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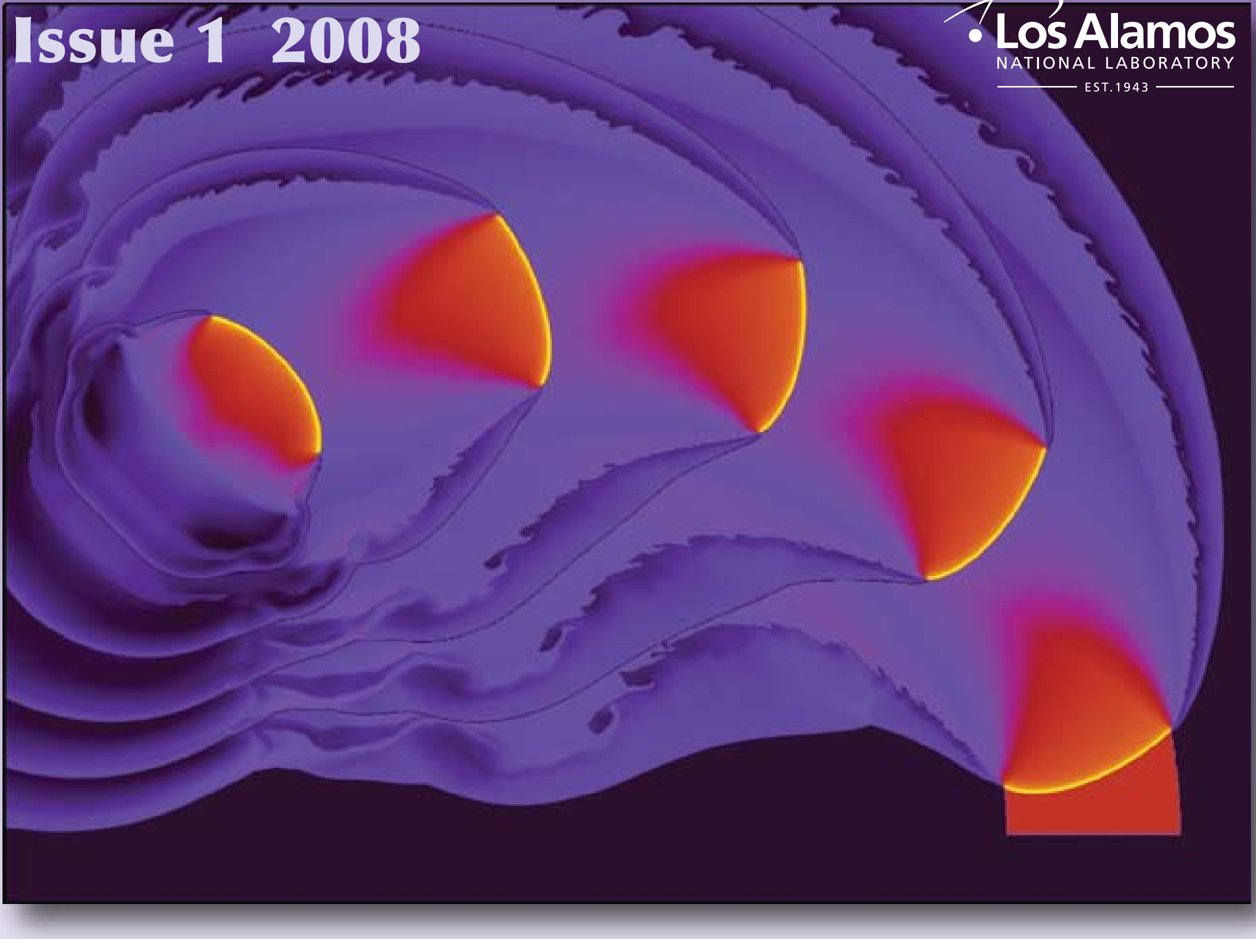

Surveillance Requirements for Nuclear Explosives Packages

Computing Detonation Waves in High Explosives with Material Variability

Enhanced Surveillance of Gas Transfer Valves for Stockpile Stewardship

Improving Security Awareness

Nuclear Science Research Contributes to Predicting and Certifying the Stockpile

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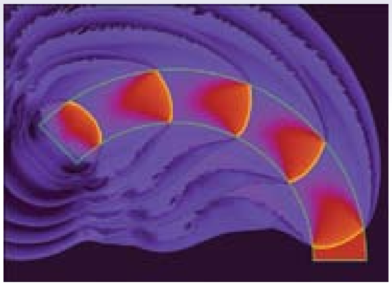

About the cover: A sequence of five overlaid snapshots shows the arc of a detonating high explosive. The green outline of the initial arc location appears in the photo to the left. Detonation is initiated at the left portion of the arc and propagates around the arc to the right and then down. A color contour plot represents the density field. Lower densities are black and purple. Higher densities are red and yellow. Bright yellow depicts the location of the detonation wave.

