. Thus, changes in physical properties of a component or system, such as its stiffness, cause changes in dynamic response.

A wealth of damage identification algorithms exists for detecting the presence of damage and location in structural and mechanical systems. Algorithms have been applied with varying degrees of success to detecting damage in bridges, the NASA Space Shuttle, and other structures that undergo flexural vibration. However, the simplified CSA models, developed earlier as a part of this program, undergo axial or membrane vibrations rather than bending (flexure). Damage-identification algorithms had not been applied to this type of vibration; therefore, two promising methods, damage-index and change-in-flexibility, were modified early in this program to specifically treat vibrations experienced by CSAs. Preliminary numerical simulations performed in FY1997 indicated that both these methods could detect as little as a 10 percent reduction in stiffness.

During 1998, construction of a vibration testbed for verification of these modified damage-ID algorithms was completed (see figure), and experiments were performed. The generic vibration model consists of a series of masses connected by springs, all free to vibrate on the mounting rod. The system was instrumented with accelerometers mounted on each mass. In addition, a force transducer was mounted at the point of vibration excitation so that frequency response functions could be constructed to provide both natural frequency and mode shape information. Excitation was accomplished either by an electromechanical shaker or impact hammer.

Damage was introduced in the system by substituting a spring of lower spring constant at selected locations. Damage levels of 7, 14, and 24 percent were introduced sequentially at three locations in the system. After data were taken for damaged and undamaged systems and reduced in terms of natural frequencies and mode shapes, the modified damage-index and change-in-flexibility

methods were applied using the data. The damage-index method consistently detected the location of the damage in the generic vibration model at all locations, even at the 7 percent damage level. Results using the change-in-flexibility method were inconsistent.

Two favorable attributes of the damage-index method: it indicates the presence and location of damage. Two significant drawbacks: the method is appropriate only for detecting linear forms of damage and spatial information is required.

Because of the mixed results of the two methods, another damage-ID method has been developed, based on principles of statistical pattern recognition (previously applied to speech recognition). Although the method does not predict damage location, it does predict the presence of damage for linear and nonlinear systems. Further, only external measurements on the CSA would be required. Using the same spring-mass data as above, this new method has been successful in predicting the presence of damage in all cases.

Detection of impact-type damage is being investigated. This problem is fundamentally nonlinear, so a simple analytical model for the components has been developed. Testing using the vibration testbed, but with an impact rod inserted between two of the masses to simulate a different kind of damage, is under way now. Preliminary data are being evaluated using the statistical pattern recognition. Soon, this method will be applied to external dynamic response measurements from an actual CSA.
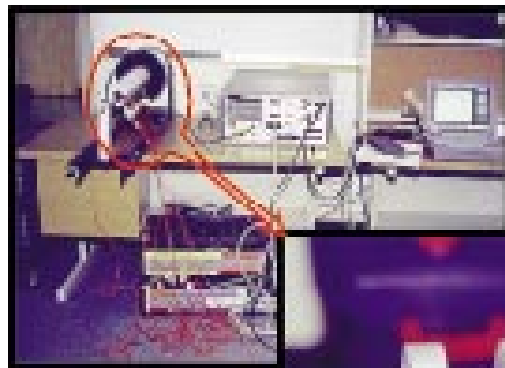
Experimental testbed used for vibration-based damage identification.

Low-Level Vibration and Advanced Signal Processing

We have combined many of the computer analysis tools developed in recent years into a toolbox known as Signal Processing and Modeling or SPAM. SPAM is a graphical user interface running in a MATLAB environment that combines common user interfaces for data management and preprocessing with the modeling and analysis tools. Modeling and analysis tools incorporated into SPAM include:
• ARMA and bilinear models
• Bendat zero-memory nonlinear model
• Canonical variate analysis (CVA) models
• Neural networks
• Probability density estimation routines
• Bootstrap statistics
• Pre- and post-processing tools including integration, differentiation, filtering, resampling, and typical spectral analysis tools

This interface makes the analysis capabilities available to a wide range of users at the Los Alamos National Laboratory and Y-12. The startup user interface is illustrated in the figure.

Any signal-processing task selects certain important features of the test data. A feature of interest may be, for example, mode shape or modal frequency. For stockpile surveillance units, we have developed a trial set of criteria. Each test unit will be ranked according to the following trial criteria:
• Resonant frequency and damping values indicated by the frequency response function and/or ARMA coefficients

• Degree of nonlinear response (CVA, coherence measures, and dimension of the state space)
• Deviation of probability density function from Gaussian
• Decision statistics for Hinich's Gaussianity and linearity tests (bispectral statistics)
• Generation of high-frequency signals in the power spectrum
• Air-bearing test results

Testing experience shows that these measurements provide useful indications of unit condition. Our ongoing air-bearing and vibration tests have produced an extensive time series database set, which is archived. Toolbox algorithms are applied to the data, and reduced set quantitative discriminating features are extracted based on the above criteria. We anticipate that these features will vary strongly with different aspects of unit condition. In concert with engineering analysis, we are developing statistical methods and criteria for categorizing the units in our test database.

Low-level vibration and air-bearing testing continues at Los Alamos and Y-12. These data add to our test database for each type of unit. For a number of systems, we have a statistically significant set of test data, both for air-bearing and low-level vibration tests. Pantex is currently developing a capability for air-bearing testing.

We are continually improving the algorithms used for the analysis of test data. Signal processing is a rapidly changing field, especially with regard to nonlinear systems. Systematic analysis of the data from recent tests, combined with research into algorithms, should add to the capabilities in our toolbox.

The startup user interface of SPAM, the Signal Processing and Modeling toolbox.

# Laser Penetration and Rewelding for Gas Sampling

The purpose of this task is to develop a laser drilling and rewelding process for sampling and resealing the canned subassemblies (CSAs) so that new surveillance diagnostics may be incorporated in the CSA. Such a technique would provide the ability to sample gas within a unit and, depending on the results of the analysis, to reseal the unit for its return to the stockpile. Our goal is to demonstrate the feasibility of the hole drilling and resealing process and also implement a laser gas sampling and real-time analysis system in routine surveillance operations. The gas analysis system incorporates techniques being developed through other tasks, including infrared analysis in OR04 and solid-phase microextraction in LL13.

During FY1998, we demonstrated process feasibility on representative geometries. We demonstrated the feasibility of using a laser to drill a hole to sample the gas in a CSA and subsequently reseal the hole using a Nd:YAG and Nd:Glass laser on stainless steel flat plates and outgassing tubes. Several tubes were resistance crimp welded using production welding procedures to simulate secondary geometries. Process feasibility on representative geometries was initiated as shown in the figure below. Tooling was fabricated to orient the tubes at a 30° angle from the incident laser beam.

We also designed, fabricated, and tested a laser gas sampling stack/chamber. This chamber was sealed onto a CSA, providing a window for the laser beam and a port to obtain the gas sample. Leak and function tests were performed on the chamber assembly revealing that the system was leak-tight, although it exhibited an unacceptable leak rate when isolated from the vacuum source. Alternative sealing materials are being identified. A new gas sampling chamber with alternative sealing materials was designed and is scheduled for fabrication.

We evaluated process control parameters for the drilling and welding operation. Holes were drilled and welded in 0.010- and 0.030-in.-thick, type-304L stainless steel sheet using Oak Ridge Y-12 Development Division's Nd:YAG laser and the Y-12 surveillance laboratory's Nd:Glass laser. We drilled additional stainless steel samples at various parameter settings to determine optimum hole size for gas flow and fractionation. On the basis of these results, we are developing models of gas flow through these holes.

We also began work on the implementation plan for the laser drilling and welding process. We modified the laser operating procedure in the Y-12 surveillance laboratory to incorporate the welding process for resealing. Drilling and welding procedure specifications were written as separate, stand-alone documents. These specifications will contain all the necessary parameters to perform the drilling and welding operations and will be used when referenced by the laser operating procedure. A test of the laser drilling and welding process on a war-reserve-quality CSA was performed in the Y-12 surveillance laboratory. Drilling of the CSA adjacent to the resistance crimp weld was a success. The resealing and welding process revealed that the laser being used in routine surveillance operations is inadequate for resealing a CSA because of inherent alignment problems with the defocused laser beam. A new laser, modeled after the laser used at Los Alamos National Laboratory's plutonium facility, is being procured and should resolve this problem.
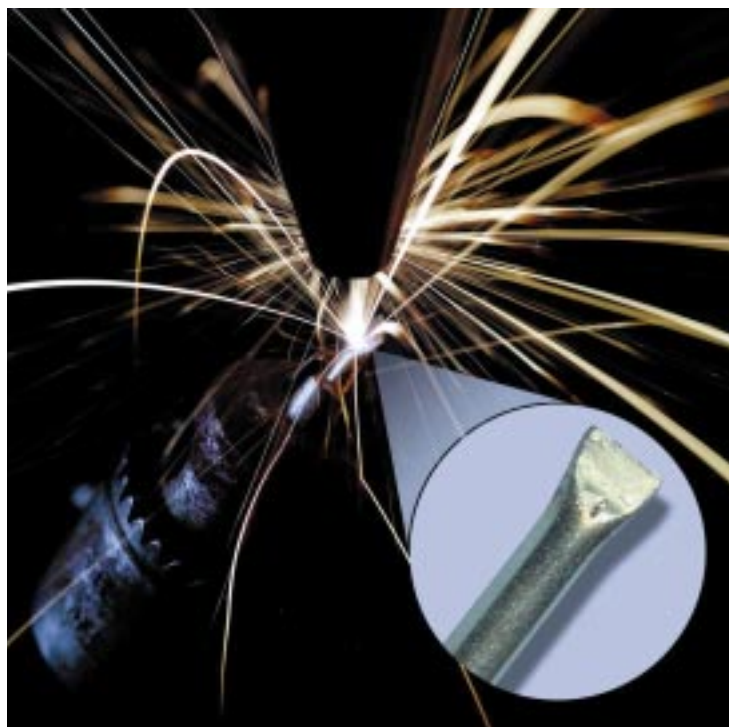
Laser drilling and rewelding process tested on a representative geometry.

Infrared Surface and Gas Analysis

We have developed two nondestructive mid-infrared inspection tools for evaluating contaminants that may be present on surfaces and in gases in returned stockpile units. The identification of the presence and quantity of contaminants provides information that is critical for assessing the effects of aging in these units.

The diffuse reflectance infrared fourier transform (DRIFT) surface inspection tool, patterned after a Los Alamos National Laboratory design variation, has been developed. DRIFT interrogates millimeter-sized spots by diffusely scattering light off the surface, from which an infrared spectrum is obtained that contains explicit chemical information about the surface. A motion stage (not shown) is used to manipulate the specimen and enable DRIFT to display the inspected surface as a three-dimensional surface map. Figure 2 demonstrates the 3D spectral imaging capability of this technology by imaging the carbonyl species of the adhesive on a Post-it note. A visualization attachment for this system, a recent Los Alamos development, was manufactured and is being procured so that the visual image of the area being inspected can be captured and coordinated with the spectral image.

The nondestructive infrared gas analysis (NDIGA) inspection tool analyzes the trace gases in a returned stockpile unit. NDIGA uses an infrared spectrometer with a gas cell that has a sensitivity to most simple, polyatomic gases. Figure 3 demonstrates the capability of NDIGA to simultaneously detect and distinguish between gaseous (sharp lines) and liquid water (broad bands). The NDIGA is part of a larger interrogation system involving technologies developed under Tasks OR18 and LL13.

During FY1998, we developed DRIFT, procured it, and prototyped it in a production environment. The NDIGA system was also developed and tested by using returned weapon materials. Both of these technologies will be transferred to the Surveillance Program in FY1999.

Fig. 1. The DRIFT surface inspection instrument (top) configured for installation into the glove box. NDIGA (bottom) can simultaneously distinguish between gaseous and liquid water.
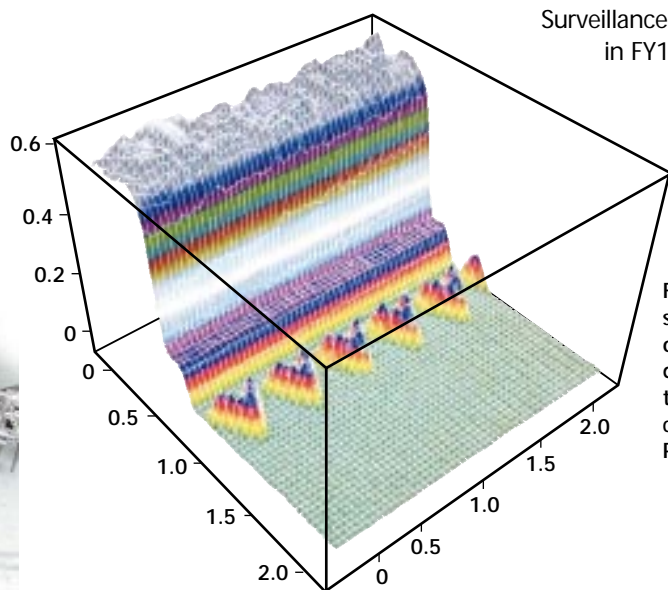

Fig. 2. A 3D spectral image of the spatial distribution of the adhesive coatings on a Post-it note.

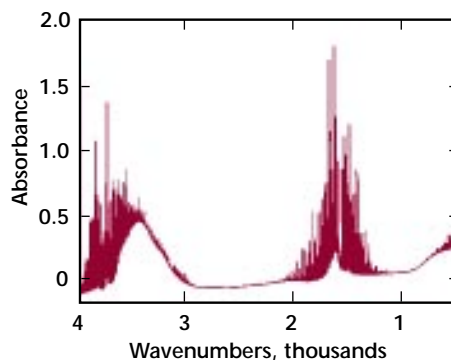
Fig. 3. The NDIGA system as presently configured for gas analysis.

Material Interactions

Although they are drier than many organics, cellular silicone cushions inherently contain moisture. A primary concern about their use in an assembly is that the moisture in the cushion will contribute to increased aging of the assembly. Key components of this task are the analysis of the moisture content of cellular silicone cushions and the effect that the moisture could have on assembly aging.

We selected a residual gas analyzer (RGA) as the moisture analysis method. A schematic of the moisture analyzer is shown in the first figure. Prior to analysis, the cushion sample is exposed to a known moisture level for a specified time. The cushion sample is heated under vacuum, and the RGA is used to monitor mass 18 versus time. The data are integrated to determine the total quantity of moisture evolved.

The second figure shows the analysis results of the cushion moisture content. The average initial moisture content of cushions at ambient conditions, shown at time = 0, is 0.1 wt%. When placed in a dry environment, the cushions rapidly lose moisture to an average level of 0.03 wt%.

Cushions were also aged with a substrate of interest under accelerated aging conditions. As shown in the third figure, the cushions increased the rate of aging of the substrate, dramatically at first, then at a more modest rate with increasing elapsed time. Overall, the increased rate of aging was within acceptable limits.

It is expected that cellular silicone systems, with proper processing, are suitable for storage in fielded units.

Schematic of the moisture analyzer.
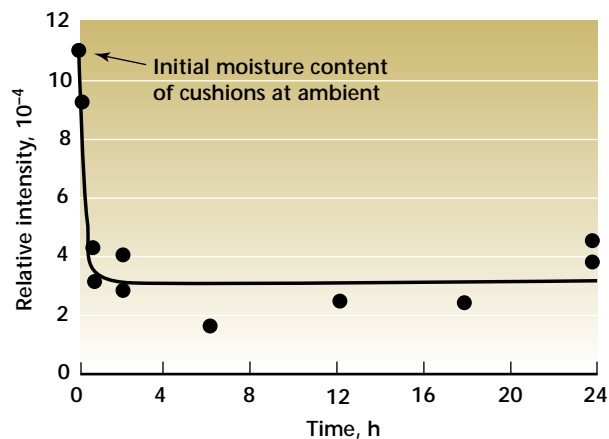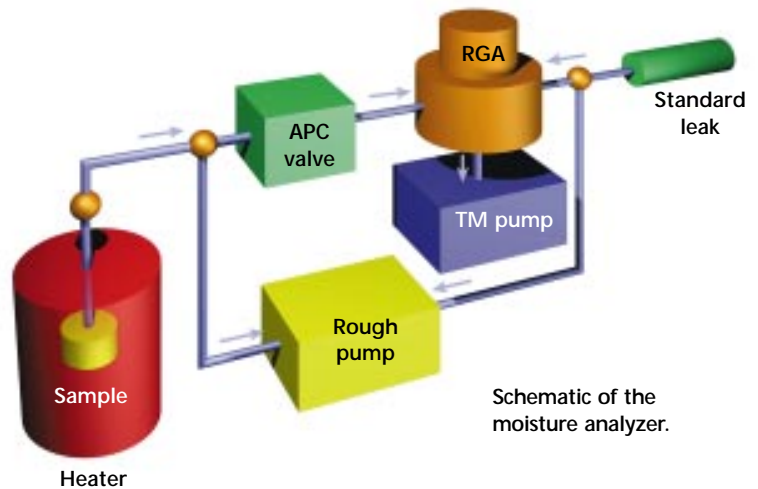
Moisture in cushions after exposure to known moisture level in nitrogen. The cushions rapidly lose moisture when placed in a dry environment.
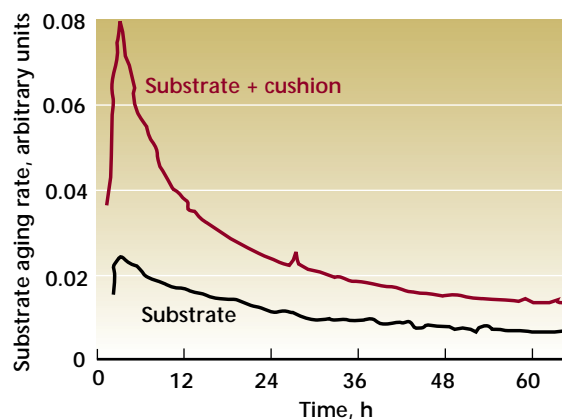
Effect of cushions on substrate aging.

Radiographic Parameter Optimization

Radiography is used to measure gap and other dimensional measurements on most parts and subassemblies manufactured at the Oak Ridge Y-12 Plant. Current radiography methods are based primarily on experience, and we do not know of any comprehensive, systematic effort to optimize radiographic parameters, hardware, or procedures. Our efforts under this task are directed toward improving Y-12's ability to identify stockpile problems, especially with regard to components, through optimization of the radiography process. Optimization will be aided by computer simulation of the radiographic process and by the development of computer-based tools that will enable radiographers to select appropriate radiographic exposure parameters for efficient production of the best image possible. The project's approach is to survey any prior optimization work, develop a computer model of the radiography process, validate the model through experimentation, and implement the model as an advisory system that radiographers can use in operations.

A survey of radiography personnel throughout the nuclear weapons complex revealed that no concerted efforts have been made to optimize radiography processes. We found that 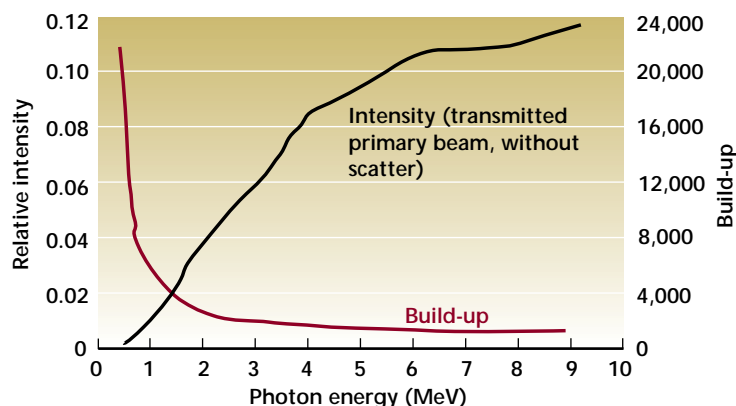capabilities were experiential rather than science-based, just as Y-12's are. Standard radiography texts and handbooks proved to be the most helpful sources, and we obtained simulation codes. TART97, from Lawrence Livermore National Laboratory, is a radiation transport code that enables estimation of radiation intensity under defined material and geometric conditions. A second code, XRSIM, written by Iowa State University, will be used to generate virtual radiographs to verify the acceptability of real exposures.

We are preparing a radiographic facility to conduct model validation experiments in a low-energy (<420 KeV) range. The 9-MeV linear accelerator at Y-12 will be used for high-energy validation experiments. We are also fabricating test rings that simulate a canned subassembly's geometry and materials for model validation experiments.

Modeling of the radiographic process is also underway, and we have developed a method for selecting a source. The method involves determining the intersection of the appropriate beam and build-up curves vs photon energy, as shown in the figure. The energy at the intersection becomes the basis for the selection of the appropriate x-ray machine and source intensity.

X-ray energy optimization (monoenergetic photons). The energy at the intersection becomes the basis for selecting the appropriate x-ray machine and source intensity.

Evaluation of Hydrogen Balance Methods

Hydrogen corrosion causes weapons to age. Through the surveillance program, the Oak Ridge Y-12 Plant supports routine surveillance tests on weapons to establish the balance between hydrogen sources and hydrogen sinks. The hydrogen inventory is a basic tool for surveillance, and its test results are used to predict the aging and reliability of fielded weapons systems, plan facility requirements to recertify or refurbish weapons, and assess the significance of observed anomalies.

Current methods have served the nuclear weapons complex well, but the push to extend weapon lifetimes beyond their design lives requires re-examination of the hydrogen inventory tools. As shown in the figure, these tools provide hard data for performing weapon aging assessments. The objectives of this task are to assess the accuracy, precision, and predictive value of each hydrogen balance test and to develop and implement methods with enhanced accuracy, precision, and predictive value where needed. The deliverables will be data sets that can be input into weapon aging models and enhanced interrogation techniques that will be implemented into routine surveillance operations.

We have surveyed hydrogen balance data for weapons on a specific system. We retrieved disassembly records for 22 weapons that were evaluated as a part of the surveillance program. Systematic review identified eight quality parameters that clearly are increasing with age. A similar number of parameters were notable because they clearly do not change with age. A published review provides objective data against which weapon aging models can be developed and validated.

We also analyzed organic hydrogen getters. Routine surveillance results to date show that organic hydrogen getters provide almost complete protection against corrosion. Most of a weapon's aging history will be recorded by the hydrogen getter. Two fundamental flaws were

identified in current analysis methods: (1) all gas uptake is not measured, and (2) one analysis is subtly but decidedly flawed. To resolve these issues, specific analytical methods will be recommended from a "round robin" experiment that is in progress involving four DOE sites.