Point of View

Air Force Fellows Program

Sherry Stearns-Boles
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The Air Force Fellows Program began in 1958 with the assignment of a small number of experienced officers to 1-year tours of duty at distinguished government institutions that studied national security policies and strategies. The purpose of the program was to promote greater understanding of national security policies among senior US Air Force (USAF) leadership. Eventually, the program expanded to include civilian fellows and nongovernmental institutions.

Over time, the program incorporated DOE facilities at Los Alamos, Lawrence Livermore, Sandia, Oak Ridge, and Argonne National Laboratories as well as academic centers of excellence such as Harvard and the Massachusetts Institute of Technology. Fellows are also assigned to federally funded centers that conduct research for the US government such as the RAND Corporation and the Institute for Defense Analyses, think tanks such as The Brookings Institution and the Council on Foreign Relations, government agencies such as the Defense Advanced Research Projects Agency, elected officials, and private industry. Each institution supports a specific fellowship program based on that institution's mission.

> **LANL offers fellows numerous opportunities for in-depth research in chemical, biological, and radiological defense and nuclear nonproliferation.**

The USAF selects participating institutions based on their prominence in national security affairs and their ability to provide fellows a range of relevant experiences and activities.

Fellows, whether civilian or military, are selected based on performance record, academic credentials, and potential for senior staff/command duty. During their year-long study, fellows are required to analyze current scholarly perspectives on defense policy and strategy issues; participate in national security discussions and exercises; research timely, relevant, forward-thinking strategic-level air- and space-power and national security topics; and prepare a research paper.

All fellows are awarded senior or intermediate developmental education credit that is equivalent to military war college or command and staff college credit upon completion of their fellowships. When their fellowships are completed, most fellows are assigned to government positions, political/military affairs staff duty, or command positions.

AF-NLTF Program

Los Alamos received its first fellow in 2004 through the Air Force National Laboratories Technical Fellows (AF-NLTF) Program, which operates under the auspices of the Air Force Fellows Program. The AF-NLTF Program was established to strengthen the chemical, biological, radiological, nuclear, and explosives technical expertise of the USAF's military and civilian personnel. The program focuses on developing a cadre of senior officers and civilians who

- are informed about and experienced with nuclear weapons and nuclear technology programs,
- understand the historical development of nuclear weapons technologies, and
- will be involved in shaping and influencing a flexible and responsible nuclear deterrent.

LANL offers AF-NLTF participants an outstanding venue for conveying critical weapons principles from award-winning scientists to military personnel who have limited experience with nuclear weapons or who are familiar only with the operation, maintenance, or acquisition of nuclear weapons delivery systems.

LANL's nuclear infrastructure and weapons technology mentoring and training potential are exceptional because internal Laboratory resources cover all aspects of active and retired weapons in the stockpile, including testing, stockpile certification, component manufacturing, and sustainability. LANL offers fellows numerous opportunities for in-depth research in chemical, biological, and radiological defense and nuclear nonproliferation. In addition, much of the Laboratory's ongoing technological and engineering research may have potential USAF applications.