We combined resources with Task OR02 to develop the low-temperature thermal decomposition (LTTD) system. LTTD uses temperature-programmed desorption to quantify component chemical characteristics that might be weapon aging indicators. A prototype system based on bench scale work performed in Task LL23 was designed and built in FY1998 and will be transferred in FY1999.

Enhancements to the bake-out operation will include programmed temperature control with data acquisition to monitor kinetics as a function of time, temperature, and isotopic composition. Enhanced bake-out will be ready for introduction into routine surveillance during FY1999.

Hydrogen inventory tools assess weapon aging and stockpile reliability.
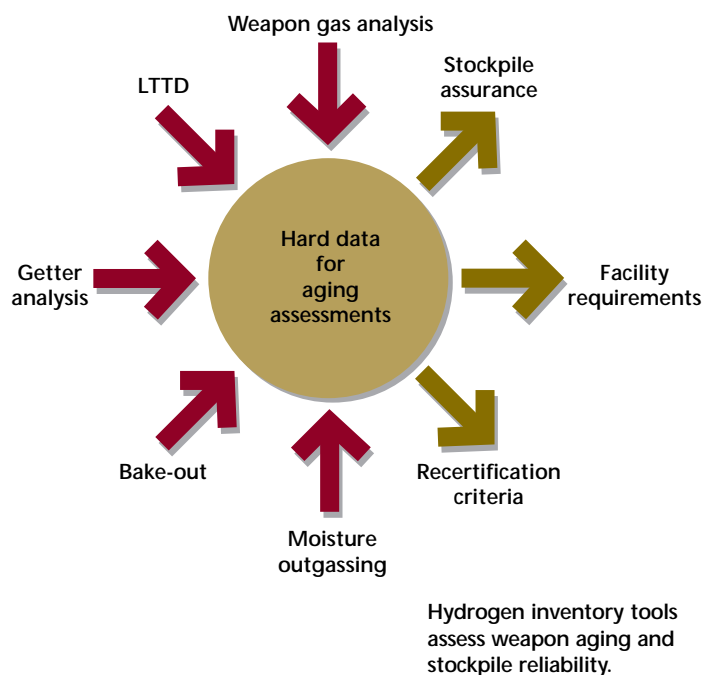
Development of High-Energy Neutron Radiography

We are developing high-energy neutron radiography and tomography for use as a nondestructive evaluation (NDE) tool for stockpile-to-target sequence (STS) device engineering tests and routine stockpile surveillance at DOE production and storage plants. Our goal is to develop an operational neutron imaging system capable of detecting cubic-mm-scale voids and other structural defects in heavily shielded low-Z materials (e.g., lithium salts) within a nuclear device. The imaging system will be relatively compact (suitable for NDE facilities at Y-12 and Pantex) and capable of capturing a full tomographic image of a weaponized secondary assembly. It will consist of a high-yield, accelerator-driven neutron source operating in the 10^{-15} MeV energy range (a nominal output $\approx 10^{12}/4\pi$ n/sec/sr in the forward direction and an effective spot size ≈ 1 mm in diameter will be required), a low-mass rotation stage to support and manipulate the device under inspection (allowing for tomographic imaging), and the imaging detector itself. The detector will be based on technology proven in underground nuclear testing. It will consist of a simple plastic scintillator viewed indirectly by one or more high-resolution, LN_2-cooled imaging cameras.

During FY1998, we built a prototype of the imaging detector using an LN_2-cooled camera with a fast lens and tested it by imaging a set of phantom targets at the Ohio University Accelerator Laboratory (OUAL) in Athens, Ohio. OUAL was selected because its physical layout is generally similar to that envisioned in an actual neutron-imaging facility. The first imaging experiments in October 1997 included radiographic imaging of a set of nine step

wedges and a polyethylene slab with 10-, 8-, 6-, 4-, and 2-mm-diam holes shielded by up to 4 in. of Pb (max. thickness ≈ 120 g/cm^2). The second experiments in January 1998 included edge-resolution measurements using a machined Cu block and radiographic imaging of a lithium deuteride slab shielded by depleted uranium (max. thickness ≈ 100 g/cm^2). Tomographic imaging data consisting of up to 64 views of a 4-in.-diam, right-circular Pb cylinder with a 2-in.-diam polyethylene insert with the same set of holes were also taken during this run. Imaging times varied from 10 min to more than 1 hr depending on the object under inspection and the accelerator beam current available. Results were excellent in all cases. The figure shows clearly visible simulated defects and associated lineouts.

We also made marked progress in developing a high-yield neutron source during FY1998. We have worked with vendors to find small accelerator systems suitable for use in an actual imaging system and are currently collaborating with Richard Lanza of MIT to develop an operational prototype of a high-yield target that can be coupled to the accelerator.

Finally, we have established implementation teams with Y-12 to determine overall system performance requirements and expedite the installation of a neutron imaging system at that facility.

(a)

(b) Lineout through full-thickness holes

(c) Lineout through half-thickness holes
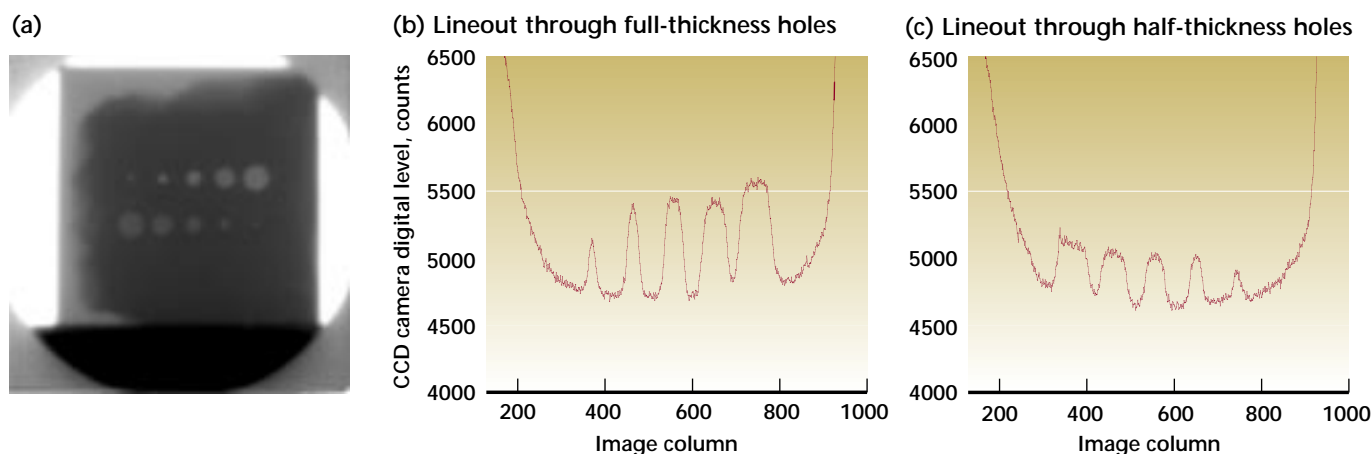
(a) A 10-MeV neutron radiograph of a LiD slab shielded by D-38. The image shows defects and fractured edges (simulated by 10-, 8-, 6-, 4- and 2-mm-diam. holes drilled 1 and 0.5 in. deep). (b and c) Associated lineouts.

Bayesian Inference Tomography

We have recently augmented the capabilities of our Bayesian inference engine (BIE) to include 3D geometric models. The BIE is a unique tool that we have developed over the last few years for analyzing radiographic images. One of the unique features incorporated in the BIE is the use of geometric models to describe the boundaries of the object under investigation.

The BIE is already being used to interpret dynamic radiographs from hydrotests in terms of models of two-dimensional or axially symmetric, three-dimensional objects. We will adapt the BIE to analyze stockpile surveillance radiographs to determine whether the dimensions of a warhead deviate from nominal. We anticipate that this may be done with good accuracy from several radiographs. Our new 3D models will enable us to make the best inferences about 3D effects from the radiographs that we will obtain from the Dual-Axis Radiographic Hydro-Test (DARHT) facility, presently under construction at Los Alamos.

The 3D geometric models are based on representing the boundaries between various regions with a finely triangulated surface. A number of challenges were encountered in the development of these models, including computation of the projection of the surface mesh onto a 3D rectangular grid and controlling the smoothness of the surface model. Given the uniqueness of these techniques, we sought collaborators and peer feedback from experts in medical imaging, which is the field that appears to be the most advanced in its use of the 3D image model.

We formed a collaboration with a team from the University of Arizona, headed by Prof. Harrison Barrett, who is renown for his contributions to medical imaging. The Arizona team supplied us with nuclear-medicine data taken of a beating, CardioWest, artificial heart. Their study was conducted to demonstrate the feasibility of a dynamic heart-imaging system that will track the time-dependent shape of the heart during a few heartbeats. The ultimate purpose was to improve a cardiologist's ability to assess heart function. A standard radiopharmaceutical, based on technicium-99, was injected into the vein feeding the right ventricle. The sequential images recorded in 24 pinhole cameras situated around the heart phantom were collected in 50-ms intervals. Only around 2,000 x rays were detected in all 24 detectors for each snapshot. The figure shows a typical x-ray image.

We reconstructed the ventricle using two types of models. The first and simplest model represents the surface geometrically, assuming a uniform interior density. The second model further includes a slowly varying density model to take into account mixing of the radioactive bolus with the simulated blood. Both of these reconstructions, shown in the figure, are remarkably good, considering the limited number of views and the extremely noisy nature of the data. The second model seems to provide a better representation of the distribution of radioactivity.

To summarize, we have demonstrated a new and unique capability for 3D reconstruction. We look forward to applying this technique to stockpile surveillance radiographs. We are using our 3D reconstruction technique to help answer the question of how many views would be necessary for the DARHT facility to certify the stockpile. We intend to develop time-dependent 3D models (4D models), which will be essential for analyzing multi-pulse DARHT radiographs. Fortunately, the University of Arizona data consist of a sequence of 100 frames. These will give us an opportunity to test our 4D models in the future.
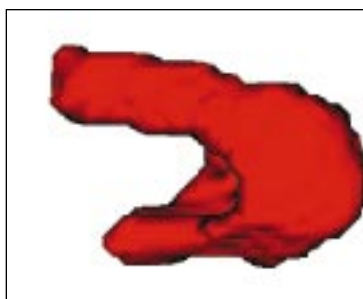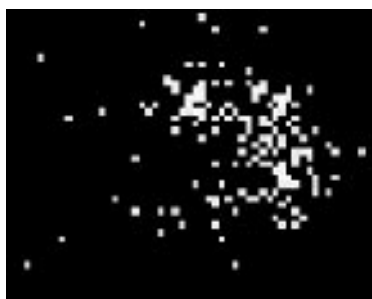
On the left, a snapshot of a beating artificial heart taken by one x-ray camera. This image is extremely noisy because less than 100 x rays were detected in the 50-ms exposure period. The surface of the bolus of radioactivity reconstructed from 24 comparable views is shown in the center. On the right is a projection through a 3D density reconstruction based on combining the geometric model for the boundary with variable interior density. This image clearly displays the hemispherical shape of the heart, as well as its values.

Systems
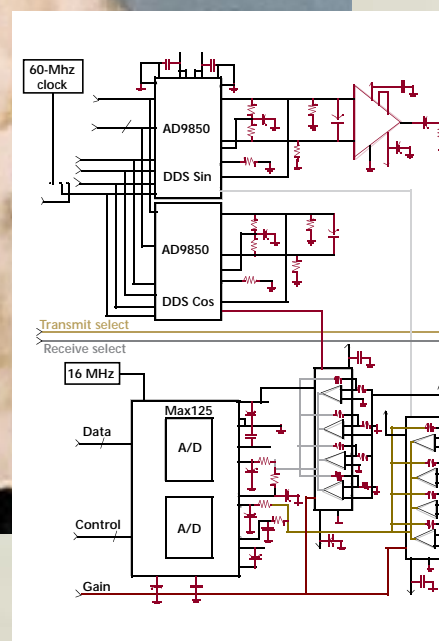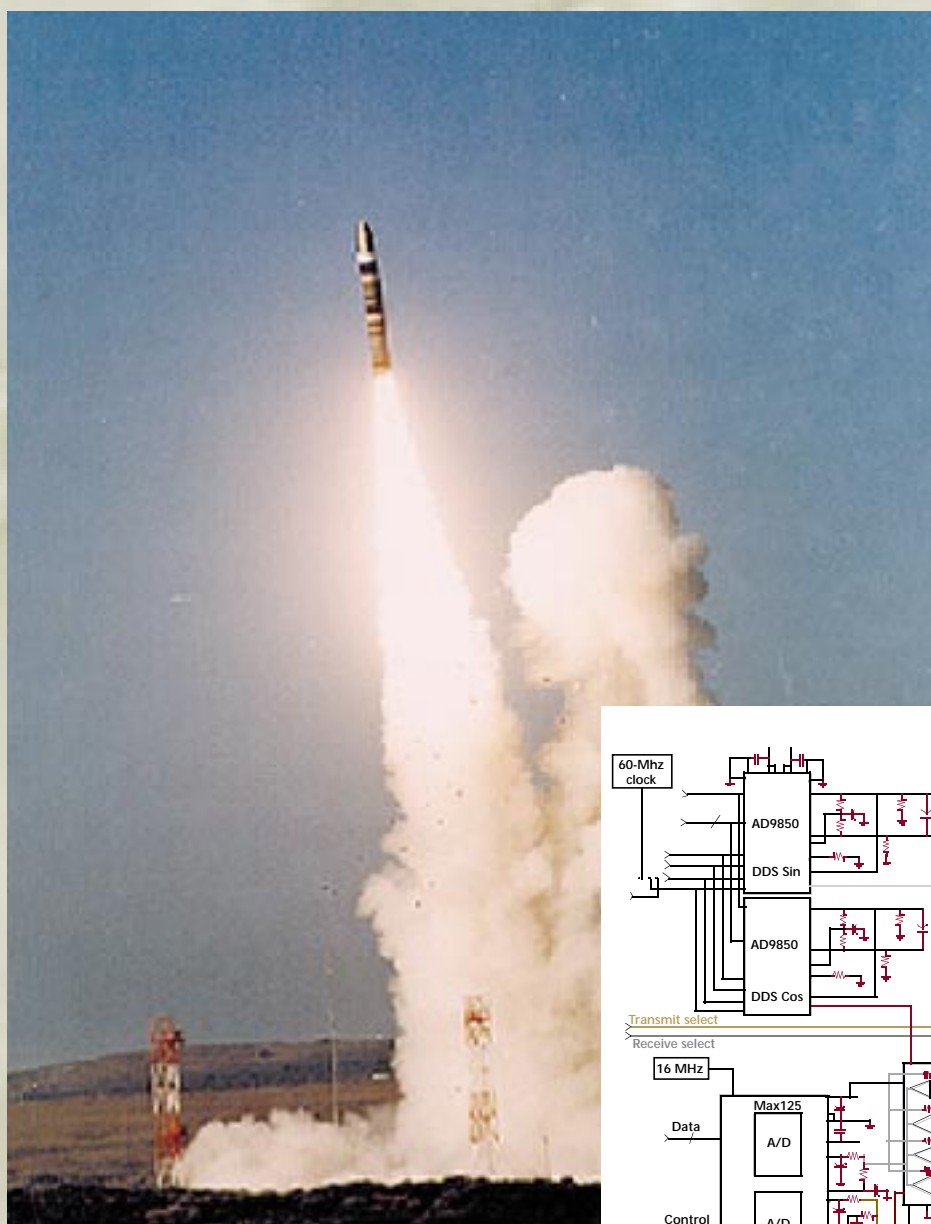
Systems

Focus Area

Several aspects of the Enhanced Surveillance Program require integration across nuclear and non-nuclear components, their surveillance methods, associated predictive assessments, and other tools in order to provide results optimized at the systems-level for use by the DOE and the DoD. The Systems Focus Area collects the outcome of those tasks in coherent groups and incorporates them into the appropriate level of system integration.

Our foremost goal is to implement a full-spectrum reliability assessment methodology, integrating advances in evaluating the reliability of the nuclear explosive package with development of predictive reliability methods for non-nuclear components. Another goal is to perform system-level flight testing with the highest fidelity consistent with diagnostic capability for key features of both non-nuclear and nuclear explosive package performance. The final goal is a surveillance information capability that addresses deficiencies in the current information management system, including transforming data to information and then to knowledge and assuring needed electronic access, with priorities determined by the surveillance community.

Presently three major classes of activities are included in this focus area: enhanced-fidelity instrumentation, database management, and reliability assessment. Enhanced surveillance efforts are supporting flight testing through the development of diagnostics and advances in miniaturization and data handling. In addition to providing data, these developments must minimize intrusion and include the integration of accountabilities: nuclear, non-nuclear, system, and those for the DoD. Many existing databases need modernization, but much of the body of data is not yet in electronic form. ESP is defining the requirements and priorities for data access by the surveillance community. Activities include prototyping a cost-effective, intuitive, desktop capability to access surveillance-relevant weapon information in both classified and unclassified environments and to cost-effectively assess trends in weapons surveillance databases.

Finally, this focus area is enabling a better understanding of stockpile reliability, including current reliability assessment and predictive reliability assessment. A critical understanding of system performance related to weapon stockpile reliability provides important data in assessing the integrity of the nuclear deterrent. Current reliability estimates for the nuclear package have historic roots that may not be entirely appropriate for a significantly longer weapon lifetime. Non-nuclear reliability tools presently lack the ability to incorporate age-aware performance models, performance trends, and early indication of unacceptable changes to provide predictive reliability assessments past the originally protected period.

Deliverables

1. Develop new flight instrumentation to characterize vehicle flight dynamics and evaluate functional performance of nuclear and non-nuclear components.

2. Specify information requirements for surveillance activities and coordinate these requirements with other programs.

3. Gain a better understanding of the impact of weapon aging on stockpile reliability.

Pertinent Tasks

KC11	Enhanced Surveillance Data Access
LA03	Advanced Diagnostics Development for Flight Test Scoring [a and b]
LA14	Material Property and Surveillance Database
LA17	Stockpile Information Group: Information Management
LA23	Enhanced Reliability Methodology Test Program
LA39	Sampling Rationale
LL27	Surveillance Information Group: Database Management Systems
LL28	Nuclear Explosive Package Instrumentation
OR01	Historical Certification Data Analysis
SN15	Data Systems
SN20	Advanced Telemetry

Historical Data Analysis at the Y-12 Plant

To reduce the aging rate of weapons, a getter is incorporated in its design. Right now, there is no nondestructive method to determine the health of this getter. However, a review of the historical data of several weapon families has unveiled a correlation between a measurement taken during surveillance before the weapon is destructively evaluated and the health of the getter inside it. This discovery could be of enormous value to a significant fraction of the stockpile: methods could be developed to routinely monitor stockpile weapons in a nondestructive manner for signs of unanticipated and excessive aging.

A common thread linking the weapon families appears to exist, as shown in the figure. This common behavior between different weapon types suggests that the same basic physical processes must be occurring in all of them.

The actual discovery of this correlation was made over a year ago. Since then, data from additional disassembled weapons were incorporated into the updated plot shown

in the figure. These new data are consistent with the behavior observed over a year ago, adding credibility to the hypothesis that a real relationship—not just a statistical correlation— exists between the two variables shown. Particularly intriguing is the specific quantitative value for the slope shown in the figure. Its value would not have been anticipated given our current understanding of weapon aging.

Furthermore, when other historical data sets were reviewed during this fiscal year, the same value for this slope was discovered. It was reported in a compatibility study conducted in the early 1980s, and it was discovered in surveillance and certification records of a particular weapon type recently reviewed. All these findings add credibility to the notion that a physical relationship, not just a statistical correlation, exists between these two variables.
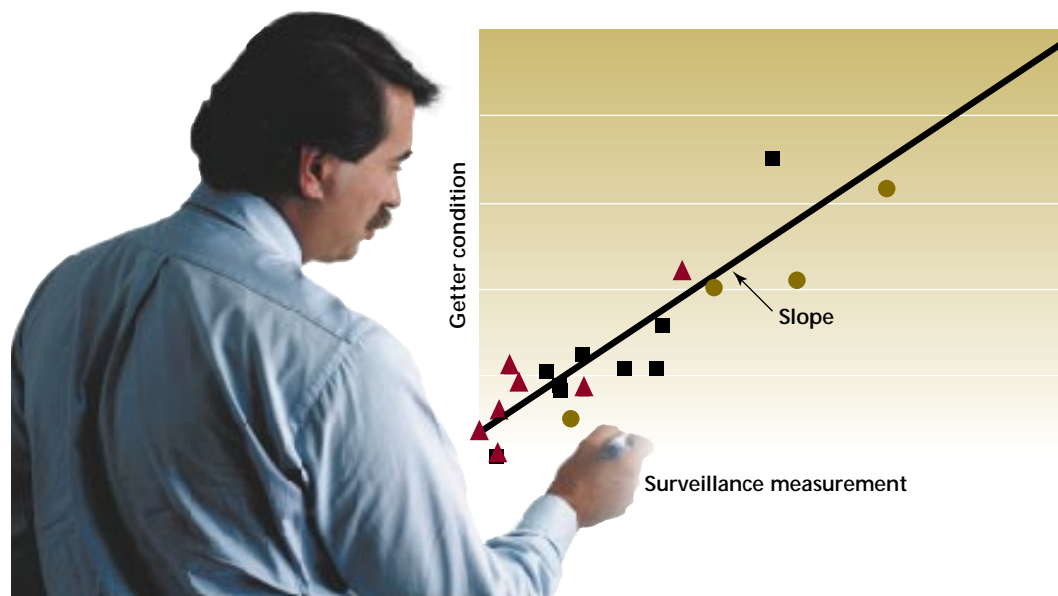
A correlation between measurements made at surveillance. The different symbols represent different weapon families.

Advanced Diagnostics Development for Flight Test Scoring

One of our most significant accomplishments was an agreement between Los Alamos National Laboratory (LANL) and Sandia National Laboratories (SNL) on a schedule to design, build, and fly development test units for both the W80 JTA5 and JTA6 configurations. This work is scheduled to be completed in FY2002 or 2003. We have a list of tasks and a timetable for the development, design, and testing of instrumentation, telemetry systems, and the complete prototype flight test units. For the first time, Los Alamos and Sandia tasks for realizing telemetered flight test systems are coordinated and linked in a self-consistent way, so the results of one set of tasks flow smoothly and logically into the initiation of another. Also for the first time, we have a coherent plan for the development and flight of the JTA6 (late telemetry) type of flight test units. This type of flight test unit monitors the performance of the W80 primary and thus is of great interest to LANL. Minimal SNL component instrumentation is involved in the JTA6.

The W80 SLEP (Stockpile Life Extension Program) may require that LANL and SNL components in the W80 be modified. For that reason, the flight test units that are the end products of the schedule are not designated DJTA (Development JTA) 5 and 6, but are rather designated EFI1 and EFI2. This name change indicates that if the SLEP results in significant changes to the W80, additional DJTAs will be needed before production JTAs for the W80 can be realized. However, if the SLEP does not cause significant W80 changes, EFI1 and 2 can be considered the Development JTAs for the early and late W80 flight tests (JTA5 and 6), respectively.

Roger Bracht of LANL has developed a miniature, ultrasonic transducer controller circuit suitable for inclusion in the JTA5 telemetry system. This circuit, shown in the figure, consists
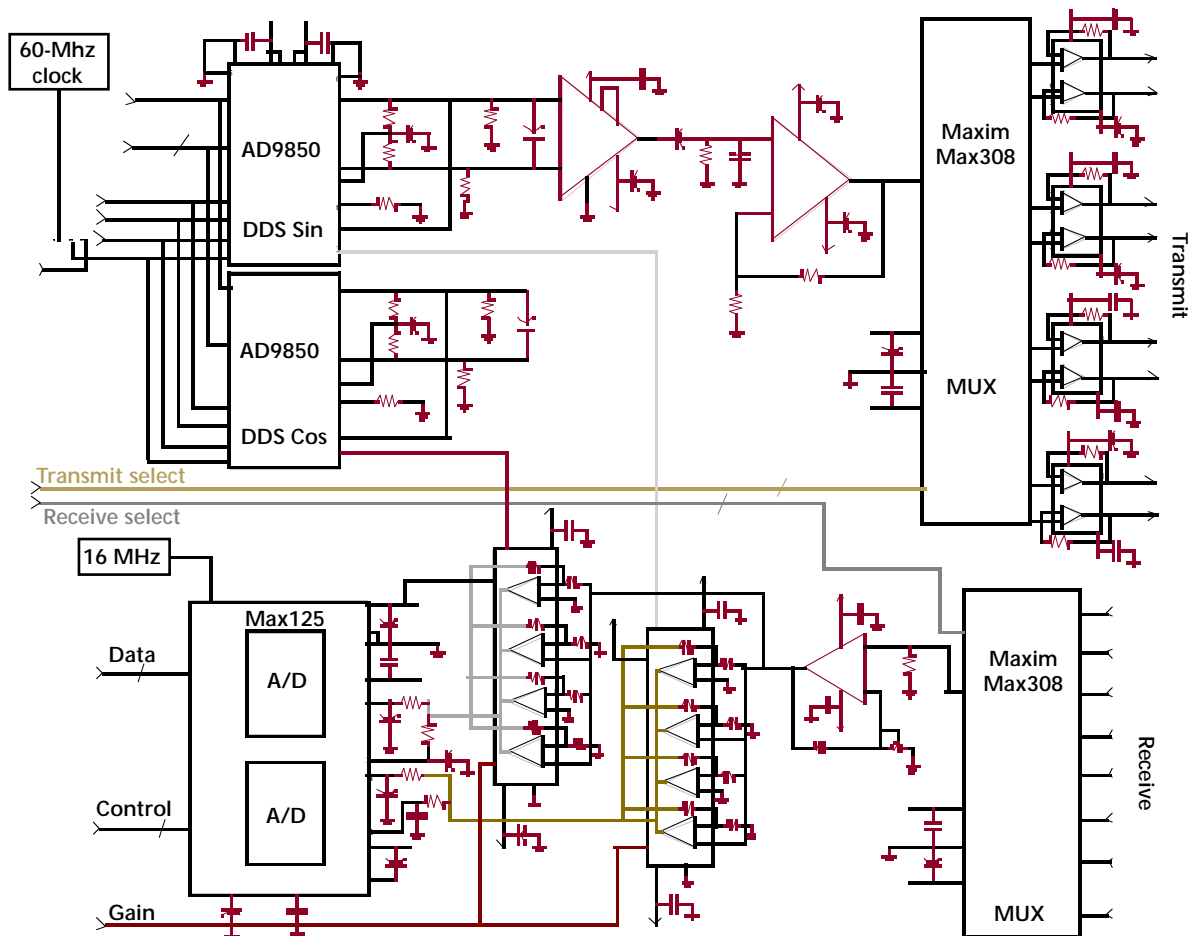
A miniature ultrasonic transducer controller circuit for the JTA5 telemetry system consists of an ultrasonic transducer driver, or transmitter module (top portion of the circuit) and a transducer receiver module.

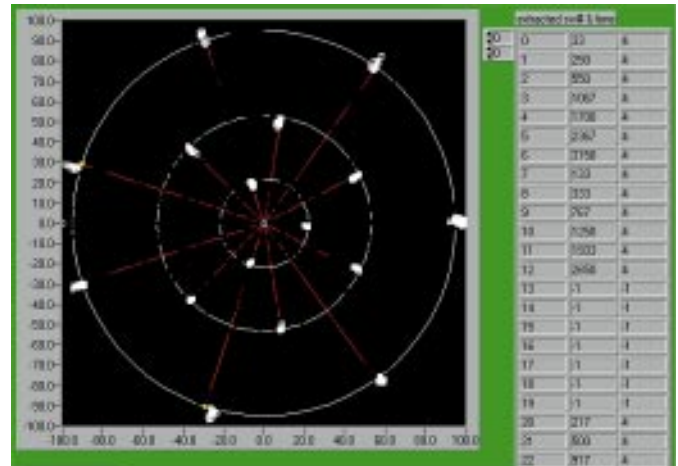of an ultrasonic transducer driver, or transmitter module (top portion of the circuit) and a transducer receiver module. The transmitter module uses signals from swept sine and cosine generators (the AD 9850 chips) to drive up to eight transducers at frequencies ranging from 1 kHz to 10 MHz. The specific transducer being driven at any given time over a specified time period is selected by a controller (not shown on the diagram) operating the MUX switch in the top portion of the circuit. The receiver module also selects the transducer to be monitored by means of the controller operating the MUX switch in the bottom portion of the circuit. The signals from the transducers are amplified and filtered and then demodulated, using the HA2444 circuits connected to the sine/cosine generators, so the amplitude/phase information in each transducer output is reduced to a data rate of about 6 kHz. In this manner, megahertz ultrasonic information can be transmitted at a much lower bandwidth. The demodulated ultrasonic data are then converted to a digital signal for telemetering to a ground station.

This shows an actual screen image of the LabView demodulation program used on an early QAM constellation. The bit assignment above the figure shows how a 20-bit block of data is transmitted as 5 hexadecimal characters. The bit assignments and constellation are not the current design.

Savannah River Technology Center (SRTC) is developing a radiation source/detector gap measuring system. Here, a small radioactive source with the strength of a smoke detector's source is positioned beneath two surfaces in contact, with block radiation emitted from the source. As the surfaces move apart, radiation from the source streams between the surfaces to a detector positioned above the surfaces. The amount of radiation that gets through the gap in the surfaces is proportional to the magnitude of this gap. SRCT has successfully developed a source/detector/counting system that can measure several spectra per second and detect a 0.004-inch change in gap magnitude between two surfaces with a 1-minute count window. The detector is small enough to fit in the available space in the flight-test unit. The next step in this development process is to interface with the telemetry system and to begin tests with gaps between actual warhead components.

High Explosive Radio Telemetry

HERT (High explosive radio telemetry) is designed to provide reliable information on the implosion process as it occurs in a mock nuclear explosive package in a delivery vehicle. Measurement of the implosion process during the terminal stages of flight provides an integrated, systems-level assessment of many components. HERT allows a diagnostic screening that is otherwise unattainable in ground-based or component-based testing.

In a terminal-stage measurement of implosion performance, time is a critical component. The time from our earliest measurement to the time when the telemetry system is vaporized is on the order of tens of microseconds. Conventional telemetry encoding transmits one bit at a time. This allows a separation, similar to a 180° phase reversal, between the two characters (1 or 0) so that they are easily identified. If we choose to transmit a character that represents more than a single bit, we would gain time to get the data out but we would lose separation between the characters, resulting in more sensitivity to noise. HERT will transmit characters that represent 4 binary bits or a hexadecimal character, which results in a factor of 4 in time saving. The tradeoff is considerably more sensitivity to noise and radio frequency (rf) transmission properties. We have chosen a 22.5° phase separation and a 1.6 amplitude ratio between adjacent characters for the current version of HERT (in a scheme known as quadrature amplitude modulation, or QAM). Extensive testing and simulation have shown that the increased noise sensitivity is acceptable. One significant advantage of the short time available to transmit data is the short burst of rf. This allows us to digitize the intermediate frequency from the receiver and store the digital data in a conventional computer. A software program can be used to demodulate the signal and provide timing data as an output well after the transmission has ceased, eliminating the need for real-time demodulation.
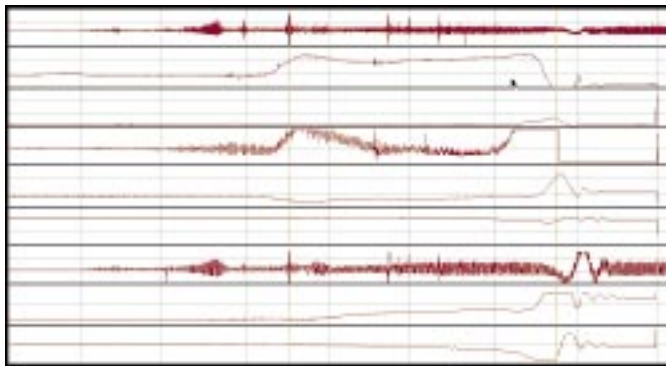
Nuclear Explosive Package Instrumentation

The Lawrence Livermore National Laboratory (LLNL) is developing diagnostics, electronic and electro-optic circuits and systems, and high-density electronics packaging technologies to enable high-fidelity weapon flight tests with on-board instrumentation and telemetry. There is an urgent need for on-board measurement of the nuclear explosive package (NEP) and NEP-reentry vehicle interactions and flight dynamics in high-fidelity configurations and for observing NEP detonation performance under flight test conditions. Technology developed at LLNL and Sandia enabled the development and successful flight of the first instrumented, high-fidelity flight test vehicle, the Mk21/W87.

The next generation of joint test assemblies (JTAs) for stockpile surveillance must include a representative NEP with a secondary and a functioning primary with full high-explosive charge. For these JTAs, survivable instrumentation and telemetry must be developed to observe and report weapon functions during detonation. New diagnostics are needed for flight dynamics and NEP performance measurements and for observing detonation events. One of our objectives is to develop and demonstrate on-board mass memory for recording telemetry data for later transmission and to enable long-duration surveillance missions.

We have developed new capabilities to instrument a high-fidelity weapon and reentry vehicle configuration to measure flight dynamics. This includes a system of sensors to observe weapon tip-off from the bus, exo-atmospheric flight, and endo-atmospheric flight dynamics. Sensors are mounted in and around the NEP and reentry vehicle with particular attention at the interfaces. LLNL and Sandia have specified, evaluated, and developed flight dynamic sensors, including accelerometers, vibrometers, acoustic sensors, displacement sensors, temperature and pressure sensors, magnetometers, and rate gyros.

We enabled and supported development and flight testing of FTU12, a Mk21/W87 configuration and the first instrumented high-fidelity flight test vehicle. In May of 1998, the Peacekeeper Glory Trip 27 mission was launched from Vandenberg Air Force Base. On board was FTU12 along with other JTAs. Flight dynamics and NEP performance data were acquired from on-board sensors, telemetered to ground stations in real time, recorded, and are being analyzed (see figure).

We have developed new diagnostics to observe terminal events. The engineering design and test of a novel, very fast shock arrival diagnostic has been accomplished. An LLNL-developed laser Doppler technique was used to measure shock arrival with 1-ns resolution in a very small package. We further investigated a new, very simple technique for observing neutron flux based on radiation effects in dielectric materials. These diagnostics and others were demonstrated and evaluated in an explosive ground test in August 1998.

We have extended the LLNL-developed laser pantography technology for packaging dense electronics for telemetry. We developed the ability to fabricate 3D stacks of unpackaged integrated circuit dies. We designed, developed, fabricated, and tested high-density memory stacks for telemetry applications, and developed and demonstrated a novel technique for mounting unpackaged integrated circuits to FR4 fiberglass-composite printed circuit boards—a long-time industry goal. This newly developed interconnect system compensates for differences in thermal expansion and enables easy mounting on the printed circuit board. We developed a 0.9 G bit mass memory module for flight test telemetry with memory control and data flow circuits. The developed mass memory module provides on-board data storage for down-range transmission, reducing battery power and volume requirements and deferring telemetry heat buildup in confined volumes. This represents a new capability enabling broad-ocean area missions for strategic weapon JTAs and long-duration JTA flight tests on cruise missiles.

Flight test reentry data from sensors aboard FTU12. Data from acoustic sensors, accelerometers, displacement sensors, and rate gyros observe lateral loads at various locations within the nuclear explosive package (NEP) and between the NEP and the reentry vehicle. Reentry events are identified and analyzed. The magnitude and phase relationships between these signals are used to develop load transfer functions and refine flight dynamic models.

Advanced Telemetry

The Advanced Telemetry project is developing technology for the high-fidelity flight test vehicles that will be needed in a reduced-flight-test environment. These test flights collect data to certify the reliability of stockpile systems for both the Department of Defense (DoD) and Department of Energy (DOE).

A high-fidelity joint test assembly (JTA) will be virtually indistinguishable from a war reserve (WR) weapon system (i.e., replacing few WR components and minimally changing mass properties), but it will monitor all required DoD and DOE functions, including implosion diagnostics. In the near term, advanced telemetry will affect development of test assemblies for the W87 enhanced-fidelity instrumentation (EFI), W80 JTA, W76 EFI, and the SLBM Warhead Protection Program. Eventually, every JTA telemeter will be designed, or redesigned, for high-fidelity instrumentation.

New sensors, enhanced measurements, and miniaturization of instrumentation systems were our FY1997 goals. Earlier this year, the EFI-2 instrumentation system provided a W87 flight test (FTU-12) with the smallest telemeter ever to be fully contained within the nuclear assembly. The successful flight of EFI-2 provided enhanced measurements of reentry vehicle dynamics and nuclear package dynamics, and it was the first telemeter to include acoustic and displacement sensors. The W76 EFI, scheduled for a flight test in January 1999, is another new miniaturized telemetry system made possible by the technologies developed by the ESP Program.

In FY1998, miniaturization efforts were concentrated on development of a new distributed architecture for telemetry systems that allows the instrumentation of flight tests with a full, live explosive main charge. This architecture is a key element of enhanced-fidelity instrumentation in future JTA systems. In contrast to conventional centralized telemeters which, despite size reductions, invariably displace WR components, a distributed telemetry (DTM) architecture places components throughout the weapon.

The EFI-3 instrumentation system (now designated DTM1) being developed for the W87 is similar to EFI-2 in size, and incorporates a DTM subsystem. DTM1 is a hybrid system architecture for validating DTM concepts while providing a mature telemeter design for most instrumentation. Several new technologies were developed or adapted for DTM1, including a new serial data link and communications protocol (to link the distributed modules), miniature connectors, and data compression within a high-resolution, analog-to-digital converter. Pioneering efforts by AlliedSignal/Federal

Manufacturing & Technologies produced a new flex-circuit cable for the new digital communications link that incorporates extremely small connectors. These new cables will eventually replace the large "horsetail" of wires to analog sensors in conventional telemetry systems. In a close facsimile of DTM1 (photo), several data acquisition modules are connected to the central telemetry package by a single cable with only nine conductors. An average module, designed with discrete components, is 1.5 in. by 1.5 in. by 0.5 in. in size. An application-specific integrated circuit is currently being developed at Sandia National Laboratories/New Mexico that will combine the functions of several components into one, further reducing the module size by at least half.

Micro-electro-mechanical technologies are also under development to make measurements from within the nuclear explosive package (NEP) that were never before possible. Magnetically excited flexural plate wave devices are extremely sensitive strain gauges, the size of integrated circuits, that can detect surface cracks when mounted to surfaces inside the NEP. Because wires are not allowed to penetrate the hermetically sealed shell of the canned subassembly, new wireless communications are also being designed to get data from sensors inside the shell to the telemetry package outside the shell.
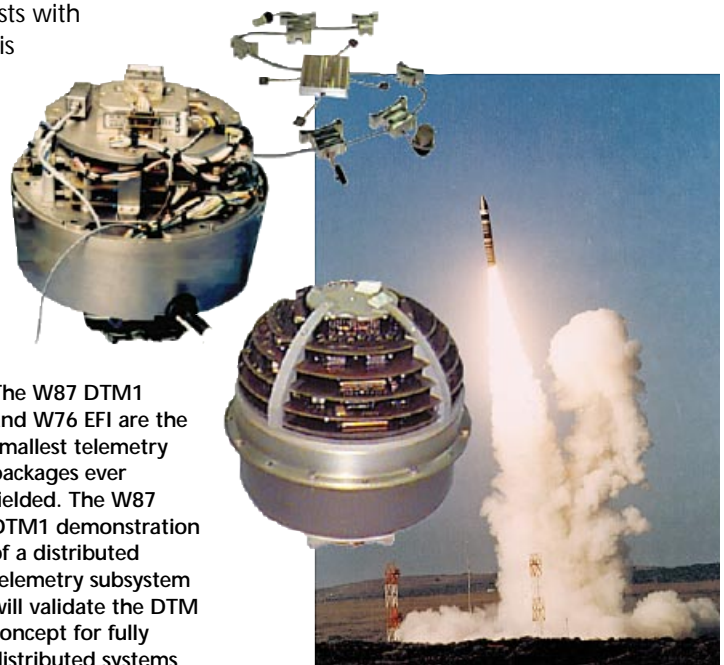
The W87 DTM1 and W76 EFI are the smallest telemetry packages ever fielded. The W87 DTM1 demonstration of a distributed telemetry subsystem will validate the DTM concept for fully distributed systems of the future.

Stockpile Information Group— Database Management Systems

This task began by forming the Surveillance Information Group (SIG) to provide, throughout the nuclear weapons complex (NWC), desktop access to legacy, current, and future weapon component information. We continue to make progress, adding content to our classified web site through a combination of scanning (for legacy documents) and electronic file submission (for current information). Our form-based process allows one to many files (including whole structures) to be uploaded to our server, with accompanying metadata providing a rich description of collection content. The information is divided into logical groups to facilitate storage and retrieval through a platform-independent web interface. Information is found either by querying the fielded metadata or by locating words and phrases within the optically recognized or electronic text of the document, using one of several commercial search engines. This task has demonstrated the feasibility of scanning and digitally storing entire vaults of classified documents at reasonable cost. We have recently added a collection of 19,000 scanned aperature cards (courtesy of Sandia National Laboratories/California). This collection allows the user to view Lawrence Livermore National Laboratory generated drawings online, which compliments our ability to view NWC-wide unclassified drawings contained in SNL's Image Management System.

At Y-12, as a first step, we transformed the surveillance cycle reporting system from paper to electronic format. In the process, we greatly enhanced the content of the report to include all pre- and post-disassembly procedures, laboratory reports, video clips, photos, and radiographs.

Secure web site at Y-12 provides desktop access to test program archives, surveillance, and current inspection and certification information.

Photo

Data

Video

All previous cycle reports and the unit's build book are also included, and delivery time for the report has been shortened from 18 months to 1 month. In a cooperative effort with the Accelerated Strategic Computing Initiative and Advanced Design and Production Technology (ADaPT) programs, Y-12 has installed a product data management (PDM) system, designed to contain all future surveillance cycle reports, an archive of information on secondaries built for the nuclear test program, and electronic data capture for current and future life extension programs. Y-12 has recently accredited a web server to deliver this information to the user. We have demonstrated desktop access to this system using a web browser over SecureNet, as shown in the figure.

The collection of information at the Kansas City Plant (KCP) resides predominately on a network of sensitive unclassified computers. NetU has been implemented as the communications infrastructure to provide the capability for desktop access to this and other unclassified resources. The focus of our efforts with regard to providing information from KCP data sources to consumers has been on developing a distributed, platform-independent, object-centric interface to part-related information stored in various computer systems throughout the site. This approach relieves information consumers from needing to know what data is stored where, in what format, and how to get it. Instead, they can think in terms of real-world objects that are familiar to them, such as parts or drawings. Queries are formulated using these objects rather than database-oriented knowledge. The technical approach is based on a three-tiered architectual model and object technologies. Using this approach, KCP has developed a prototype Part Object and web-based user interface. Plans are to have seven major surveillance-related data sources available online via the Part Object approach by the end of FY1998.

At Pantex, we are making progress under the ADaPT extended data capture and electronic procedure pilots. The data capture pilot seeks to capture W87 assembly and inspection records in an electronic data warehouse for access from the desktop over SecureNet. Savannah River also participates in the SIG effort and is close to accrediting both its SecureNet and NetU networks.
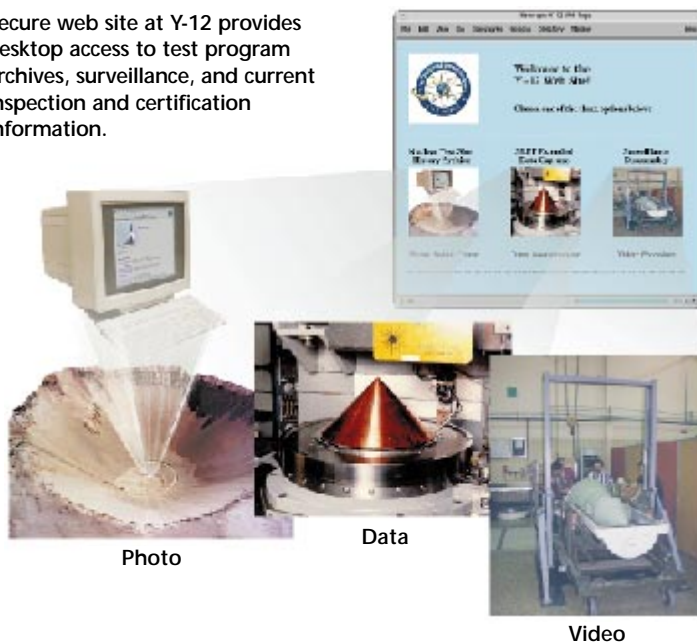
Online Material Property Databases

We are assessing the feasibility and utility of making relevant engineering material property databases easily accessible on nuclear-weapons-complex (NWC) computer networks and then to implement access in cases deemed beneficial. Ultimately, we also plan to assess the quality of existing databases and promote needed upgrades.