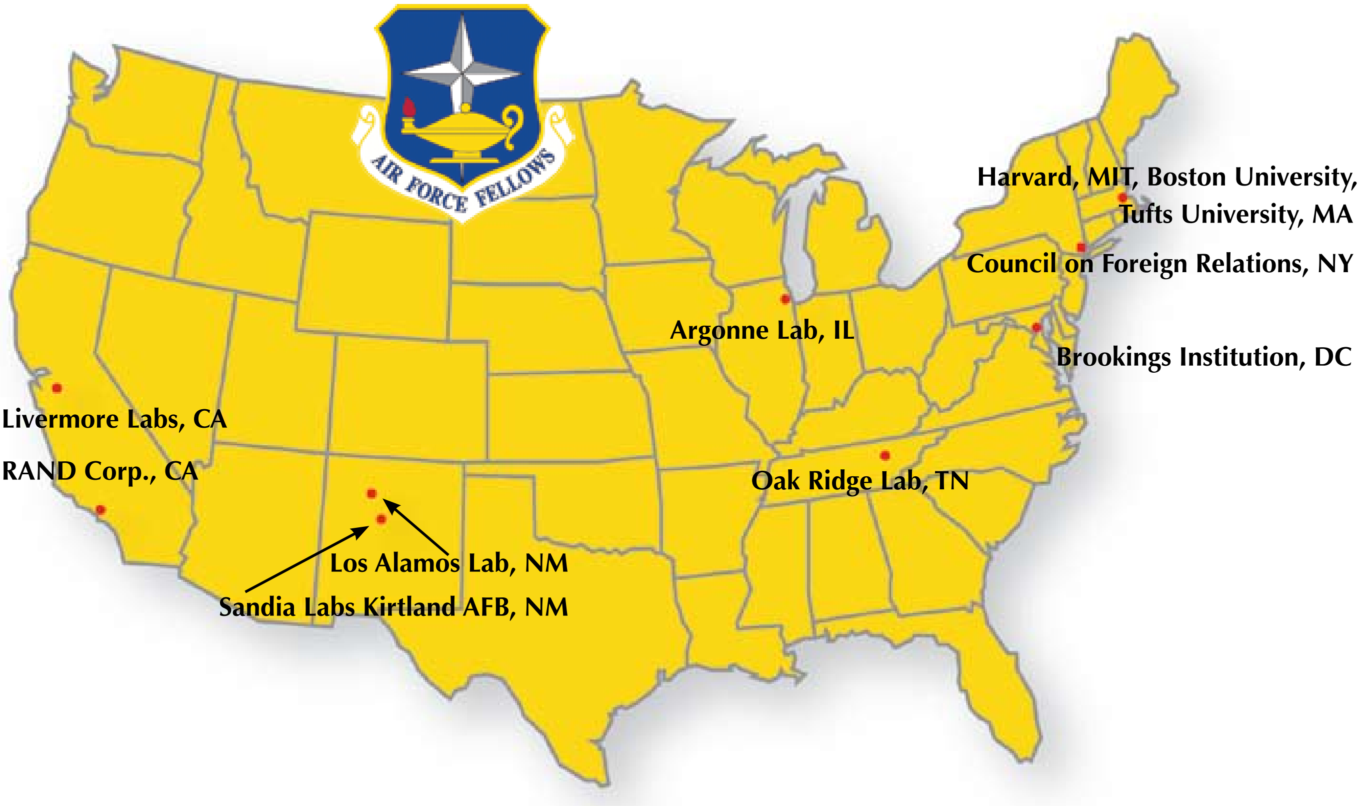
Program Benefits

Ultimately, the AF-NLTF Program benefits both LANL and the USAF.

By mentoring officers about the complexities of LANL defense, research and development, and stockpile stewardship issues, the Laboratory helps develop a group of senior officers equipped to understand the Laboratory's approach to its national security commitments.

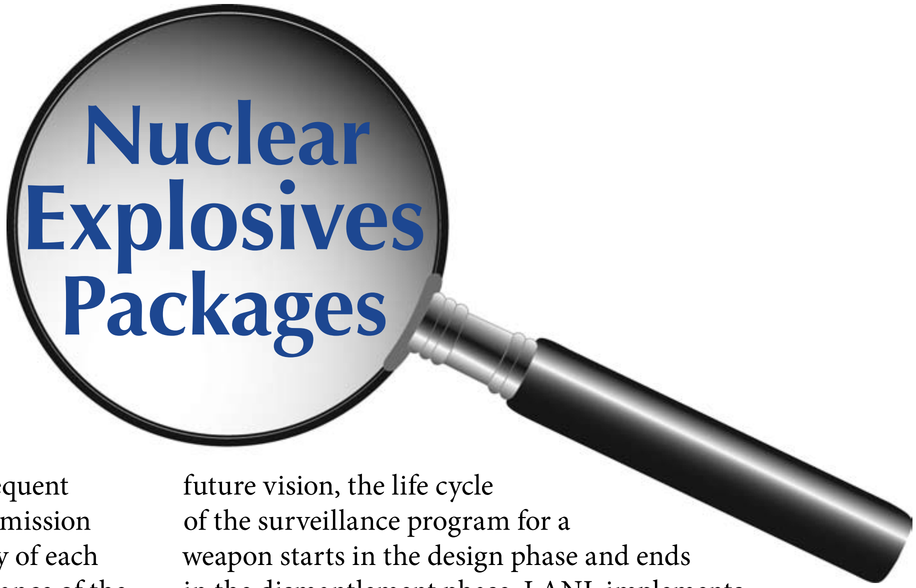
Also, the fellows' extensive daily interaction with civilian scientists and engineers could lead to future DOE/DoD cooperative efforts as fellows acquire first-hand knowledge of strategic issues and challenges faced by LANL and the Nuclear Weapons Complex in safeguarding the nuclear weapons stockpile.

At the same time, the USAF acquires a growing cadre of well-informed senior officers and civilians who, as a result of their in-depth comprehension of the nuclear weapons community, are better prepared to participate in resolving future USAF nuclear weapons-related issues.



Some of the institutions in the Air Force Fellows Program.

Surveillance Requirements for Nuclear Explosives Packages



The cornerstone of assessment and subsequent confidence in the continued reliability, mission performance capability, and inherent safety of each LANL-designed nuclear weapon is surveillance of the nuclear explosives package (NEP). The surveillance process includes disassembly, examination, testing, and inspection of NEPs randomly selected each year from the stockpile.

Surveillance provides information on the current state of the NEP to the Laboratory Director to aid him in the annual assessment of each weapon system. He then reports to the Secretary of Energy, Secretary of Defense, and the Chair of the Nuclear Weapons Council.

Requirements for Implementing LANL Surveillance

The requirements for conducting a surveillance program are stated in NNSA's Technical Business Practices for Stockpile Management, TBP 800. As the design agency, LANL is required to evaluate the NEP and the gas transfer system (GTS) to ensure that they meet the required military characteristics (MCs) in the applicable stockpile-to-target sequence (STS). In order to accomplish that task, LANL's Weapon System Surveillance Group developed an evaluation program that provides direct surveillance results for the current status of the NEP and the GTS in the nuclear weapons stockpile.

In January 2007, NNSA implemented the Surveillance Transformation Project (STP) to better understand the health of aging weapons and to increase confidence in stockpile assessments. As a part of the STP and NNSA's future vision, the life cycle of the surveillance program for a weapon starts in the design phase and ends in the dismantlement phase. LANL implements the STP through selection, disassembly, inspection, testing, and evaluation of the assembled NEP, each of its subsystems, and the materials in components of subsystems.

The surveillance process includes disassembly, examination, testing, and inspection of NEPs randomly selected each year from the stockpile.

Challenges for LANL Surveillance

NEP surveillance presents several challenges that result mainly from LANL's inability to perform and evaluate explosive tests of the complete NEP or its major subassemblies (the primary and secondary components) due to the moratorium on underground nuclear testing. Devising an indirect testing scheme to gain information about the NEP, while not actually testing a real NEP, is facilitated by

- a shelf-life program to monitor, evaluate, and artifically age components in order to predict the future condition of the stockpile,
- material compatibility stackups (material coupons placed in a container to age together and provide data on unanticipated material interactions) that are used to assess the effects of aging on combined materials used in production, and
- a subsystem test that represents stockpile production and aging.

Weapon designers set specifications for all aspects of a weapon's design and manufacture during traditional weapons development programs and system life-extension programs. These specifications are based on physics, engineering, and materials considerations; results and lessons learned from past underground tests; and new tests that are fired within current constraints.

The specifications represent what LANL determined to be a manufacturable design that will meet the required MCs during the STS. LANL's surveillance program assesses deviations from the original as-built product and works with weapon designers to determine any impacts to safety, performance, or reliability that are incurred because of deviations.

LANL scientists assess deviations from as-manufactured components and assemblies to the present time (aging) by establishing aging trendlines. The key to a robust surveillance program is establishing and analyzing trendlines because they are used to estimate the life of the component being trended. Credible trendlines require a thorough characterization of each critical material and component represented.

Surveillance Life Cycle

Surveillance focuses on evaluating the production process in the early years of a weapon's life cycle. It is highly likely that surveillance investigations will result in findings that are caused by production of the part or subsystem. As the production process matures, these findings are remedied and a system stockpile begins to take shape in which there are few, if any, concerns or defects. Concerns and defects uncovered in this first phase of the life cycle can be greatly reduced by implementing a well-defined, -documented, and -controlled production process.

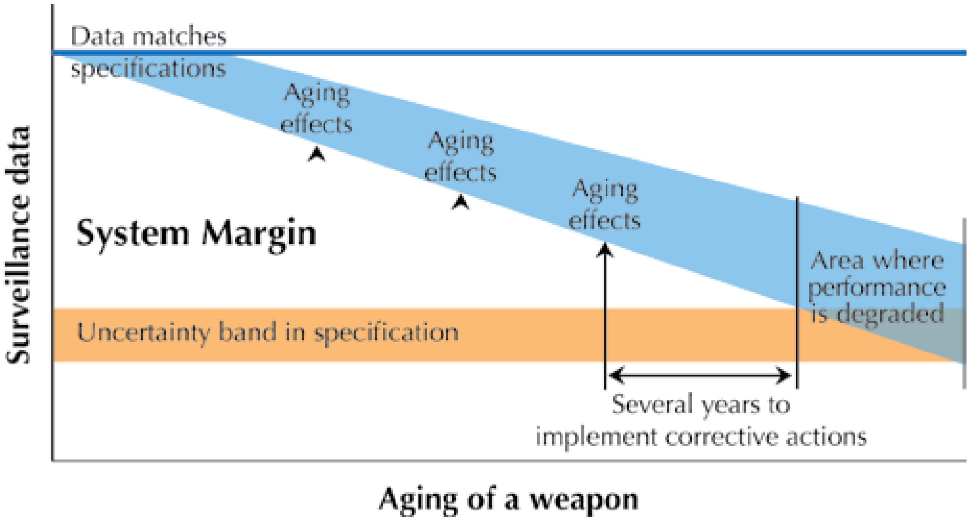
The second phase of the life cycle, the aging phase, is characterized by a lengthy period of time in which every material, component, and subsystem remains within specifications. Trendlines are established and monitored in this phase.