We have acquired the hardware and software required to create databases for those production facilities that did not previously have adequate equipment. These acquisitions have allowed us to generate and partially populate at least one relevant prototype electronic database at every nuclear weapons complex production facility. This has improved the internal availability of important material property information and helped ensure its preservation. The emphasis to date has been on unclassified information so that it may be easily used to test communications protocols. With these pilot databases available in-plant, local demonstrations to visitors have been possible, all of which have been well received. Most who view these pilots would like to be able to access them from their own desktops.

We are now attempting to make our prototype databases available at the desktop computers of weapon engineers. Unfortunately, we have yet to overcome the technical and administrative hurdles to implementing such communications except for the Kansas City Plant (KCP) materials standards database that can be accessed by anyone in the NWC via the open Internet through the path shown in the figure. Since the principal benefit to surveillance-related activities from this task is easy access for weapons engineers to materials data, our attention now centers on surmounting these hurdles to communication. Originally, we had planned on demonstrations using the open Internet with later transition to SecureNet. However, using the open Internet even for unclassified data raised concerns in several cases, while plants with largely unclassified data preferred not to be burdened with the extra security issues surrounding SecureNet for their unclassified databases. To address both of these issues, near-term efforts at KCP and Savannah River (SR) will now focus on use of the DOE NetU system for sensitive unclassified information rather than a combination of open systems and SecureNet.

The unclassified electronic version of the KCP materials standards database originally made available on the open Internet last year with limited data was well received and has now been almost fully populated. Y-12 spent much of the last year populating databases with materials-related information, reviewing and correcting it during entry. Textual data from all of the unclassified Y-12 technical data

sheets have been captured, and scanned images from the reports are being added to these electronic files. Pantex completed the design of an electronic high explosive surveillance database and has populated it with some of the higher quality unclassified data available from existing sources. (The final product will be an edited database, not merely an archive). Equipment now exists at Savannah River to scan and digitize reports and micrographs, although an effort is underway to upgrade its quality to better capture micrograph information. An SR material property database home page has been developed and will be put online via NetU as soon as administratively possible. Widely used (or specifically requested) SR documents on material properties in hydrogen isotope environments will be accessible electronically from this page.
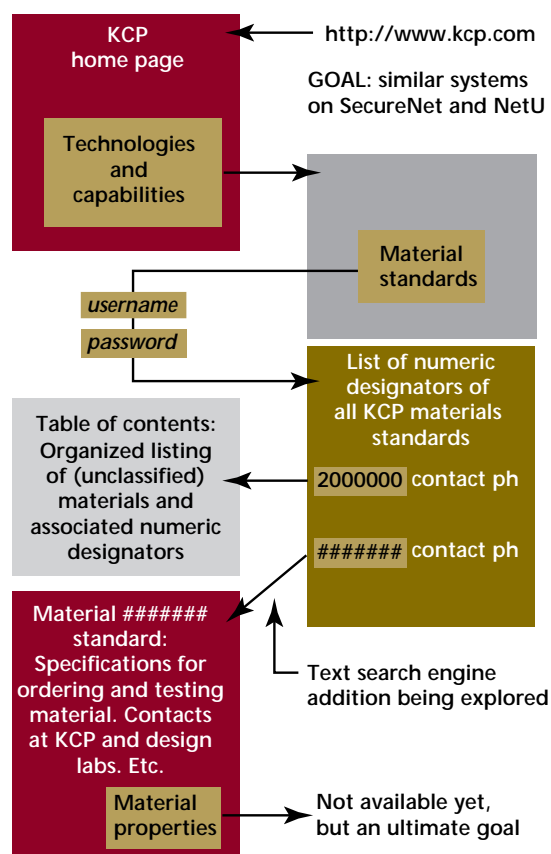
Easy access to unclassified Kansas City Plant material standards database from a desktop computer.

Enhanced Surveillance Information Management Program

The purpose of this task is to improve access to all necessary information so that surveillance engineers and scientists can answer questions concerning the safety and reliability of stockpile weapons in a timely and efficient manner. Our goal is to implement a better system for information acquisition, storage, and retrieval. This task is being undertaken in conjunction with Task LL27 and the Surveillance Information Group (SIG).

In addition to identifying specific information needed to analyze surveillance units, we have mapped the current process and identified limitations and roadblocks in retrieving surveillance information and in delivering it to the nuclear design agencies. We demonstrated communications protocols to bring weapon part or surveillance data to the desktop of engineers across the nuclear weapons complex

(NWC). In conjunction with other initiatives, such as the Accelerated Strategic Computing Initiative, the Advanced Design and Production Technologies, and the Nuclear Weapons Information Project, we have also initiated pilot projects to improve access to information.

Classified communication throughout most of the NWC is now possible via classified email. We have also established connectivity that uses SecureNet to access the Y-12 web site. To improve electronic information dissemination, we also helped with the design of a CD-ROM system containing dismantlement information from Y-12. All future dismantlement information will be provided in this manner.

Historical product manufacturing information as well as current electronic data from tests were captured electronically and converted to a format (portable document format, or PDF) that can be accessed and searched across different computer platforms. For example, we helped incorporate a CD information system into the W80 cycle reporting system from Pantex. The goal is to improve surveillance analysis by providing the necessary tools for surveillance engineers to analyze trends and do statistical analysis of each weapon system for cycle reporting.

We have developed a prototype Surveillance Quality Evaluation Tracking System using Microsoft Access for tracking surveillance components in the stockpile. The quality evaluation tracking (QET) points of contact (POCs) are beginning to use the Microsoft Access database system. We are exploring the cost effectiveness of upgrading all QET POCs to the latest version of Microsoft Access. We designed, developed, and presented several QET reports to DOE.

We have developed and implemented data-collection process flow throughout the complex for two weapon systems, the W88 and the B83. This information was reported on a CD and included record-of-assembly data, test data, radiographic reports, etc. The exercise defined many pitfalls to be corrected in the data-collection process throughout the NWC. The first figure outlines the flow of information at the highest level used in this process. The second figure is Sandia National Laboratories' process flow.

Process flow for the Surveillance Information Group.
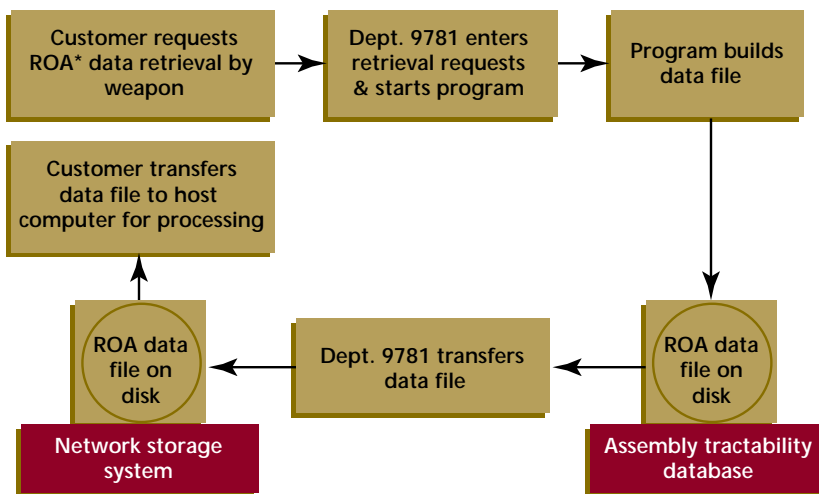
Process flow at Sandia National Laboratories.

*Record of Assembly
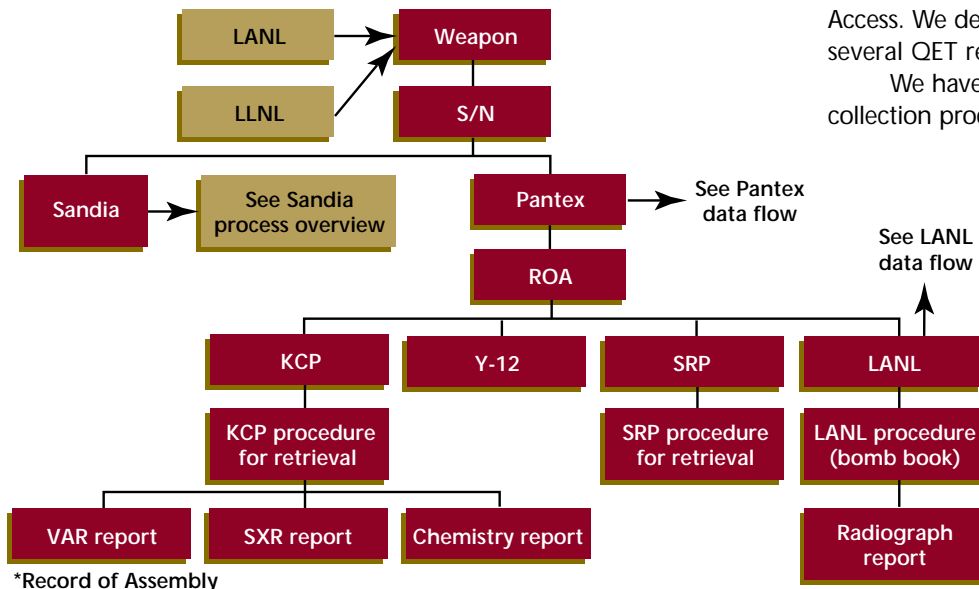
Enhanced Reliability Methodology Program

The objective of this task is a validated methodology, based on expert judgment, for assessing the reliability of the stockpile. Reliability is defined as the probability of a component or system achieving some performance measure (e.g., the reliability of a nuclear package would be its probability of achieving the certified yield).

Expert judgment is used to assess available knowledge and interpret and synthesize it to estimate performance, namely, reliability and its associated uncertainty. When experts deem that there are sufficient test data, reliability can be calculated through classical statistics. However, when data are insufficient, experts may have to give subjective estimates of performance based on their synthesis and interpretation of limited nuclear and non-nuclear tests, numerical simulation, material properties, communications with colleagues, and/or production and surveillance data.

The methodology includes several elicitation techniques that may be used, depending on circumstances or the expert's needs. For example, the rule-based performance prediction technique has been used when quantitative data were lacking. This technique involves interviewing an expert on the component or subsystem being evaluated to learn which conditions would lead to degraded yield. It elicits the expert's membership functions and fuzzy rules on these conditions (e.g., if x condition is high and y condition is low, then yield is low); has the expert assign numbers to these rules; and generates plots of yield as a function of the conditions with the associated uncertainties. The technique provides a means for forecasting reliability as a function of the components' expected conditions. Forecasts have been obtained using hypothetical component conditions.

The methodology includes a knowledge base, logic models, and elicitation techniques. Users can electronically browse the information underlying the reliabilities and uncertainties, as well as the experts' interpretation of this information. The methodology is expected to offer a systematic and quantitative way to evaluate the effect on reliability of such actions as replacing a component, or conducting additional studies/testing, such as for stockpile

life extension. The test bed for the methodology is the W76 nuclear package.

The methodology is being validated in the automotive industry, where test data are more plentiful. The aim is to check engineers' early reliability estimates for systems such as fuel pumps against subsequent test results and later "road warranty" data.
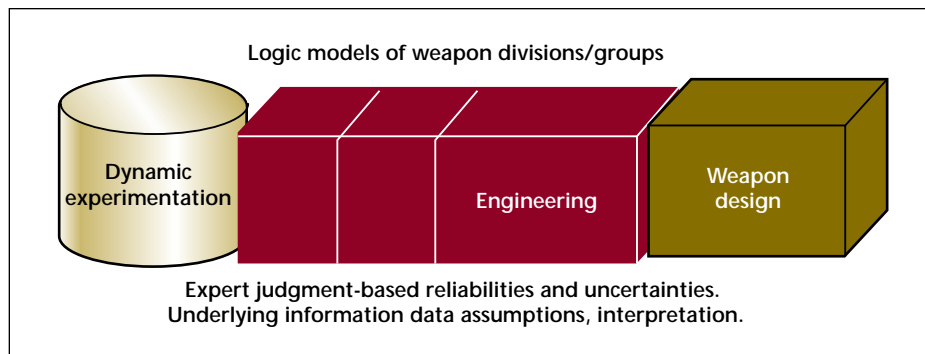
Three early validation results have been received from the automotive environment as of July 1998.

Reliability and uncertainty estimates by auto experts on two systems predicted successful performance, later confirmed by test data. For a third system, the experts predicted a 95% chance of failure to meet specifications and being recalled. Unlike the other two, this system was totally new, so its initial predictions had to be based solely on subjective expert judgment. Independent tests of prototypes showed that all of the 40 tested systems failed, and in the way predicted by the experts. This result has increased our confidence in the methodology and in the accuracy of experts' subjective assessments, especially where test data are sparse; it has positive ramifications for estimating nuclear physics weapon reliability.

The prototyped software is available for demonstration on a small, secure networked system. It is being adapted and fielded at Los Alamos National Laboratory (LANL).

We incorporated physics-related chemical/ engineering information into the knowledge base. Such information was obtained through our interaction with the Global Weapons Information System (GWIS) project and through our collaboration with the surveillance program.

We investigated ways of integrating physics performance with the larger reliability framework. We have linked to other secure web pages at LANL as part of our plan to participate in the archive integration effort.

Logic models of weapon divisions/groups

Dynamic experimentation

Engineering

Weapon design

Expert judgment-based reliabilities and uncertainties.
Underlying information data assumptions, interpretation.

Expert judgment is needed in our methodology to assess available knowledge to estimate reliability and its associated uncertainty.

The Stockpile Surveillance/Data Management System

The Stockpile Surveillance/Data Management System (SS/DMS) is a comprehensive database that serves as the record copy of the data required by the Department of Energy for the Stockpile Surveillance Program. Existing stockpile surveillance data sets were converted into a modern, structured query language-compliant format. The SS/DMS currently contains the data from new material and stockpile surveillance laboratory tests. That set of data consists of over two million attributes of data entries from over 43,000 data sets collected from approximately 19,000 sampled weapons.

The analytical toolset developed as a result of this task provides an automated, mathematically rigorous capability with which to examine existing and future data for trends from any cause. Because component production dates are part of the SS/DMS test data sets, component performance as a function of age is readily observable.

For example, the plot in the figure below was generated directly from a desktop computer linked to the SS/DMS server through a classified local area network (data shown here are unclassified data resident in the SS/DMS database). The system evaluation engineer first submitted a request to plot the values of the regulated high voltage at firing as a function of component age. The SS/DMS query engine collected the appropriate data (from the over two million data entries) and passed the selected data to the analytical toolset, which generated the screen shown in the figure. The elapsed time from request submittal to screen display was 30 seconds, with no further human interaction. The screen display shows all the data collected, a least-squares fit linear-regression plot (estimating equation), a

95% confidence interval for the estimating equation, the parameters for the estimating equation, and the value for the coefficient of determination (R-squared). These results show both visually and mathematically that there is essentially no significant mathematical relationship between the regulated high voltage at firing and the age of the component. Data values outside the confidence interval bands are due strictly to natural variation, not age. Given the number of data points collected for this query, the analysis demonstrates no discernible trend of degradation due to component aging.

Without the availability of the analytical toolset, obtaining this figure and the understanding gained from it would have required many hours of transcribing individual data points into a statistical data analysis package with the potential of transcription errors. With the analytical toolset embedded in the SS/DMS, the entire data collection and analysis process took 30 seconds, all under computer control with no further human interaction. This significant saving in time allows the system evaluation engineer to evaluate and interpret the data rather than struggle with data transcription. The incorporation of the analytical toolset funded by this task has contributed substantially to our ability to manipulate the millions of test data values collected over the last four decades by the Stockpile Surveillance Program.

SS/DMS plot of regulated high voltage at firing as a function of component age.
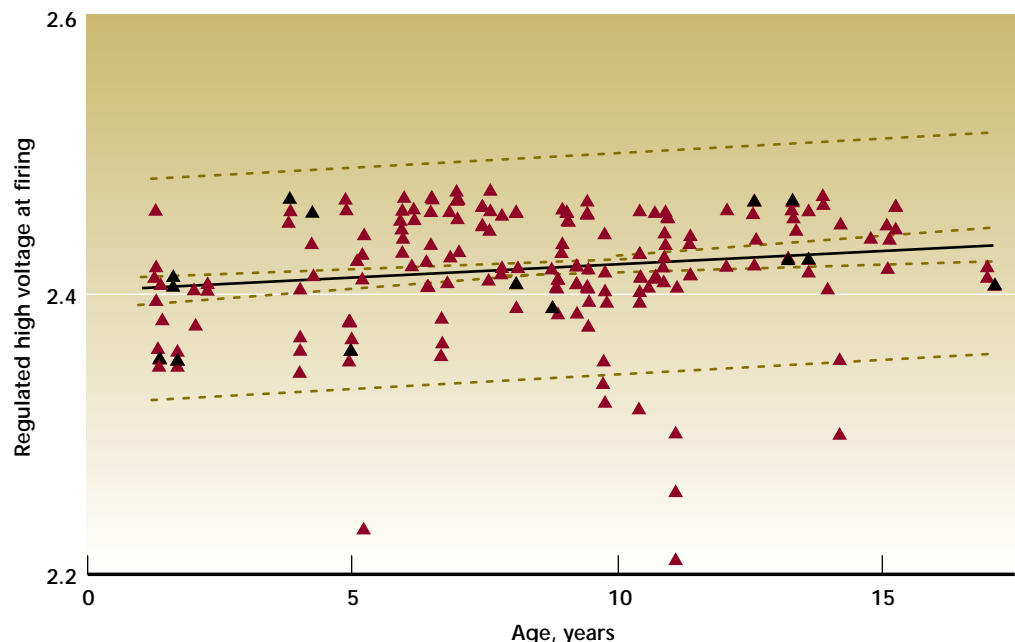
Secondaries
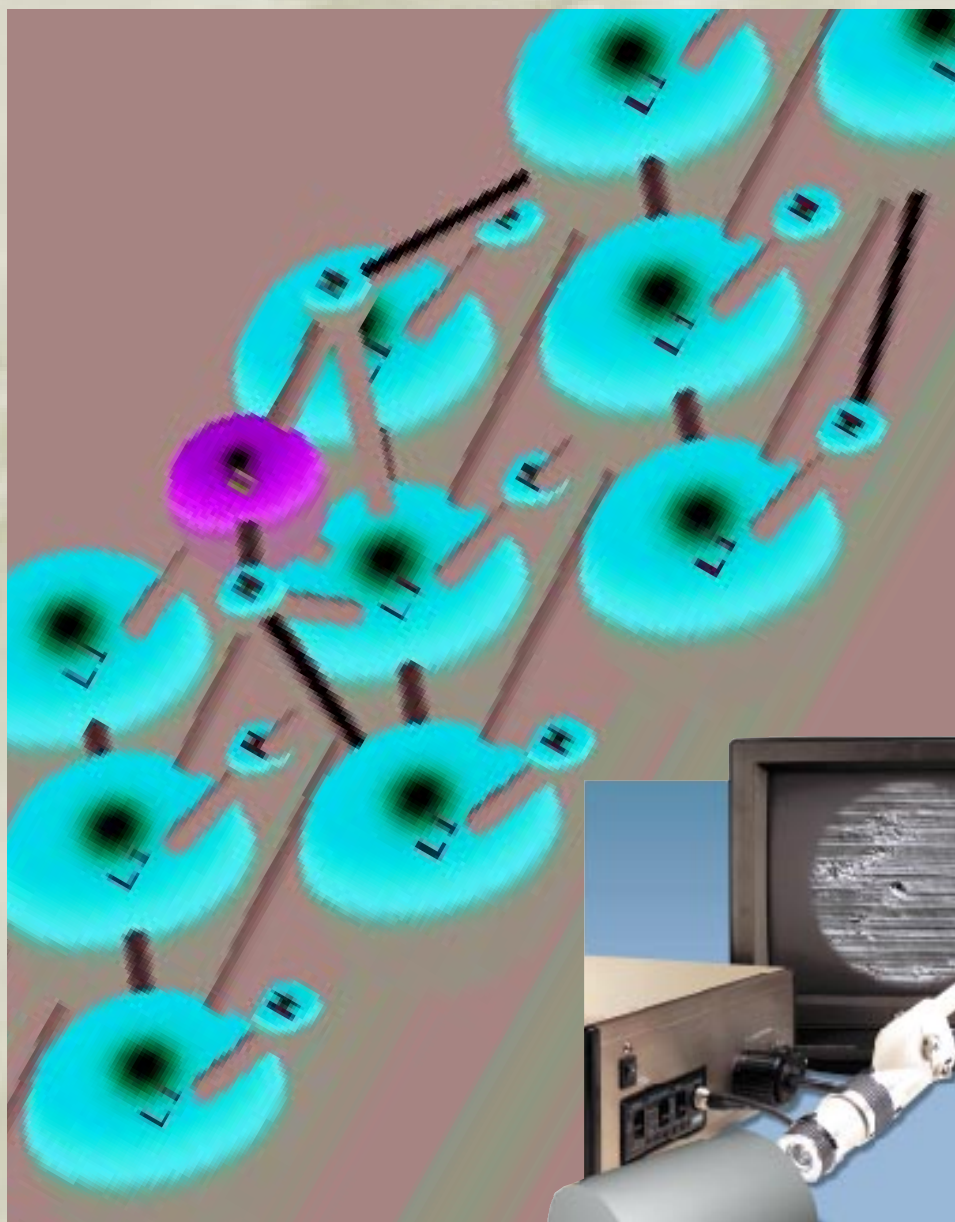
Secondaries

Focus Area

Assuming non-nuclear firing devices and the primary portion of a nuclear weapon function as designed, the yield of the weapon depends upon the performance of the secondary portion. The secondary is a complex device with several potential avenues for performance variation because it is composed of many materials and components assembled in a variety of ways. The assembled unit must be geometrically precise, and the materials included must remain in their as-designed, as-installed condition to meet performance expectations. Historical surveillance data have revealed that materials interactions may affect performance of the secondary in the aging stockpile. The Secondary-Specific Focus Area is benchmarked by these observations and by investigation of other potential areas of concern.