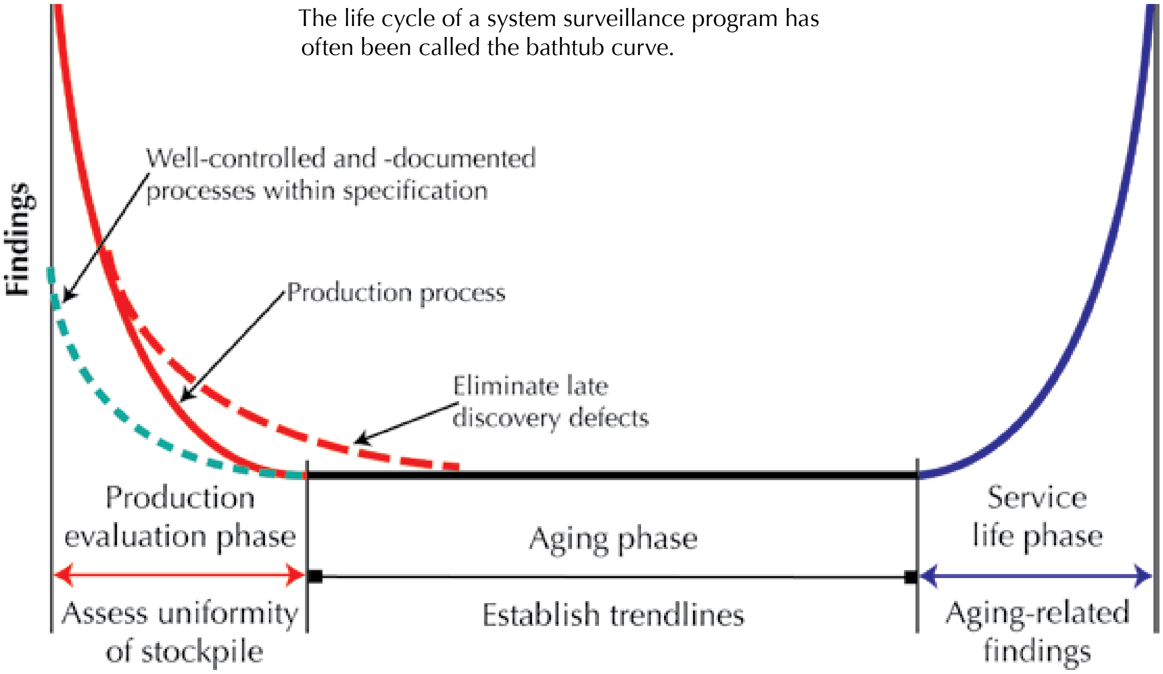
The service life phase, in which the weapon system reaches its intended service life, is the third phase of the life cycle. In this phase, aging of materials and components progresses to the point at which some action must be taken to maintain the safety, reliability, or performance of the weapon system.

Major findings discovered in any phase of the surveillance life cycle often result in the design agency opening a significant finding investigation (SFI). Frequently, research into the basic science and engineering must be conducted to obtain information on the importance of each deviation from production specifications. This research is part of the investigation closure plan that identifies required resources, priority, and funding. A hydrodynamic test is an example of research necessary to answer physics questions and problems related to an SFI.

In the past, production-related SFIs have been opened throughout the production and aging phases of a weapon's life cycle. The well-controlled and -documented processes, contained in the specifications to the production plants, greatly reduce (with a goal of eliminating) a production-type defect in the stockpile after the build of the weapon is complete. This leaves aging of the weapon system and its components as the focus of LANL's surveillance efforts. Historically, the first aging-related SFIs develop after many years of service life.

The trendline represents the as-built or baseline requirement, the performance requirement, and the threshold of failure. The orange band is the uncertainty that is present in knowing exactly when performance is degraded and the point at which the component, material, or subsystem will no longer function as advertised.





Evaluate Production Concerns

Uniformity of the stockpile is the foundation of an efficient, manageable surveillance program. A uniform stockpile means that all components, subassemblies, and the assembled NEP have been manufactured within all specifications issued to the production plants during the development engineering and production engineering phases.

Production uniformity is verified through identification and inspection of retrofit evaluation system test/new materials laboratory test (REST/NMLT) units. Those units, designated from the production run, are selected at the Pantex Plant after the warhead is assembled and NNSA diamond stamps the warhead assembly. REST/NMLT units are randomly selected at a predetermined rate with earlier production months and years weighted more heavily than later years.

Assess Material and Subassembly Aging

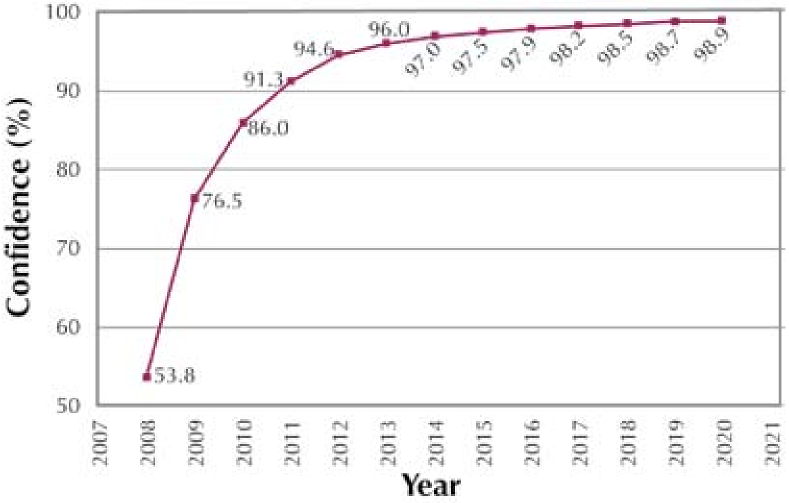
When a NEP is selected as a stockpile laboratory test (SLT) or stockpile flight test (SFT) unit, it undergoes a surveillance evaluation through disassembly and inspection (D&I). During the initial inspection of the NEP, radiographs are taken to assess the integrity of the GTS and high explosives and assess the re-entry body, vehicle, or case. Each component is subsequently examined at its production plant according to surveillance specifications issued to that plant.

With confidence in and credibility of a uniform stockpile established in REST/NMLT examinations, deviations from production specifications that may be found in these surveillance D&Is will most likely result from aging phenomena. A component-aging trendline can be established with initial production data and life cycle surveillance results. Aging effects trendlines provide lead-time to develop and implement corrective actions that may be required to mitigate adverse effects of component aging. Results trendlines may also target sample selections to fill in missing data points and to better understand the collected data.

Information Management in Surveillance

Information management is key to a successful surveillance program. Surveillance is integrally tied to production records, past experience, part specifications, and system requirements, which must be documented and readily accessible to the surveillance engineer.

Accurate electronic production records are required to establish baselines from which the surveillance engineer can construct trendlines as new data are received. Past SFIs and their resolutions provide



This representative confidence curve shows the probability of finding a problem (a deviation from the established production specifications) in 5% or greater of the entire build of a weapon. As the number of REST/NMLT units selected and examined increases each year, confidence in detecting a problem, if a problem exists, increases to the percentage indicated.

information on what was previously studied, what progress was made on a particular component, and how their resolutions could be applied to a current problem. Part specifications and system requirements are the reference points for new surveillance data.

Current Surveillance Process

Because a rigorous data collection and archival program was not in place for any of the current weapon systems, a solid baseline of critical surveillance parameters (CSPs) does not exist. CSPs are data points and pieces of information that are critical to assess a material, component, or subsystem.

LANL's surveillance approach compares yearly surveillance data with the weapon's product specifications. Those specifications were arrived at and validated by means (underground nuclear testing) that cannot be reproduced in today's engineering environment. As long as new surveillance data compare favorably with product specifications, the weapon system's NEP is considered to be safe, reliable, and functional.

The current surveillance process has several limitations. The most severe limitation is the inability to conduct system and subsystem performance tests using actual war-reserve hardware from the stockpile. Function testing the GTS is one exception. Other limitations include flight tests, which currently have no impact on NEP surveillance assessments because the high-fidelity joint test assemblies (JTAs) are built shortly before the flight test from off-the-shelf or new components; thus, the materials and subsystems are not aged and do not represent production. Also, substitute materials are used for some key components. The JTA for re-entry vehicles is strictly an engineering test. The high-fidelity JTA for bombs yields some pertinent surveillance due to the nature and profiles of the tests. The remaining limitation is that in most circumstances, the surveillance component is not conditioned (thermally, mechanically, or radiologically) before its D&I.

Desirable Additions to the Surveillance Program

Three things would increase the value of the surveillance program in assessing each weapon system.