This focus area includes a mix of materials science, supportive experiments, data analysis (historical and new data), and modeling. These secondary-specific activities integrate closely with related activities in other program elements, such as diagnostics. The overall objective is to develop understanding of the aging of materials, components, and systems to enable assessment and prediction of performance for decades to come. Past knowledge and experience have been bounded by relatively short stockpile lifetimes because weapons were replaced frequently with new designs. Modeling and prediction based on several decades of performance were adequate. Performance models are constantly being improved and benchmarked against new data generated by ESP tasks. By approximately FY2000, performance models for the secondary will be complete. Recognizing that prediction is not 100% accurate, new stockpile surveillance techniques are also being developed to give early indication of any adverse changes in components.

Deliverables

1. Results of experiments that characterize the chemical, physical, and mechanical changes that may occur as a result of aging.

2. Reports that describe the changes that might be expected as a result of aging in constituent components.

3. Predictive models that include aging mechanisms of the actual secondary configurations and can be used to assess the expected life of secondary components.

Pertinent Tasks

LA10	Material Study on Special Material
LA15	Uranium Corrosion and Aging
LA22	Aging of Special Material
LA42	Integrated Canned Subassembly Modeling
LL20	Experimental Interaction and Degradation of Materials of Interest
LL22	Modeling of Materials Compatibility
LL23	Atomic Site-Specific Chemistry and Physics
LL24	Development of High-Energy Neutron Radiography
LL25	Development of Tests for Non-Traditional Components
LL32	Microsensors for Real-Time Evaluation of Materials Degradation and Corrosion in Weapon Systems
LL42	Sensitivity Analysis
OR02	Interrogation of Disassembled Units
OR07	Hydrolysis Reaction on Special Material
OR14	Materials Properties Evaluation of Uranium Components

Effects of Solid–Gas Interactions on Component Aging

We are combining a series of experimental and theoretical tools to generate an improved understanding of canned subassembly (CSA) aging and a corresponding predictive computer model. Three interrelated projects include study and experiments in (1) materials interaction and degradation, (2) material compatibility modeling, and (3) site-specific atomic chemistry and physics. The goal is to blend together studies of the fundamental nature of important gas-solid interactions with macroscopic models and experiments on the systems in relevant geometries. Understanding CSA components will also help us to understand the effects of any aging changes on structural components.

Because a CSA is large, expensive, and complicated, small-scale experimental test units have been prepared. By placing small amounts of materials in various simple controlled geometries, we can investigate the gas and surface chemistry using techniques developed under other ESP tasks. These techniques then can be used as a test bed for the macroscopic aging code.

The secondary is a sealed assembly containing a variety of solid materials. The components can be characterized as nuclear or structural. Components that often include uranium and lithium compound are the nuclear elements of the thermonuclear device. The structural components include organic materials (among others) for maintaining the correct geometry. The important distinction between the two classes of materials is that, in the absence of nuclear testing, it is very unlikely that the system's nuclear components can be changed without affecting its performance, whereas there is considerably more leeway on changes to the structural parts.

If the CSA contains uranium, the most likely destructive event in a CSA is the hydriding of uranium by molecular hydrogen. Despite efforts to remove H_2 introduced during the manufacturing process, a small amount of moisture is always present. The water in the CSA can react to form uranium hydride. These ESP tasks are a combined effort to examine competing reactions and required gas transport at a molecular and macroscopic level.

Our primary long-term goal is a predictive computer model using both realistic CSA geometries and accurate detailed chemistry and transport. In the first step toward that goal, we are performing detailed three-dimensional "zoning" of the gas transport pathways through a representative CSA. Using Lawrence Livermore National Laboratory's considerable expertise in transport codes, such as TOPAZ and ALE-3D, we are modifying these codes to include solid-gas reactions. In 1998, we developed a 3D mesh and preliminary mass transfer calculation for H_2 migration in a stockpile system using the ALE-3D code.

One possible CSA reaction, the LiH/H_2O reaction, is being studied with molecular beam techniques and quantum chemical modeling. Both theory and experiment show that the initial reaction, $LiH + H_2O \longrightarrow LiOH + H_2$ is very rapid on a fresh LiH surface. It could be regarded as instantaneous on the timescale of the macroscopic simulations. However, as this is a gas-surface reaction, the resulting hydroxide slows continued reaction considerably. There are then two other reactions, $LiH + LiOH \longrightarrow Li_2O + H_2O$ and $2LiOH \longrightarrow Li_2O + H_2O$, which are much slower. These reactions are also being studied experimentally and theoretically in order to develop a rate model for the predictive capability.

A similar effort is underway for developing uranium hydriding and organic hydriding models. Experiments indicate that the reaction is highly localized on the surface. A model has been developed that incorporates nonlinear kinetics. The presence of preferred sites shows behavior similar to that seen in molecular beam experiments. After the model is refined and parameterized, it will be incorporated into our transport code.
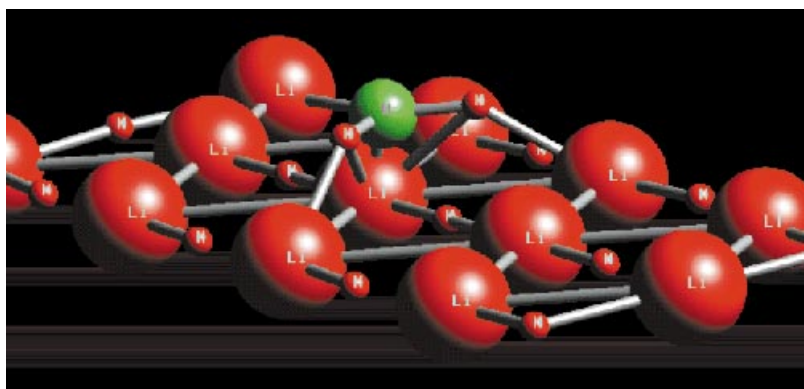
"Snapshot" from a quantum chemical study of the reaction of water with a lithium compound. A water molecule attaches rapidly to the surface and then rapidly reacts.

Interrogation of Disassembled Units

Because of the nuclear test ban and the need for weapon life extension, information about the aging of weapons and predicting lifetimes of the enduring U.S. nuclear stockpile is more crucial than ever. Many of these weapons have been in service far longer than their designed service lives, and they are being removed from the stockpile for dismantlement because of the reduction in the U.S. nuclear arsenal. This dismantlement effort provides a window of opportunity to gather data on real-time-aged parts from disassembled canned subassemblies (CSAs).

The main purpose of this effort is to secure material, components, and information from returned weapon assemblies for aging assessment and life prediction tests. This task also implements enhancements to the current interrogation techniques in the surveillance program. The components and information recovered under this task are being used in other Enhanced Surveillance Program (ESP)

tasks to establish benchmarks and predict the aging of weapons in the enduring stockpile.

During FY1998, we transferred more than 100 components to ESP task leaders for aging prediction and life extension tests. An additional 616 components have already been identified for transfer.

We combined resources with Task LL27 to retrieve historical weapons assembly and disassembly reports. All of the disassembly records published for the Los Alamos and Lawrence Livermore national laboratories weapons were converted to digital media. We also worked with Task OR18 to assess the procurement of surveillance instruments.

We incorporated new interrogation techniques into routine surveillance. The first figure shows the video imaging system that was implemented in FY1998 to characterize, map, and digitally archive anomalies in weapon components. Prototypes for two other techniques have been designed and built for integration into routine surveillance in FY1999. These techniques include the low-temperature thermal decomposition (LTTD) system and the diffuse reflectance infrared fourier transform spectrometer. Both of these technologies provide real-time, online diagnostic capabilities for understanding weapon aging. LTTD, shown in the second figure, uses temperature-programmed desorption to characterize component chemical characteristics that might be weapon aging indicators.

Video imaging system characterizes weapon anomalies (top). LTTD system studies aged component chemical characteristics (right).

Uranium Corrosion and Aging

This multifaceted project is working to understand the microstructure and chemistry of unalloyed uranium in stockpile components as they influence corrosion. This year, we also focused on the CSA aging modeling effort and, in collaboration with the U.K. Atomic Weapons Establishment, on experiments and modeling of uranium corrosion.

Microstructural studies have focused on the effects of carbon (the most common impurity in uranium) in the evolution of the uranium microstructure during accelerated aging tests. Data have not yet been fully analyzed, although some very interesting results have been observed. For example, at constant carbon levels, we observed significant variations in hardness, grain refinement, and carbide morphology. Because variations in mechanical properties clearly correlate with gross variations in the nucleation and growth kinetics of uranium hydride, these studies are leading us toward a better understanding of how physical metallurgy of the material affects the corrosion mechanism.

We are also studying how the local nucleation of hydride affects the structure of the surface oxide by using atomic force microscopy (AFM), scanning tunneling microscopy (STM), and Auger electron spectroscopy (AES) in inert gas at ultrahigh vacuum. Our studies show that the oxidized surface is very complex, exhibiting wide variations in thickness and topography between samples, between grains in the same sample, and within individual grains. However, relating this fine-scale variability to the relatively sparse hydride initiation sites is very difficult. The surface oxide layer does not appear to control the sites where hydride attack is initiated, although it must play a role in the induction period prior to hydride initiation. This work is discussed in greater detail in the *Proceedings of the Materials Research Society Symposium on Hydrogen in Metals*.

Our studies on *in situ* observations of hydride nucleation and growth have, over the past two years, led us to conclude that variations in the chemistry of the near-surface region of the sample strongly affect the local hydride initiation phenomenon. Numerous experiments with uranium samples of various carbon contents, thermal histories, and levels of cold work show that hydride nucleation sites are in the region of second-phase particles (inclusions) in the uranium. We postulate that the region around inclusions, while depleted in the elements that form the inclusions themselves (C, Si, etc.), is also enriched in elements that are insoluble in the precipitate. This gradient in impurity concentration around inclusions therefore controls the locations where the hydride nucleates. In the figure below, apparent hydride nuclei have formed in rings around an inclusion. The hydride appears to precipitate below the surface of the metal. This behavior is consistent with published models of hydride growth but has never been previously documented. We suspect that some impurities may act as catalysts for the formation of uranium hydride. For example, we have determined using AES that sulfur, calcium, and chlorine segregate to the uranium surface during a brief anneal at 200°C.

We are working to isolate the effects of individual impurities. Collaborators at Y-12 have researched historical documentation of the chemistry of uranium parts produced there and identified a stock of aged, depleted uranium that appears to closely parallel the processing history and chemistry of similar-vintage enriched uranium. We have taken advantage of new capabilities for analyzing traces of uranium. We are also preparing to produce test specimens with tightly controlled levels of various impurities of interest. This effort is made possible by the recent acquisition of very-high-purity electrorefined uranium produced by researchers at Argonne National Laboratory and material purified by researchers at Los Alamos National Laboratory.
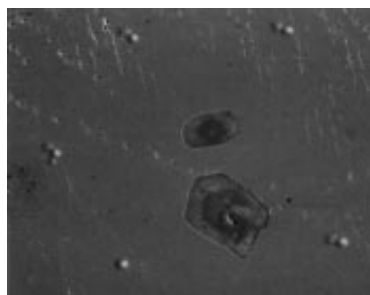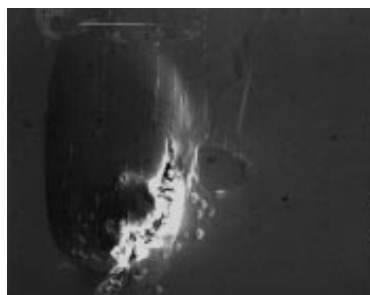
These images show the surface of a cylinder of uranium containing nominally 300 ppm of C, which was exposed to hydrogen for 10 min at 70°C. The hydriding appears to initiate adjacent to inclusions. The pit (left image) is adjacent to an inclusion in the center. The right image shows a ring of what apparently are hydride blisters formed around a pair of inclusions.

Material Properties Evaluation of Uranium Components

This task was begun in 1998 to develop an understanding of the aging process of components made from uranium-6% niobium alloy. The primary concern is the varied appearance of binary material after aging and how this may relate to changes in bulk properties. The surface condition varies from a very thin, light scale to a heavy black oxide. A limited number of previous studies have shown that the varied surface scales may be associated with local variations in Nb content. However, this relationship has not been quantified nor is there any basis upon which to relate the observable surface condition with the bulk properties of the metal.

To correlate surface scales with variations in Nb content, we need an understanding of the oxidation mechanism and measurements of reaction kinetics. Although the development of oxidation-resistant U-Nb alloys was started in the early 1950s, no studies published to date have explained how niobium imparts oxidation resistance to uranium. One of the most commonly repeated theories is that the dissolution of Nb in the UO_2 lattice modifies the electronic structure of the oxide, resulting in slower oxygen transport through the lattice. If this were true, the oxidation rate would be reduced relative to that of pure U, but over the long term oxidation would still proceed unabated. An alternate theory is that the Nb forms a very thin second-phase oxide (Nb_2O_5) that protects the underlying metal by acting as an oxygen diffusion barrier. Therefore our initial research has concentrated on determining the corrosion mechanism of U-Nb alloys.

In this study, the initial stages of corrosion of a U alloy with 6 wt% Nb by O_2 or H_2O were examined using the surface-specific techniques of x-ray photoelectron spectroscopy (XPS), thermal programmed desorption, static secondary-ion mass spectroscopy, and sputtered neutrals mass spectroscopy (SNMS). X-ray photoelectron spectroscopy studies of the U6Nb surface following oxidation using O_2 at 300 K indicate production of a thin oxide overlayer of stoichiometric $UO_{2.0}$ intermixed with Nb_2O_5. While the same stoichiometry is exhibited for uranium when the oxide is prepared at 500 K with O_2, niobium is much less oxidized exhibiting a mixture of NbO and Nb. Contrary to previous XPS literature, the SNMS depth profiling studies reveal that oxidation by O_2 is much greater (as judged by oxide layer thicknesses) than that exhibited by H_2O. Oxide layer thicknesses of less than 20 Å are created using H_2O as an oxidant at 300 K with exposures of <5000 L (oxide layer thicknesses created from O_2 exposures are approximately an order of magnitude higher). Formation of a critical density of Nb_2O_5 is suggested to be responsible for the enhanced corrosion resistance by preventing diffusion of O^- (O^{2-}) or OH^- into the oxide/metal interface region. This work is consistent with studies of material intentionally oxidized in air.

It is therefore apparent that the addition of niobium to uranium results in oxidation resistance solely by the formation of a protective Nb_2O_5 network within the UO_2 scale. At lower niobium levels, the oxide must grow to a greater thickness before this network is established. At still lower levels or in metal where the niobium is not uniformly distributed, the oxidation proceeds identically to that of pure U. We are now proceeding to demonstrate the relationship between oxide thickness and Nb content in controlled ingots produced at Los Alamos National Laboratory and with actual stockpile components obtained from disassembly. In FY1999, we plan to expand our studies to include mechanical properties characterization in order to correlate variations in Nb content and possible environmental embrittlement of the metal.

The niobium *3d* core levels for U6Nb exposed to 500 L O_2 at 300 K (bottom trace), U6Nb exposed to 500 L O_2 at 500 K (middle trace), and clean U6Nb (top trace).
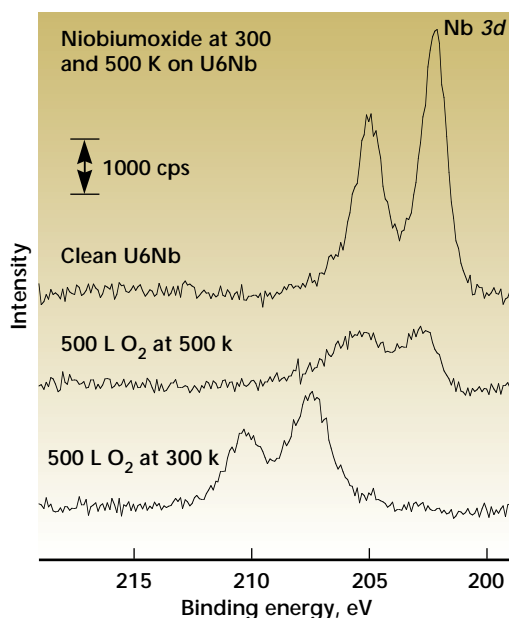
Materials-Aging Models

Materials-Aging models

Focus Area

The reliability and surety of non-nuclear components and subsystems in the enduring stockpile will change with time as a result of the age-related degradation of their constituent materials. Existing stockpile assessment methods typically address materials-aging and reliability problems after they occur, rather than anticipating and avoiding future problems or failure mechanisms. This focus area promotes efforts to improve our ability to anticipate surety and performance-reliability problems caused by materials aging.

In order to predict and thus avoid or correct reliability problems in the surety and performance of weapons, significant improvement must be gained in modeling and simulating the behavior of materials as they age in the stockpile environment. Detailed understanding of materials encompasses the signatures of aging and degradation phenomena and projecting these phenomena out to eventual failure. This focus area supports investigations to improve the fundamental understanding and modeling/simulation of materials-aging behavior in stockpile environments. Individual tasks emphasize the prediction of failures that affect the surety or reliable performance of weapons. Supported investigations focus on quantifying the difference between "performance requirements" and "performance limits" and how this changes with time. This understanding is necessary to extend the lifetime of weapons in a safe and dependable manner. The relevant integration of materials understanding, materials modeling, and performance simulations is the hallmark of this focus area.

Five principal categories of time-dependent changes in stockpile materials are being addressed. They include (1) energetic materials models, (2) organic materials models, (3) solid-state materials models, (4) corrosion models, and (5) interface models. Our selection of these categories is the result of a risk assessment of stockpile materials, which identified materials with the highest likelihood of age-related changes and with the highest consequence of material changes. Likelihood of aging is based upon a combination of data from the stockpile surveillance history and engineering judgement from our present understanding of the kinetics and thermodynamics of material degradation mechanisms in stockpile environments. Evaluation of the consequence of aging is based on our understanding of the design intent of the materials in the weapons, the impact of degradation of safety and reliability, and of other related factors.

We will develop and validate age-aware materials models that will be used in quantifying the useful service lifetimes of non-nuclear components and subsystems in the enduring nuclear weapon stockpile. We will also account for confidence bounds related to production or environmental variability. Where time-dependent changes in the structure and properties of critical weapon materials cannot be modeled with confidence, appropriate materials characterization tools and surveillance methods that provide early signatures of aging will be identified. Models developed will be incorporated into higher-level electrical and mechanical models for component and subsystem performance (developed in the Non-nuclear Components Focus Area) to support the prediction of overall changes in system reliability with time.

Deliverables

1. Develop model of the degradation of solid film lubricant for application in the dynamic performance model of the MC2969 stronglink.

2. Apply the PACER gas analysis surveillance method to quantify the leakage or permeation of outside air into the sealed weapon environment.

3. Develop aging model for T-111 base and weld metal for inclusion in the pressure burst simulation of radioisotopic thermoelectric generator, or RTG, power sources.

4. Develop aging model for PBX9501 in lens isolator.

5. Integrate atmospheric corrosion model into electronic device performance model.

6. Apply the "wear out" remaining life prediction technique to polymers from returned weapon hardware.

Pertinent Tasks

SN01	Atmospheric Corrosion of Weapon Electronics
SN02	Aging of T-111 Welds in Radioisotope Thermoelectric Generators
SN03	Stress Voiding of Integrated Circuits
SN04	Energetic Materials Predictive Capability
SN05	Predicting and Verifying Elastomer Lifetimes
SN06	Ceramic Materials Lifetime Predictive Capability
SN07	Degradation of Materials in Electromechanical Devices

Atmospheric Corrosion of Weapon Electronics

Corrosion caused by the atmosphere within nuclear weapons is the leading age-related degradation mode observed in the stockpile and forms the single largest Significant Finding Investigation category. Traditionally, the severity and potential consequences of corrosion problems were addressed using engineering judgment, and when necessary, materials of construction and the local environment were changed. Now, faced with an aging stockpile and active interest in weapon lifetime extension, our high standards for surety demand that we effectively anticipate any effect of corrosion processes on weapon reliability and nuclear safety.
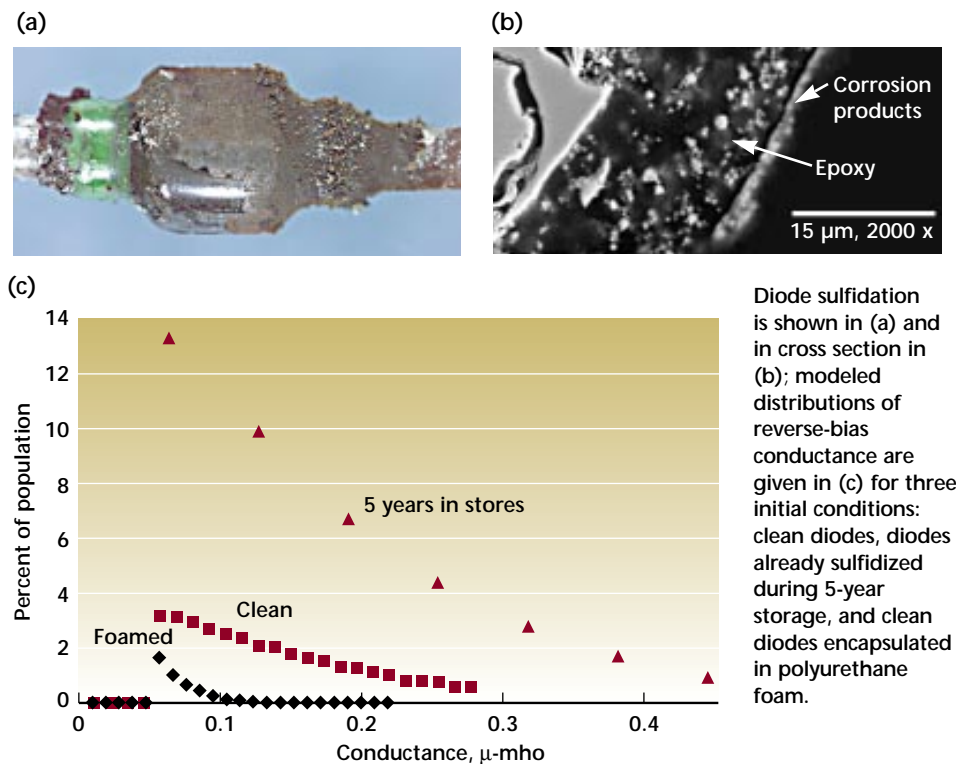
Two general corrosion modes are relevant to weapon-system degradation: (1) product-layer growth (e.g., sulfidation of electrical contacts) and (2) metal dissolution (e.g., corrosion of microelectronic aluminum metallization). Although structural and mechanical components also corrode, our main concern is corrosion in electronic components because of the direct consequence on system function and therefore reliability.