First, initiate a testing program that indicates the state of the NEP in its stockpile-assembled condition. Currently, the NEP is disassembled into its component parts with each part sent to a production plant for D&I. The tolerances and piece-part results are matched with the data to try to gain some understanding of the weapon's condition when it was in the stockpile. A series of tests and more rigorous nondestructive examination (NDE) of the NEP before its disassembly would take much conjecture out of the surveillance assessment. Two examples of NDE are a computerized axial tomography scan of the NEP and a surveillance hydrotest. A surveillance hydrotest uses parts manufactured at the time of production and allowed to age in a way that is representative of the stockpile.

The second recommended addition to the surveillance program is a flight test program that adds value to the surveillance assessment of a weapon system. This flight test JTA would use production-build and -assembled components that age together and so better represent the stockpile. Additionally, a redesigned diagnostics package is necessary to provide feedback and diagnostics relevant to the condition of the NEP and provide data pertinent to its functioning.

The third recommended addition is to precondition subsystems before D&I. Preconditioning subsystems exposes them to some portion of the STS, thereby simulating any adverse effects that transportation, storage, or launch conditions would do to the subsystem. Thus, the subsystem undergoing D&I better represents the final delivered product.

Surveillance Strategy Summary

The surveillance strategy for a NEP is based on separating concern over production defects from concern for aging phenomena. The REST/NMLT testing program generates production quality data on the NEP. If all specifications and tolerances are met in production and verified in the REST/NMLT program, the NEP enters the stockpile without known defects. LANL relies on REST/NMLT units to build confidence in the uniformity and quality of the production process.

Information management is critical to the surveillance process. The production plants must electronically record pertinent build data defined by each product realization team (PRT). PRTs use their knowledge of the requirements, specifications, and critical performance parameters to set the electronic data-capture requirements for each component. For example, dimensions and tolerances should be recorded as measured and not simply recorded and signed off as having met the specification. Documentation, archival records, and use of production as-built data are key to trending components and to the entire surveillance program.

Data from D&I of selected SLT and SFT units should be used to trend aging of the NEP by comparing the as-built data for each assembly with the identical type of data collected at the time of surveillance disassembly. This approach permits developing a forecast that shows time frames in which component performance may be degraded and provides LANL time to develop action plans for mitigation.

A robust surveillance program requires that information be gathered through supplemental programs. These programs include

- shelf-life program for major subassemblies,
- surveillance hydrotests,
- material compatibility stackups,
- conditioning of subassemblies (thermal, mechanical, or radiological),
- gas sampling, and
- state-of-the-art nondestructive evaluations.

Applying the concepts outlined in this article would give an up-to-date assessment of the safety, reliability, and performance of a weapon system and meet the objectives of NNSA's STP to better understand the health of aging weapons and increase confidence in stockpile assessments.

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Computing Detonation Waves in High Explosives with Material Variability

A major responsibility of LANL's Dynamic and Energetic Materials Division is the study of detonating high explosives (HE). Detonation research is divided into four broad areas: detonation wave propagation, detonation initiation and failure, detonation product gas properties, and the interaction of those product gases with surrounding materials (explosive effects). These areas represent a substantial research effort at the Laboratory, and provide data for computer hydrocodes that compute the complex behavior of weapons systems. We present some recent advances in detonation wave propagation modeling developed by our group, Shock and Detonation Physics.

In the era of science-based stockpile stewardship, LANL is tasked with understanding and modeling HE behavior with greater detail and fidelity than had been done earlier. Historically, detonation models assumed that all explosive materials of a given nominal type and formulation (e.g., TNT or Comp B) have identical detonation properties. However, detonation propagation in condensed-phase explosives actually depends on composition, pressed density, microstructural characteristics, and temperature.

The manufacturing variables (composition, pressed density, and microstructural characteristics) can be controlled with effort and expense. Substantial measures are taken to maintain these factors within acceptable tolerances in HE designed for precision applications. Composition and density can be maintained within fractions of a percent. However, controlling—even characterizing—microstructure is more difficult. Particle size, morphology, and crystal flaws can vary considerably with the details of the manufacturing process in a way that is hard to quantify.

Although the three manufacturing variables can be controlled, the initial HE temperature can vary significantly (often uncontrollably) in the field. Therefore, it is particularly important to understand and characterize HE behavior with respect to the predetonation temperature.

The difficulty in quantifying material variations is that they usually occur in combination and their interacting effects are not easy to separate. However, we have recently developed a scheme for doing so, and have also acquired enough data to begin to quantify material variations for LANL's plastic-bonded explosive (PBX), PBX 9502. We now possess sufficiently advanced theoretical and computational technologies to effectively use this material-specific information in weapons engineering calculations. This new combination of capabilities will greatly advance modeling fidelity.