During 1996, a relevant example of Type I corrosion was observed on SA1388 diodes. During a 5-year storage period for war reserve product, a gaseous sulfur species emitted from rubber bands caused the growth of a copper-sulfide layer across the surface of a significant number of diodes, increasing reverse-bias leakage current (see figure). Once a corrosion product layer bridges the two leads, a conductive path is formed and conductance increases as the film spreads and thickens. This degradation process can produce subsystem and system failure that could occur in an actual weapon when an undesirable sulfur-containing environment exists (e.g., polysulfide staking material or SO_2-containing micro-balloons).

Our corrosion study combines continuum/phenomenological-level modeling with age-aware electrical subsystem models, addressing both uncertainty and the structure of the end-user interface. Many types of uncertainty are applicable, including extrinsic factors (environment), intrinsic factors (material properties, stochastic nature of corrosion initiation), modeling simulation (process simplification), and experimental measurement error (bias, unknowns). To ensure that a proper end-use focus is part of every aspect of the integrated program and to allow time for unique computational or database requirements, this task is proceeding in parallel with the development of physically based corrosion process models.

We took a primarily empirical approach. A governing equation, based on the solution of the mass balance (continuity) equation for the production and consumption of gaseous sulfur species, was derived to describe the rate of production of copper sulfide on the diode. While several rate constants are deterministic, epoxy porosity, initial sulfide source concentration, and eventual film-growth characteristics are stochastic. Traditional computational reliability techniques (Monte Carlo, pseudo Monte Carlo) were applied to treat the uncertainty and solve the equation. Because of the stochastic nature of the corrosion process and environmental variability, the specific output is a distribution of short-circuit electrical resistance (conductance) values as a function of time. This materials-degradation information is input into age-aware, sub-system-level electrical models of the components of interest to predict when the components will no longer meet performance requirements.

(a)

(b)

Corrosion products

Epoxy

15 μm, 2000 x

(c)

5 years in stores

Clean

Foamed

Percent of population

Conductance, μ-mho

Diode sulfidation is shown in (a) and in cross section in (b); modeled distributions of reverse-bias conductance are given in (c) for three initial conditions: clean diodes, diodes already sulfidized during 5-year storage, and clean diodes encapsulated in polyurethane foam.

Welds in Radioisotope Thermoelectric Generators

Radioisotope thermoelectric generators (RTGs), such as the MC2730 and MC3500, are electrical power sources that essentially consist of a radioisotope heat source in contact with a thermocouple pile. The heat sources used in RTGs, such as the MC2893, MC2893A, and MC3599, are plutonium oxide fuel encased within a welded tantalum alloy (T-111) capsule. During stockpile life, decay products from the plutonium oxide increase the pressure within the capsule, which—in order to avoid plutonium dispersal—must be contained during both normal operation and accidental fire exposure. We are making an integrated assessment of RTG integrity as these heat sources exceed their original design life.

Capsule survival in a fire is the most demanding performance requirement because high temperatures can cause creep in the tantalum weld, and the capsule could leak. Finite-element models using base metal properties predict that the highest stresses occur in the dome of the capsule, whereas failure often occurs in the weld region (see figure). This indicates that welding changes the properties of the alloy and results in an unexpected failure location during simulated fire testing.

Our current surveillance activities include periodic, pressure burst-testing of inert capsules. Because of significant variability in qualification and surveillance data, an accurate predictive model has not been developed, which explicitly incorporates effects of materials aging. To overcome these difficulties, we initiated an enhanced surveillance program to improve understanding of creep and aging of T-111 welds. The program includes characterization of creep deformation and failure modes

and development of weldment creep data for T-111 welds. Potential aging mechanisms were also evaluated, improved thermal and mechanical response models were developed, and results were correlated with qualification and conventional surveillance tests.

Our completed critical assessment of available creep data and behavior for T-111 translated base metal data into a uniform and usable format and showed that very little data for welds in this alloy are available. A welding system that reproduces the procedures used in the original war reserve (WR) fabrication has been constructed to fabricate test welds with microstructural features as similar as possible to those in the WR components. The welds will be used to develop creep properties data for T-111 welds and to assess the effects of aging on these properties. The specialized facilities for conducting the creep tests have been designed and are being assembled.

In parallel, we conducted metallographic analysis of surveillance pressure burst test samples. Initial indications show there is substantial microstructural variation in capsules depending on material lot, fabrication site, failure time, and possibly aging conditions. Hafnium oxide precipitates (hafnium is a constituent of the alloy) are present along the grain boundaries in the welds as well as within the grain interiors; they may affect the failure mode and represent a mechanism of aging. A first generation finite-element model of the capsule was constructed, and a plan for model characterization of the effects of weld properties on heat source pressure burst response was developed. We exercised the model using tentative values for creep strain-to-failure for weld and base metal over a range of pressure burst test temperatures and pressures. The results appear to correlate, at least qualitatively, with available qualification and surveillance experiments. Experimental weldment properties data are currently being generated that will be used to validate the current computational model and pinpoint areas where refinements are needed.

These activities are coordinated with component and weapon systems personnel to maximize the utility and impact of the work. Further, the efforts are complementary with conventional surveillance activities and, when completed, should provide an integrated and predictive surveillance capability for RTG heat source reliability.
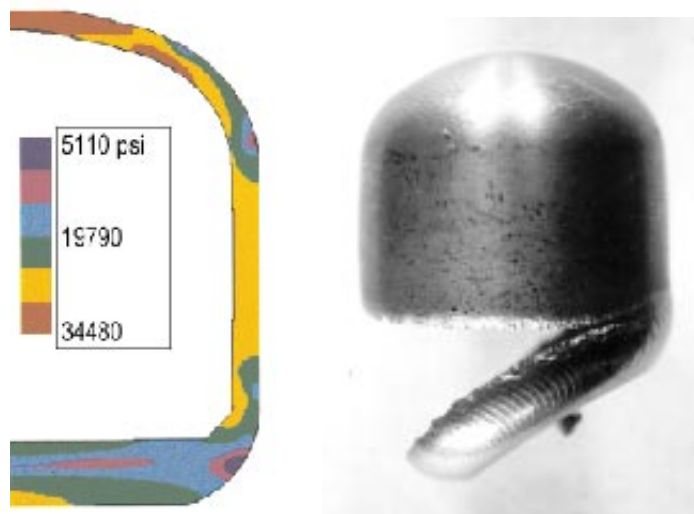
Finite-element analysis using currently available properties data predicts that highest stresses would cause failure in the dome. Test failures typically occur in or near weld, with burst severity and time-to-failure highly variable.

Energetic Materials Predictive Capability

Sandia National Laboratories and Pantex are collaborating in an effort to qualify changes in aged pentaerythritol tetranitrate (PETN). Understanding these phenomena will give us a stronger technical basis for making recommendations regarding replacement, rebuilding, or reacceptance of components containing this material.

PETN and a silicone binder are components in the explosive composite (XTX8003) used in the MC3028 firing set. The PETN incorporated into XTX8003 is non-equilibrium material and, with aging, can change thermodynamically into new morphological forms. Changes in crystal-size distribution can alter detonation characteristics and potentially alter component performance. More importantly, the growth of crystals at a free surface represents the migration of energetic material from the bulk composite, which could produce non-detonable regions depending on the nature of the diffusion. We have found that accelerated aging of XTX8003 causes PETN to recrystallize into perfected crystals at free surfaces. This redistribution of crystal sizes is also being followed in bulk PETN samples. To avoid such changes, PETN is typically stabilized before long-term use, but stabilization is not used for the PETN in XTX8003. Because performance of the firing set depends on both energetic output and simultaneity, we intend to rigorously quantify the extent and effects of these aging phenomena.

In previous years, we developed the analytical tools to identify numerous decomposition products of PETN. These products are not seen in naturally aged stockpile samples. The chemical stability of PETN in XTX8003 appears to be excellent when the weapon environment is considered. Accelerated aging of PETN under conditions outside the stockpile-to-target sequence (STS), however, produces traces of decomposition gases, acetone from the recrystallization of the explosive, and small amounts of ionic species.

Detailed studies of the diffusion of PETN within the silicone binder demonstrate anomalous behavior. Though not yet quantified under STS conditions, diffusion is rapid above 50°C and apparently is influenced by mobile, low-molecular-weight species within the cured binder matrix that are known to influence aging and/or traces of acetone from the PETN.

We have also examined the mobility and vapor pressure of PETN homologues and the effects they might have on the vapor pressure and mobility of PETN. These data will allow us to understand the effects of homologues on PETN composites.

Ongoing velocity-of-detonation (VOD) experiments on aged XTX8003 in thin troughs have shown both increased and decreased VOD depending on aging conditions. The relationship between XTX8003 composition changes and component performance is spectacularly complex, but we are quantifying the nature and extent of ongoing diffusion phenomena. As we refine our quantitative understanding of these actions, we will provide input to an evolving explosive/mechanical finite-element model of the firing set so that we can understand resulting effects on the function of the whole component.

Importantly, we have not identified any issues that would lead us to lose confidence in the performance of the MC3028 in its current configuration. Rather, we have identified aging phenomena that we must quantitatively understand in order to confidently recommend lifetime extensions for the stockpile.
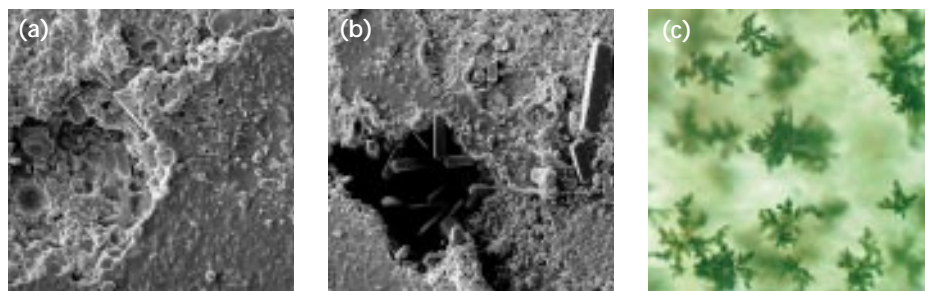
Explosive composite XTX8003 (a) before and (b) after aging shows the growth of crystals on free surfaces; the size of the large crystal is 20 × 160 μm. Diffused PETN (c) precipitates from silicone binder in minutes upon cooling in 20- to 40-μm crystal clusters.

Predicting and Verifying Elastomer Lifetimes

We are developing unique methods and models for better predicting and verifying elastomer lifetimes and applying these advances to other polymeric weapon components and materials. We have previously shown the importance of diffusion-limited oxidation (DLO) during air-aging and developed theoretical models and unique experimental approaches for predicting and verifying the importance of such effects. We also derived the ultrasensitive oxygen consumption approach, the first and only quantitative method for testing extrapolations from accelerated aging data. This approach was applied to W88 EPDM (ethylene-propylene rubber) O-rings, resulting in a confident prediction of lifetimes exceeding a hundred years.

Environmental O-ring seals are an important polymeric component used on all weapon systems to protect the weapon interior from oxygen and water vapor leakage. The two most common measurements for following degradation of seal materials are compression stress-relaxation (CSR) and compression set (CS). CSR, which follows the decay in force between the seal and its metal mating surface, is the ideal method to use for laboratory simulations, modeling, and development of extrapolated predictions. However, because CSR cannot be easily applied to real weapons, surveillance activities have used CS measurements as an immediate indicator of following the condition of field-aged O-rings. The results from these CS measurements have often been quite interesting, as evidenced by a puzzling bimodal distribution of data for butyl O-rings used on the W76. Unfortunately, there has been a trend towards eliminating such measurements because they have been difficult to perform using the historic hand-held caliper approach. Working with Pantex, we successfully transferred a superior CS method based on a laser micrometer. In addition, working with AlliedSignal/ Federal Manufacturing & Technology (AS/FM&T), we have now determined that the W76 bimodal CS behavior is due

to manufacturer differences, with Vendor A supplying better butyl O-rings than Vendor B.

Although ideally correlated to the failure criterion of a seal material, historic CSR measurement procedures were found to be lacking. We recently published our improved procedures, which include new methods for separating physical and chemical relaxation phenomena and finite-element modeling of DLO for the disk-shaped samples used for CSR experiments. We applied these new ideas to butyl O-rings from Vendor A that are used as environmental seals for the W76, W78, W80, and W87. Modeling and experiments showed that important DLO effects for standard CSR samples (15-mm-diam disks) led to meaningless results. To solve this problem, we developed a novel approach that eliminated DLO anomalies by compressing 50 mini-disks (2-mm diam) in parallel. This approach shows oxidative scission processes dominate the CSR force decay, suggesting that our unique, ultrasensitive oxygen consumption approach might allow us to confidently extrapolate CSR data to ambient weapon temperatures. We are currently obtaining oxygen consumption measurements down to room temperature to further test this approach. In addition, due to the recent discovery of the cause of bimodal CS behavior, we initiated a series of experiments on butyl material (W76, W78) from Vendor B. Another important question concerning CSR results is the force level that constitutes failure (leakage) of the seal. Working with AS/FM&T, we modified a CSR device so the sealing force of an O-ring can be correlated to the leakage rate between the O-ring and its metal mating surface.

Theory for DLO of disk-shaped samples explains large errors in force decay for standard CSR experiments: (left) integrated relative oxidation (%) as functions of DLO theory parameters α' and β for a disk of radius a, where α' is a dimensionless parameter proportional to a^2 and β is a dimensionless parameter proportional to the partial pressure of oxygen; (right) the large effect on force decay caused by diffusion-limited oxidation.
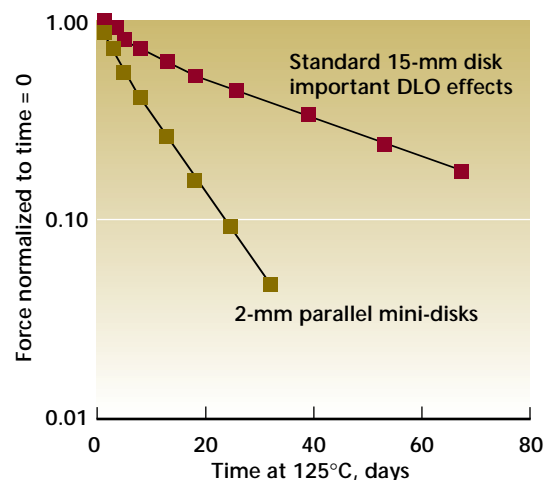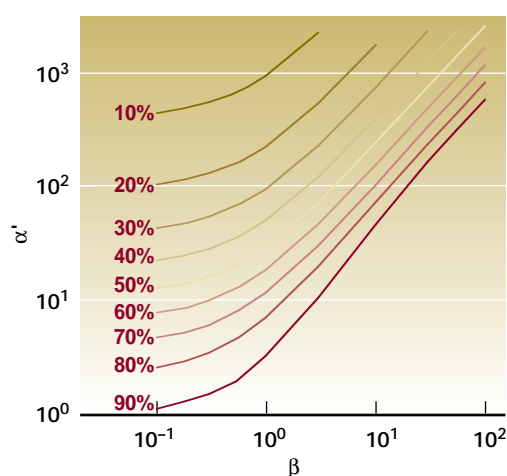
Non-nuclear Components
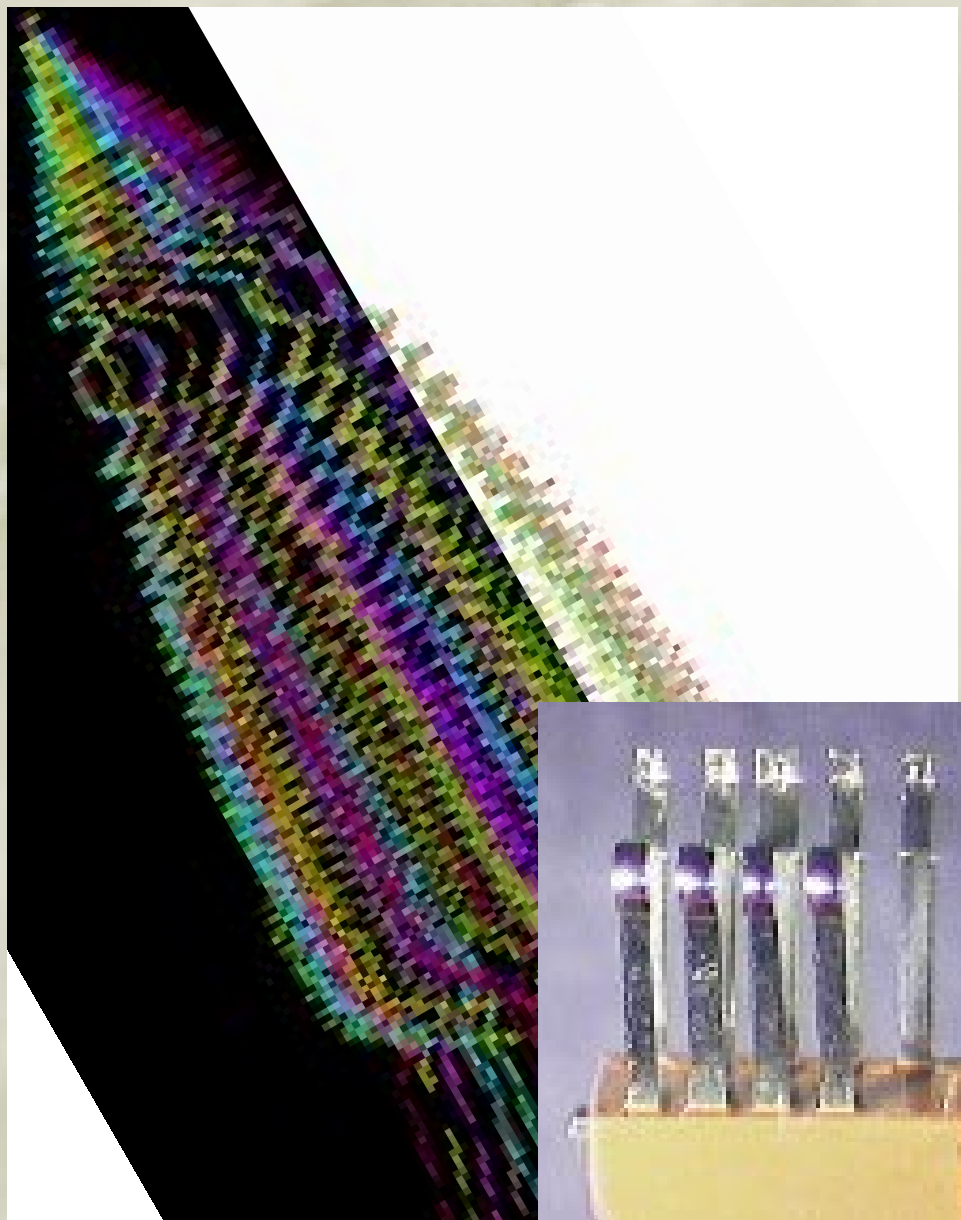
Non-nuclear Components

Focus Area

The fundamental objective of the Non-nuclear Components Focus Area is to provide improved information and tools to support stockpile management decisions for the enduring stockpile. Historically, surveillance of non-nuclear components and subsystems has been based upon system-level functional testing. While system-level testing will remain as the principal method of non-nuclear surveillance, such performance testing is forensic rather than predictive in nature—failures are found, but early indicators of unacceptable changes are generally not observable. This focus area is designed to increase our ability to monitor, anticipate, and manage time-dependent changes in non-nuclear components that would otherwise pose high risks to stockpile management. It will link together information about the aging of weapon materials with understanding of the performance margins of non-nuclear components to enable a predictive understanding of the future evolution of non-nuclear components in the stockpile. This program is intended to identify the time scale to loss-of-confidence in non-nuclear components and subsystems and to provide component-level surveillance methods and recommendations geared to discovery of changes before unacceptable performance degradation occurs.

There are more than 200 major non-nuclear components and subsystems and literally thousands of supporting parts. These components (and subsystems) have been prioritized in order to assess and manage risk across the stockpile. The highest-priority components for enhanced surveillance studies were selected on the basis of their pervasiveness in the stockpile, their effect on reliability and safety, and the likelihood that problems with their materials would occur. The initial prioritization, performed in FY1996, will be reviewed and revised on a regular basis as increased information on component-level risks is available. There are presently three tiers of non-nuclear component priorities. Tier I has 14 components that pose the highest risks to the stockpile, Tier II contains 35 components with substantial risks, and Tier III lists the remaining 150+ components. It should be noted that meaningful life-extension decision of Tier III components would still require some R&D.

There are three major classes of non-nuclear components and subsystems: electronic components and subsystems, electromechanical components, and components and subsystems containing energetic materials. Work performed within the Enhanced Surveillance Program is organized into three groups of

Pertinent Tasks

OR11   Arming, Fuzing, and Firing Shields
SN23   Age-Induced Degradation of Nuclear Safety
SN24   Component Prioritization and Stockpile Life Extension Program Integration
SN25   Electromechanical Component—Stronglinks
SN26   Electronic Components and Subsystems—Capacitive Discharge Unit (CDU) Firing Set
SN27   Energetic Components and Subsystems—Slim-Loop Ferroelectric (SFE) Firing Set

tasks, each representing one of these major classes of components. Objectives of these tasks are to assess existing component degradation information, develop predictive component-degradation models that can be used to predict the system reliability over time, recommend and develop additional component-level surveillance methods, and guide future stockpile decisions regarding component replacement.

This focus area has three principal objectives:

1. To identify methods for augmenting the existing stockpile surveillance program. These methods offer the real possibility of substantially improved insights into age-induced degradation processes.

2. To develop validated age-aware component and subsystem models that link time-dependent material changes (characterized within the Materials-Aging Focus Area) to changes in system performance, with an emphasis on system reliability and nuclear safety. Validation of these models is accomplished through a combination of materials characterizations, evaluations of stockpile-returned hardware, and stockpile surveillance observations (likely to play a greater role as new methods are developed and deployed).

3. To provide much of the technical basis for Stockpile Life Extension Program refurbishment decisions through characterizations of age-induced degradations that likely affect system performance during future deployment intervals.

Deliverables

1. Support W80 decision milestones for CDU firing sets, intent stronglink, trajectory stronglink, and trajectory sensing signal generators.

2. Develop age-aware performance for rolamites.

3. Furnish refined aging and low-dose-rate radiation models for critical electronic components for W80 subsystems.

4. Develop a component level model capable of incorporating aging effects for stronglink environmental sensing devices for the W76.

5. Complete validated age-aware SFE firing set model for the W76 and W78.

6. Develop age-aware performance model for radar on the W76.

7. Complete aging and nuclear safety evaluation for the W78.

8. Estimate safe life of radioisotope thermoelectric generators.

Age-Induced Degradation of Nuclear Safety

This project explores the effects of material aging on nuclear safety through a materials-based evaluation of components whose performance is critical to nuclear safety. The framework for identifying, prioritizing, and evaluating materials issues of potential importance to nuclear safety is identical to that used for original design and certification, emphasizing the principles of isolation, incompatibility, and inoperability to ensure a predictably safe response across the full spectrum of credible accident threats. In addition to providing initial aging evaluations, this project provides a technical basis for guiding future assessments of field-returned hardware as well as a material basis for making Stockpile Life Extension Program (SLEP) refurbishment decisions.

Materials used in the manufacture of the components comprising the nuclear safety implementation for specific weapon systems were chosen for specific roles in integrity, form, and function. Aging could threaten the safety of a weapon by compromising the integrity and function of components made up of those materials.
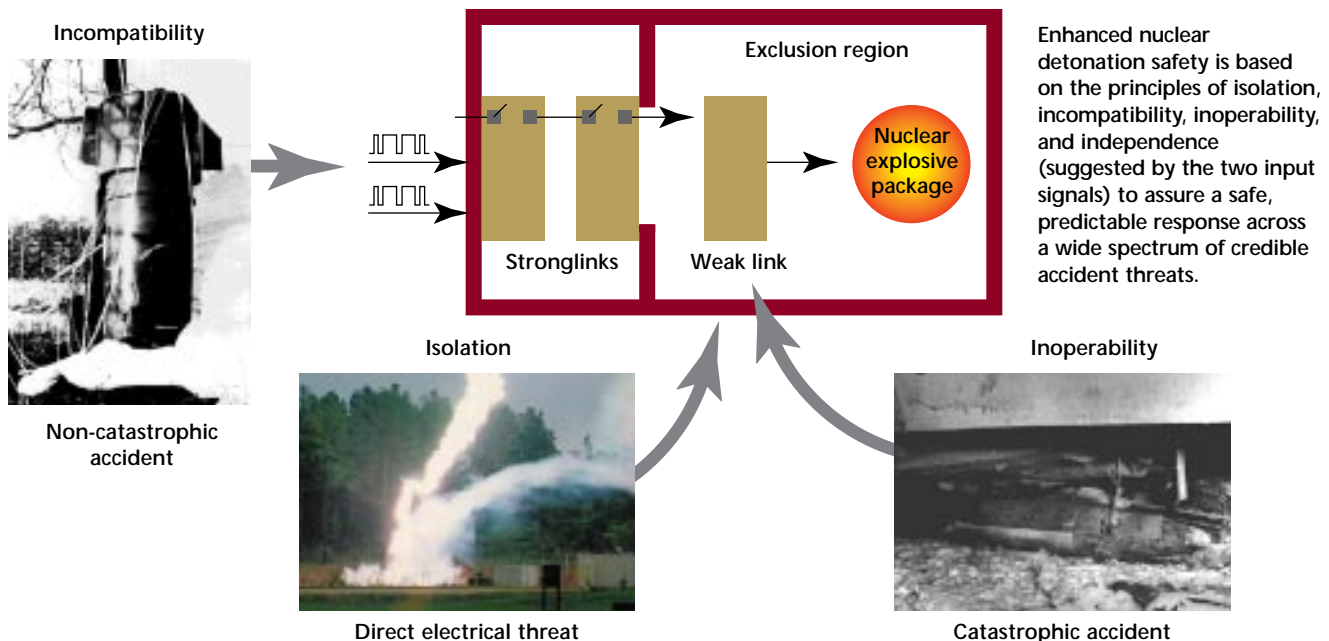
This project has focused on the following: (1) identification of nuclear safety critical components, their materials of manufacture, and the potential time-dependent material degradations that could affect the nuclear safety function of the components; (2) prioritization of material issues and qualitative placement of issues into categories based on importance to the weapon nuclear safety theme; (3) for each identified potential degradation, qualitative categorization of the impact severity to the nuclear safety function of the component; (4) development of a process for potential materials degradation information to be communicated and acted upon by the system and component engineers in their SLEP, dual revalidation, and stockpile surveillance activities; and (5) incorporation of the potential materials degradation information into the nuclear safety assessment activities of specific weapon systems.

The loss of the internal silicone fluid of a stronglink is an example of a plausible time-dependent degradation that would adversely affect weapon nuclear safety. Such a fluid loss may allow the stronglink to respond to non-unique forms of energy (i.e., to forms of energy not unique to the intended use environments), thus violating the safety principle of incompatibility.

To date, this project has examined four weapon systems and hundreds of materials and material combinations with respect to their nuclear safety impacts. There is a process in place to systematically work through the open materials issues, and field-returned hardware is being examined for evidence of the potential degradations. The potential degradations are also being communicated to the appropriate system engineers to be incorporated into the ongoing SLEP and revalidation efforts in progress.

To facilitate a rapid and managed retrieval of specific weapon system, component, materials, and safety information, the entire Enhanced Surveillance Report on each system in this project will be incorporated into the new format for future safety Sandia National Laboratories reports on weapon systems. Future nuclear safety assessment reports will be a five-volume series. Volume 5 will be the ESP project results from the Age-Induced Degradation of Nuclear Safety task. This change is a direct result of this project.

Incompatibility

Non-catastrophic accident

Exclusion region

Stronglinks

Weak link

Nuclear explosive package

Isolation

Direct electrical threat

Inoperability

Catastrophic accident

Enhanced nuclear detonation safety is based on the principles of isolation, incompatibility, inoperability, and independence (suggested by the two input signals) to assure a safe, predictable response across a wide spectrum of credible accident threats.

Component Prioritization and Stockpile Life Extension Program Integration

The Sandia National Laboratories, AlliedSignal/Federal Manufacturing & Technologies (AS/FM&T), and Pantex have been investigating since early FY1997 the aging characterizations of non-nuclear components whose performance is critical to sustaining the nuclear safety and reliability of the enduring stockpile. These activities, which build on materials research whose origins pre-date the Enhanced Surveillance Program (ESP), grew under ESP sponsorship to encompass component-level characterizations with a continuation of relevant materials support. Most recently, ESP has tried to enlist Sandia weapon system organizations as equal partners to assess the system impact of preliminary component characterizations and to champion ESP objectives and contribute to meaningful outcomes.

Natural partnerships with weapon system organizations were impeded by their more immediate commitments and a lack of resources to provide the necessary coordination. The W76 Dual Revalidation (DR) program, conducted concurrently with ESP, was an important exception to these generalizations. At both Sandia and AS/FM&T, ESP was well underway in characterizing selected components and materials from the W76. Dual revalidation investments at both facilities broadened the investigation of W76 components well beyond the original ESP portfolio, and DR was instrumental in acquiring substantial stockpile hardware to aid in validation of postulated aging mechanisms. The DR experience was a vital exploration of how system and component organizations can work together to ensure useful, achievable, and timely ESP outcomes.

Nevertheless, it was not the DR model but the emergence of the Stockpile Life Extension Program (SLEP) that drove partnerships with other weapon systems. Through SLEP, the project groups began to specify dates for system refurbishment decisions. The W76 and W80 systems, which have the more immediate decision milestones, are entering into phase 6.2/6.2A studies to evaluate refurbishment options and costs. The W80 program has already identified a minimum set of components for replacement. Other components are less obvious and represent the greatest opportunity for ESP to influence the decision process. While the W76 study is less certain to result in near-term stockpile refurbishments, component aging will weigh heavily in refurbishment decisions for W80/W76 systems as we explore the risks of stockpile components that are well beyond their original expected life. The most valuable ESP outcome would be high-confidence predictions of component lifetimes, but the real challenge is maximizing the utility of lower-confidence predictions. The W76 system, through its DR experience, leads in ESP capabilities and how they affect refurbishment decisions. The W80/ESP coordination only began this fiscal year and is still evaluating how to prudently define ESP's role in the 6.2/6.2A study timeframe.

Some component characterizations were redirected more specifically to the W80 system in early FY1998. Today, the entire ESP component portfolio is providing characterizations to support identified SLEP decision milestones, and FY1999 program growth is aimed at recent candidates for "double lifetimes" on the W76 or W80. We will follow a greater degree of formality in negotiating and monitoring ESP milestones to ensure usefulness of the content and schedule of aging characterizations. Frequent ESP reviews are planned with annual reports beginning in August 1999 to document the characterization conclusions for both the W76 and W80 systems.

It is important to note that, while the program has adopted a strong emphasis on supporting SLEP refurbishment decisions, it has not sacrificed its initial emphasis on broad stockpile applicability. The current component portfolio still includes performance critical components that are used in multiple systems together with components whose design features, materials, and environmental drivers provide meaningful aging insights into larger families of components throughout the stockpile.
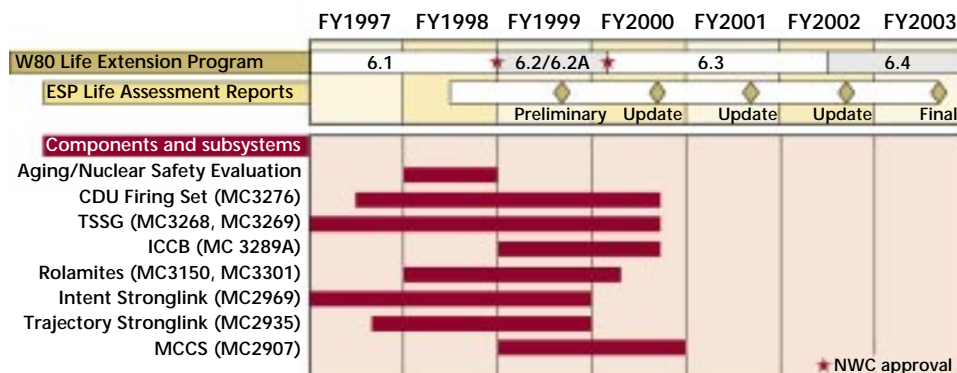
A complex-wide ESP plan has been developed to support W80 decision milestones as part of the Phase 6.2 Life Extension Study for non-nuclear components and subsystems. In the above chart, 6.1 represents concept assessment, 6.2 feasibility & option select, 6.2A definition, planning & costing, 6.3 design and development, and 6.4 production readiness (phases 6.5, first production, and 6.6, full-scale refurbishment, are not shown on this timeline).

Electromechanical Components—Stronglinks

Many war reserve electromechanical components (e.g., environmental sensing devices and stronglinks) in the stockpile play critical roles in weapon nuclear safety and reliability. We have made significant progress assessing the useful lifetimes of some components that are approaching or have already exceeded their intended design life.

We now have dynamic performance models of critical functions for the MC2969 stronglink, the MC2854 fluid integrating environmental sensing device (ESD), the MC2897 verge escapement ESD, and rolamite ESDs. Recently, using DADS (dynamic analysis and design system), we developed a highly realistic and detailed dynamic performance model of the MC2969 stronglink timer. Its features include: inertial properties of all the moving parts, contact between the star wheel and pallet, contact between the cam follower and the drive cam, spring force on the drive cam, torque transmission through the gear train, spring force on the follower, and friction on the pallet and star wheel journal bearings. Model parameters that evaluate aging effects include contact friction (see box, top) at the star wheel/pallet interface, contact friction at the drive cam/follower interface, and journal bearing friction.

Changes in friction and other variables can alter the timer beat rate, resulting in the misinterpretation of the pulse code that the mechanism discriminates. Component, subsystem, and weapon system failures occur when the well-defined limits to the beat rate are exceeded. The predicted beat rate of the timer from the MC2969 timer model (below, left) has been compared to the beat rate of several of the timers assembled and tested as part of the solid lubrication oxidation study. Model results compare very favorably with experiment. Hardware testing conducted in the solid lubrication study will play an

important part in the validation of this model. Stockpile-aged MC2969s were obtained from dismantled weapons and are being tested and disassembled for materials studies.

High-speed video and acoustic emission data have been gathered from the stockpile-aged units as well as from artificially aged timer assemblies. Significant progress has been made toward digital capture of the acoustic emissions of aged units, and we are developing a method to more accurately analyze the analog acoustic emission data of the MC2969 original production units for comparison to the digital data from aged units. The contributions of AlliedSignal/Federal Manufacturing & Technologies have been crucial to our successes in collecting acoustic emission data, obtaining high-speed video data, defining component performance margins, and recovering hardware. The validation process for the MC2969 timer model will help increase confidence in DADS performance models of other electromechanical components (e.g., the MC2897) now being studied.

A problem that has long plagued our efforts to observe stockpile degradation is the potential for damaging the MC2969 during removal from the next higher assembly. Damage inflicted during disassembly often cannot be distinguished from aging effects. A new approach to unit testing and residual gas analysis has reduced this damage; it requires only partial removal of foam and potting material from around the unit and significantly reduces the time needed for the lengthy depotting process.

Other ongoing areas of study for the MC2969 will increase the certainty of lifetime extension assessments. These include the observed degradation of ceramic hermetic seals for electrical feedthroughs (see box, middle) and the measured effects of age on electrical contact resistance during switch closure (see box, bottom). High-voltage holdoff testing is also underway to characterize the effects of abnormal environments (600°C) on the performance of this nuclear safety critical component.
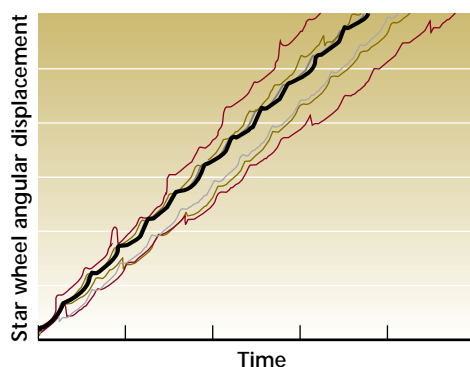

Predicted beat rate (heavy black line) and experimentally observed beat rates (light lines) from the MC2969 timer show good agreement. The solid model of the timer assembly used to generate the dynamic analysis model is shown on the right.
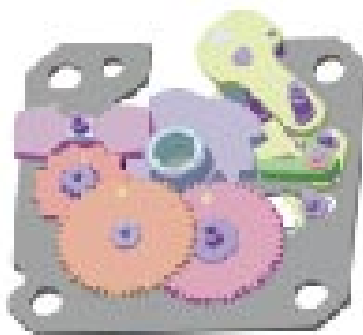
Effect of Friction Changes

Reactions between the internal atmospheric environment and the solid lubricant used in stronglinks can produce compounds with different frictional properties than the starting material. We have shown that oxidation of molybdenum disulfide under conditions present in the stockpile can increase its starting friction as well as steady-state friction coefficients. The effect of these friction changes on stronglink performance is now being evaluated. The run-in data for artificially aged subassemblies show the influence of oxidation on device timing and are being used to validate a dynamic simulation of the device that includes an age-aware friction model.
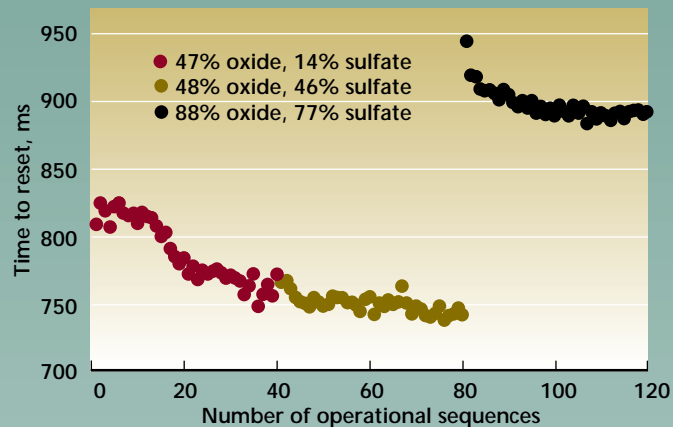
Measured effect of run-in and oxidation on device timing. At 40 operational sequences and then again at 80, the test was stopped and the samples oxidized.

Ceramic Electrical Feedthroughs

Ceramic of 94% alumina is used to make hermetic electrical feedthroughs in MC2969 stronglinks. Failure of these hermetic seals allows ambient atmosphere to react with the solid lubricants and electrical contacts. The time-dependent aging mechanism that degrades the ceramic is subcritical crack growth (SCG). Our experiments quantify the SCG susceptibility of alumina. Examination of returned hardware is used to validate the materials aging model. This project is also developing the methodology for predicting lifetimes of other components containing ceramic or glass.


Crack growth has been observed in ceramics used in the MC2969 electrical feedthroughs.
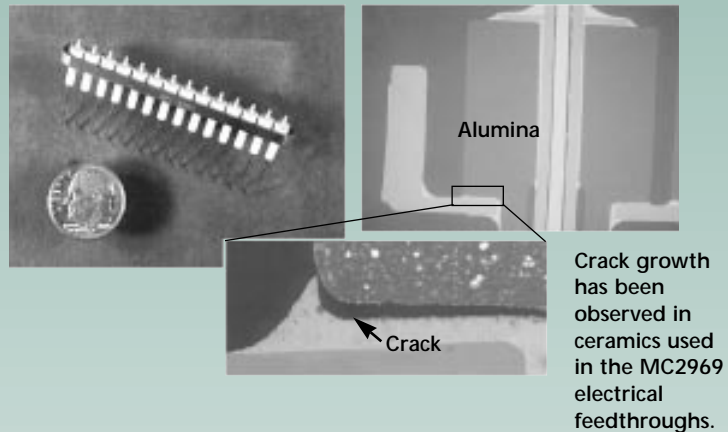
Electrical Contact Resistance

Alloy aging processes, surface reactions, and contaminant adsorption can all increase contact resistance, preventing circuit completion. Using field-returned hardware, we are measuring and correlating local contact resistance with surface chemical composition, component-level contact loop resistance, and ambient gas composition. Local contact resistance has been shown to be a function of surface chemical composition, applied contact force, and resistance probe voltage level. Measurements on the aged contact surfaces with and without cleaning by dynamic wiping will help establish higher confidence lifetime assessments.
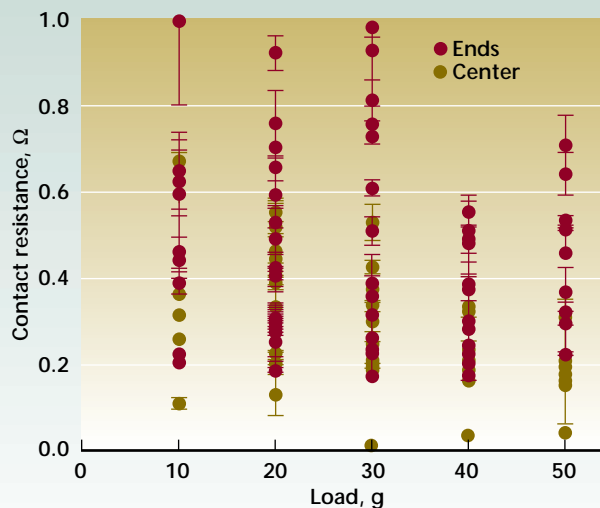
Electrical contact resistance in MC2969 switches was measured as a function of contact force and shows a large variability, which must be explained by component performance modeling.
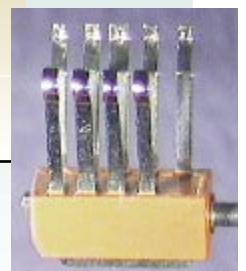
Electronic Components and Subsystems—Capacitive Discharge Unit Firing Set

We are developing a new set of analytical and evaluation tools for making informed decisions about whether to replace, rebuild, or reaccept weapon electronic subsystems. These tools will be used for early identification of performance trends and potential concerns with specific devices and materials; they include advanced circuit simulation, improved physics-based device models, statistically derived sensitivity analysis, accelerated aging tests of electronic devices, and improved surveillance data acquisition and trend analysis.

The MC3276, a capacitive discharge unit (CDU) firing set, is representative of several CDU firing sets in the enduring stockpile. This project will evaluate stockpile-aged materials and components to identify potential material, mechanical, and electronic device degradation. The project will also develop (1) advanced circuit simulation, device models, and analytical tools; (2) accelerated aging tests to apply controlled aging stress to electronic devices; and (3) improved surveillance data acquisition and trend analysis. In collaboration with Pantex and AlliedSignal/Federal Manufacturing & Technologies, we have developed benign processes for recovering stockpile-aged firing-set materials and components from dismantled stockpile weapons. These components are used for materials investigations that include the soldered connections on one of the oldest flat-pack integrated circuits in the stockpile (see box). By applying advanced circuit simulation techniques, we identified the components that most significantly affect the performance of the MC3276 type of CDU firing set. This information can be applied to several firing sets currently in the stockpile, and the project can concentrate testing and analytical resources on the few most critical components and conduct meaningful accelerated-aging studies.
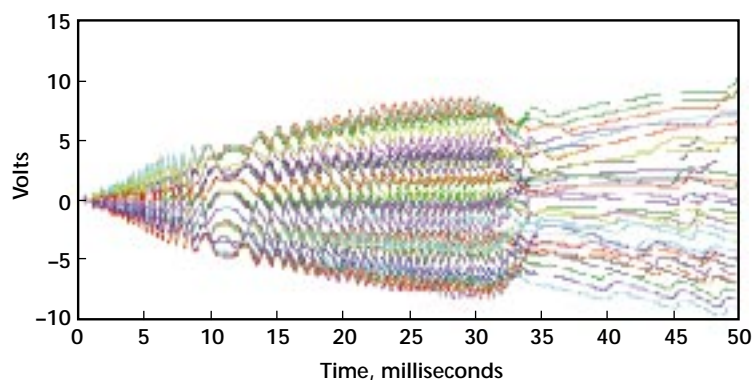
Our improved accelerated-aging test methodologies include a screening test to evaluate the susceptibility of electronic devices to low-dose-rate radiation degradation and a method for the automated acquisition of device parameters during test. Using these methodologies with the quick-look screen, we identified the semiconductor devices that are most likely to exhibit enhanced low dose-rate susceptibility. More than 200 B61 and W80 devices (10 part-types) were screened, and two of them demonstrated enhanced low-dose-rate susceptibility—the SA1889 NPN transistor and LM185 voltage reference. Second, the project identified, through circuit simulation, more than 300 W80 and B61 critical devices (three part-types) that are installed on circuit boards, characterized, and ready for the long-term study. Third, we developed a generic age-aware model for a ceramic capacitor that uses Z5U dielectric. Fourth, we characterized potential age-related degradation of four semiconductor device types currently undergoing a thermal aging study. Accelerated aging tests will extend the aging process of electronic devices beyond currently available hardware, identify life expectancy, and provide the data needed to develop accurate device models for physics-based circuit simulation.

The project is developing an advanced diagnostic test for use in surveillance. Typically, there is only one internal test point on war reserve firing set circuits that measures the charge on the main CDU capacitor. However, a significant amount of relevant circuit data are contained within the basic waveform. The objective is to determine if the performance characteristics of internal and physically inaccessible devices (e.g., transistors and operational amplifiers) can be derived solely from the circuit output waveform. Circuit analysis of this complexity has never been performed before and requires the use of a new 64-processor computer at Sandia National Laboratories. The results of a proof-of-principle calculation show that the values of an internal resistor and capacitor can be predicted based solely on the output waveform of the circuit.

Significant changes in the CDU charging waveform result from small changes in values of a selected resistor and capacitor.

Aging Evaluation of Flat-Pack Solder Joints

The SA2371 integrated circuit (IC) represents one of the oldest flat-pack electrical components in the stockpile. As a surface mount package, the tin–lead (Sn-Pb) solder joints are particularly sensitive to fatigue due to fluctuations in the temperature. Those solder joints are also subjected to additional stresses caused by dissimilar elastic properties and thermal expansion of the foam used to encapsulate the printed circuit board. An extensive investigation is underway to assess the aging characteristics of the SA2371 solder joints. Measurement of the thickness of the solder/copper intermetallic compound layer thickness, together with the kinetics model of layer growth rate, provides a measure of the effective aging temperature (35–40°C). A second series of measurements evaluates the Pb-rich phase size distribution in the solder microstructure. These measurements are affected by two aging factors: (1) the temperature and (2) residual stresses imposed on the solder joints. These are coupled into a constitutive model that computes thermal mechanical fatigue damage to the solder.

Both the intermetallic layer thickness and Pb-rich phase size are being used, not only to compute the degree of aging by the stockpile environments, but also to predict future reliability under extended lifetime conditions. Concurrently, we are documenting the conditions of solder joints in returned field units and then subjecting the joints to accelerated thermal aging. These results will be used to validate the computational predictions and benchmark the performance of the SA2371.
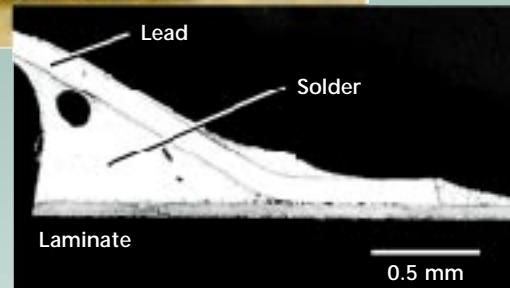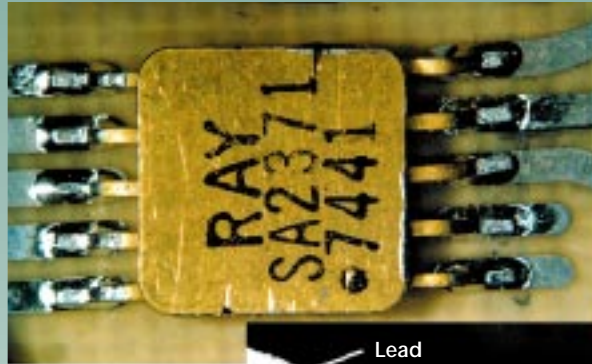
Gull wing solder joint on the SA2371 flat-pack operational amplifier.

Energetic Components and Subsystems—
Slim-Loop Ferroelectric Firing Set

The MC3028 slim-loop ferroelectric (SFE) firing set fires the main weapon detonators and the neutron generator on the W76 and W78 weapons. Large quantities of a similar firing set, the W68 MC2370, have been made available as the result of the W68 dismantlement activities at the Pantex and Y-12 plants. Using this hardware, we created a database of firing set operational characteristics. Our goal is to (1) model and replicate the electrical output of the MC3028 as a function of multiple input parameters, (2) reflect the effects of aging of internal firing set subcomponents, and (3) validate these effects with hardware characterization and analyses.

An apparent problem was discovered early in the investigation while evaluating dismantlement (MC2370) and shelf hardware (MC3028). Approximately 90% of measured capacitance (Cap) and dissipation factor (DF) values were out of range. This was construed to indicate degradation within the ceramic-ferroelectric-conductive layer stack, and low electrical output was thus expected. However, when MC3028 and MC2370 units were functionally tested, all MC3028 hardware (which had not been in the field) performed properly and only 4 of 24 MC2370 units had low electrical functional output. The failed MC2370 units were from dismantled weapons and consequently had extremely short electrical leads, which may have been responsible for the failures. Concern with apparent interface degradation (low Cap and DF) led to a related materials investigation to determine the nature of aging within the stack interfaces (see box).

Pentaerythritol tetranitrate (PETN) in the XTX explosive in the lens has been shown to be chemically stable within the weapon environment (see SN04, Energetic Materials Predictive Capability). However, the nonequilibrium PETN used in the XTX explosive has shown potential for significant changes in crystal size distribution. Despite the potential for morphological change within stockpile-to-target sequence conditions, thermally aged units have performed within specifications even after the severe aging of 1 to 1.5 years at 60 and 80°C. These units were already 25 years old at the beginning of the high-temperature aging. This performance within specifications demonstrates a considerable insensitivity of the firing set to thermally activated aging mechanisms that may be occurring in the explosive.

Our progress in the modeling area includes significantly increasing the realism of the underlying physics-based model, incorporating additional critical subcomponent parts into the model, and using a larger number of smaller-sized cells to describe the component. The time over which the transient behavior of the functioning firing set is modeled has also been increased. Highlights are: (1) nearly full-device simulation using 7 million cells at 200-μm resolution incorporates all subcomponent features; (2) physical model of only one-quarter of the stack (device is nearly symmetrical) generates current output that represents the function of the firing set; (3) 45-million-cell computer simulation of the full stack of ferroelectric, ceramic, and conductive layers shows XTX explosive pre-ignition in an unexpected area; and (4) explosive timing validation experiments have shown that the EMMA (electromagnetic model)/HVRB (explosive burn model)/XTX (explosive) model burns 50% slower than experiment. This indicates the need to refine the HVRB model.

To date, no significant functional degradation has been observed in the SFE firing set; however, a validated SFE computational model will accelerate hypothesis testing in assessing the consequences of material changes. Finally, the SFE firing set modeling—characterized by an extremely large cell count, multiple physical processes, complex visualizations, and real opportunities for experimental validation—has resulted in significant computational advances likely to be of benefit to a wide range of future components and systems.
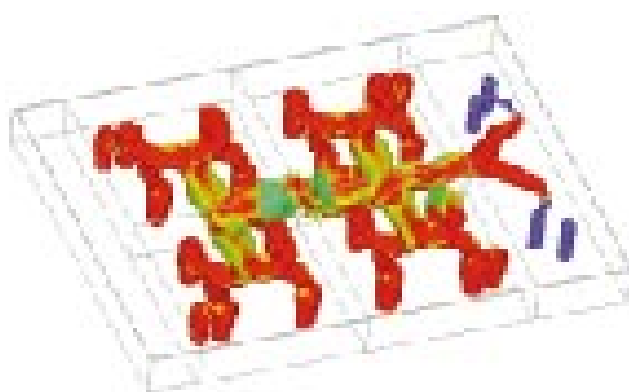

A visualization of the output from the computer simulation of the explosive burning in a quarter-cell representation of the track plate of the MC3028 SFE firing set. This calculation uses 5 million cells at 200-μm resolution.

Degradation of Slim-Loop Ferroelectric Interfaces

The electrode interfaces in the firing set are laminate structures with an adhesive layer sandwiched between copper and gold electrodes. These interfaces are extracted from the transducer using cryogenic fracture techniques. Electrical testing and acoustic imaging allow a specific interface to be targeted. The exposed electrode is then subjected to composition, structure, and morphological characterization. The interfaces age as (1) copper is distributed throughout the adhesive, explaining observed electrical conductivity; (2) the electrode primer diffuses into the adhesive with time, resulting in a structurally altered interface; (3) accelerated aged units (100°C) show severe electrode oxidation, with cryogenic fracture producing adhesive delamination; and (4) the time-dependent nature of the interface most likely explains variable electrical properties between units.

We are trying to correlate the void density and structure with aging in an effort to understand how materials aging might impact firing set performance.
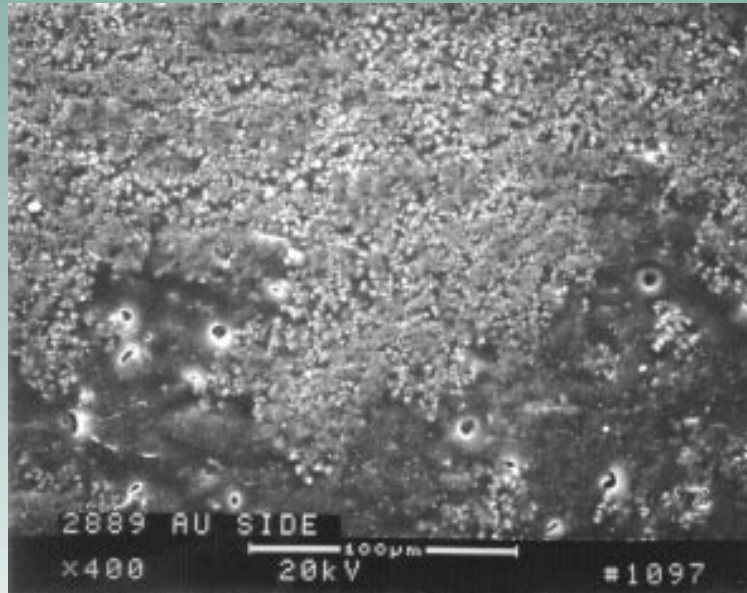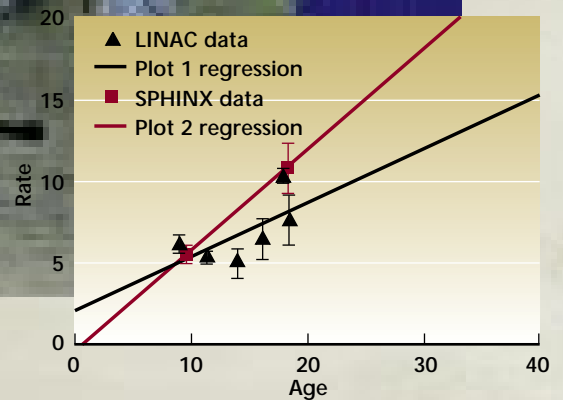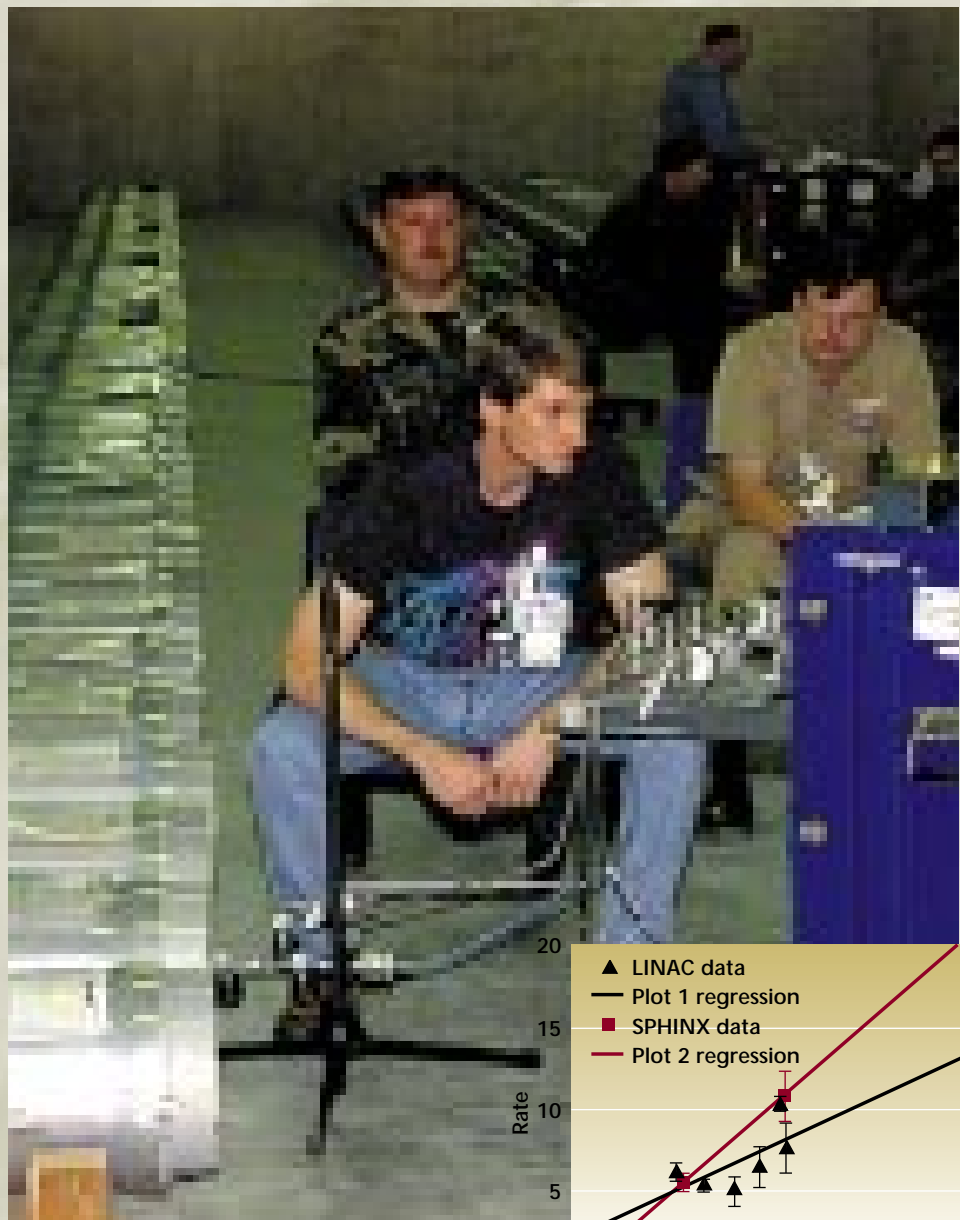

Scanning electron microscopy of the adhesive at an aged interface shows a range of microstructures, including voids and adhesive filler agglomeration.

Routine Surveillance

Routine Surveillance

Focus Area

The nuclear weapons complex (NWC) laboratories and production agencies support their stockpile stewardship through the integration of enhanced techniques into surveillance testing. New techniques and technologies will result in the NWC's ability to identify failure mechanisms that are of interest in an ever-aging stockpile. As such, tasks related to this activity are specific to affected areas and provide coherence only through their augmentation of the routine surveillance program.

The purpose of the tasks in this focus area is to meet the needs of the individual agencies while developing ongoing capabilities and resources within the NWC. Affected surveillance information and systems developed in this effort provide enhanced understanding of the nuclear weapon stockpile.

Deliverables

1. Integrate new testing methodologies that significantly enhance the capability for early detection of aging degradation into the routine surveillance program.

2. Implement reliable measurements of dew point and multi-gas analysis to evaluate the gas-phase signatures of weapon aging.

Pertinent Tasks

PX07   Air-Bearing Technology Transfer to Plants
SN16   Enhanced Test Methodologies
SN17   Enhanced Gas Analysis for Diagnostics and Surveillance

Enhanced Gas Analysis for Diagnostics and Surveillance

The end-of-life for the desiccant in the W80 was of particular concern because it was thought to drive the Stockpile Life Extension Program (SLEP) schedule, including production and/or delivery of several components (neutron generator, type 1K valve, interconnecting control box) planned for replacement at the same time as the desiccant. An analysis of desiccant weight gains obtained during surveillance activities at Pantex Plant had suggested that the desiccant could reach its end-of-life within the next 5–10 years. The surveillance data were inadequate, however, to yield predictions with enough statistical precision to unambiguously establish the end-of-life. Subsequent field analyses of W80 weapon atmospheres, described here, have uncovered significant new desiccant properties that apply not only to the W80 but to most weapon systems.

To develop the data, we set out in FY1997 and FY1998 to more accurately and precisely determine the projected end-of-life of the W80 desiccant. We designed, developed, fabricated, tested, qualified, and fielded two war-reserve-certified field portable gas analyzers and used them to obtain dew point measurements on 94 W80 warheads at two service locations. More than 50 people from the Sandia National Laboratories (SNL), Los Alamos National Laboratory, Pantex Plant, DOE Albuquerque (DOE/AL), and AlliedSignal/Federal Manufacturing & Technologies contributed to this large project. The diverse set of customers includes DOE/AL/WQD, DOE/AL/WPD, SNL W80 Program, SNL Military Liaison Department, SNL Mechanical Measurements Team, U.S. Navy, and U.S. Air Force. The project was performed to DOE QC-1 requirements and fully documented through the SNL engineering drawing system, where full details on the design requirements, product specifications, operating procedures, safety analyses, and equipment qualification can be located. Two DOE-approved ("diamond-stamped") analyzers were delivered on December 15, 1997, and our field activities were successfully carried out between December 1997 and February 1998.

Results of field measurements (see figure) exposed a large discrepancy between the internal dew points of the W80 and those expected on the basis of the desiccant weight gain measurements. Specifically, the internal atmospheres of the warheads were much drier than expected. More than half of the warheads sampled had dew points below –60°C, whereas the prediction based on surveillance results was for a dew point of approximately –45°C. Further laboratory studies uncovered some important desiccant properties that quantitatively accounted for this discrepancy. The lab results demonstrated conclusively that the desiccant used in the W80 (and most other weapon systems) can adsorb substantial quantities of carbon dioxide, a possibility previously unrecognized in the weapons community. In fact, we currently estimate that >50% of the desiccant weight gain observed in the W80 can be attributed to CO_2 adsorption. Additional experiments indicated that CO_2 is displaced by water as water becomes available, so the desiccant should perform as intended. Our new understanding of competitive adsorption enabled us to significantly extend the W80 desiccant end-of-life estimates, and desiccant replacement no longer drives the SLEP schedule.

This revolution in our understanding of desiccant performance impacts all desiccated weapon systems in the enduring stockpile (B61, W62, W76 AF&F [arming, fuzing, and firing], W78, W80, B83 trajectory sensing signal generator and radar, W84, W88 case, and AF&F) as well as desiccated shipping/storage containers (AL2100). The budgetary impact is estimated to be in the tens of millions of dollars, primarily through relaxation of schedule and budget pressures on the W80 SLEP and on neutron generator development and production. Further, the capacities of the desiccants combined with the measured rate at which they are adsorbing water in the stockpile has raised the possibility of performing Alt 346 (W80 refurbishment) in the field. This would provide tremendous additional savings as well as contributing to work load leveling at Pantex.

A W80 engineer measures the dew point of a warhead using Sandia's W80 field portable gas analyzer while U.S. Air Force and U.S. Navy personnel monitor the activity. A second analyzer (background) is also in use.

Enhanced Test Methodologies

Two important contributions to the Stockpile Surveillance Program were made possible by this task: (1) significant improvement in measuring the compression set in W76 environmental O-ring seals and (2) increased understanding of the aging behavior of W76 radars.

Compression set in O-ring seals

Environmental O-ring seals are an important component used on all weapon systems to protect the weapon interior from oxygen and water vapor intake. The two most common measurements to monitor the degradation of seal materials are compression stress relaxation and compression set. Compression stress relaxation is the ideal method to use for laboratory simulations and modeling. But because compression stress relaxation cannot be easily applied to real weapons, surveillance activities have used compression set as the method to monitor the condition of field-aged O-rings.

In the past, the validity of the surveillance compression set measurements for the W76 has been questioned because of method inconsistency. The past method employed hand-held calipers. This was highly operator dependent and lacked a standard technique, and thus the results could not be standardized. This precluded statistical analyses of the results and the development of inferences regarding aging degradation.

We introduced the use of a laser micrometer into the routine measurements as part of the data collection for the routine surveillance program. The Sandia systems evaluation engineer and the Pantex program engineer for the W76 modified the disassembly procedures to incorporate the use of the laser micrometer to measure

O-ring compression set during weapon disassembly and inspection. The laser micrometer method is operator-independent because standardized fixtures are used and no human handling is involved during the measurement process. This enhancement provides reliable measurements that are systematic and consistent. As a result, the data collected now can be used to develop a better understanding of the viability of the environmental seals used on the W76.

Aging behavior of radars

In December 1997, tests were conducted on two W76 radars using the Sphinx flash x-ray machine at the Sandia National Laboratories. The Sphinx results shown in the figure indicate a possible aging effect in the protection circuitry, i.e., the increase in the y-axis parameter (Rate) is undesirable. The components organization that conducted the test presented the results to a W76 working group that had been formed to identify near-term enhancements to surveillance testing. The working group agreed that insights could be gained regarding whether or not an aging effect is occurring by conducting further tests; results from two radars were deemed insufficient to make any inferences.

Funds were provided, and another series of tests were conducted to further investigate the possibility of aging effects. Six W76 radars of different ages were tested at a linear accelerator (LINAC) machine operated by the Boeing Company. The results of that test series are also shown in the figure. Although the best fit linear regression line for the LINAC data does not have as steep a slope as does the regression line for Sphinx data, the LINAC data do show a definite trend in increase with age.

These results warrant further investigation. Current plans are to disassemble the radars and extract the circuits and devices of interest. We will look for possible effects of aging and also examine non-aging effects, such as differences in devices between early production units and those assembled later.

Test results for radiation effects on field-aged W76 radars: Sphinx (red) and LINAC (black).