Acoustic, Shock, and Detonation Waves

The term acoustic wave is used to describe the weak limit of a pressure wave. The essential feature of an acoustic wave is that all 1-D waveforms maintain their shape as they travel. The term sound wave is usually used to describe an acoustic wave propagating in air. We can tell that sound waves propagate substantially undistorted (even when expanding into three dimensions) by the fact that a person's voice quality sounds much the same whether he is near or far away.

As a pressure wave becomes stronger, its shape distorts as it propagates. The distortion happens in a particular way: regions of rising pressure steepen and regions of falling pressure flatten. This happens because regions of higher pressure travel faster than regions of lower pressure. The end result of the steepening effect is a shock wave—a near instantaneous jump in pressure, temperature, and density.

If a shock wave in a combustible material is sufficiently strong, the temperature rise it causes can ignite the material. Under some circumstances, a shock wave and a burn wave can travel together in a cooperative union whereby the shock triggers reaction and reaction sustains the shock. This phenomenon is a detonation wave. Detonation initiation is the process by which the two waves merge to form this cooperative structure; detonation failure is the process by which they separate.

Not all violent reactions and explosions are detonations. The explosion caused by firing a gun is both violent and energetic, but it is not a detonation. In rare instances, the gun propellant detonates and destroys the barrel. The more extreme conditions produced by a detonation wave are not caused by an increase in the level of energy release, but rather by a dramatic increase in the rate of energy release. For example, the high-performance, solid explosive PBX 9501 detonates at ~8.8 km/s and generates ~350,000 atm of pressure in a narrow region. This stress level greatly exceeds the strength of any material.

Heterogeneous Explosives and the Effects of Microstructure

The structure of a detonation shock and its subsequent reaction zone tend to be complicated with respect to both chemistry and motion. Moreover, the exhibited behavior can vary considerably between gas, liquid, and solid explosives.

We have identified a single experimentally obtainable parameter to characterize how any PBX 9502 lot performs with respect to detonation shock propagation.

The most useful material distinction is whether an explosive is physically homogeneous or heterogeneous. Detonation in homogeneous materials (gases, pure liquids, and single-crystal solids) is quite sensitive to the initial temperature and is prone to inherent instabilities leading to complex, nonsteady motion. Liquid explosives are particularly dangerous because they are greatly sensitized by bubbles, which can arise through air entrainment or form spontaneously if the pressure is reduced. This is why nitroglycerin (NG) is highly dangerous as a liquid but is relatively safe in the form of dynamite or gun propellant to which various solid materials have been added to solidify it.

The same undesirable effect that sensitizes bubbly NG can be manipulated to our advantage. To do so, one starts with a very insensitive HE and sensitizes it to the desired extent by introducing a myriad of controlled, small-scale physical inhomogeneities. The most common way to sensitize HE is by compacting an HE powder into a heterogeneous bulk solid. A shock wave propagating in a heterogeneous material creates a nonuniform temperature field. Because the reactivity of HE molecules is extremely temperature sensitive, reaction begins in the hottest regions and spreads to the surrounding material. This hot spot mechanism can effectively initiate reaction even in situations in which the average temperature is too low to do so under homogeneous conditions. Sensitizing the HE in this manner results in an explosive that behaves much more consistently over a range of shock pressures and initial temperatures.

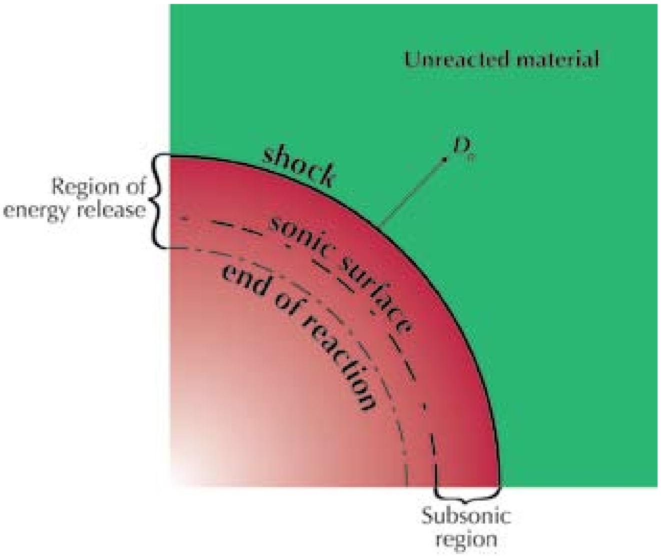
A consequence of tailoring reaction behavior by means of an explosive's microstructural properties is that one must control and reproduce those properties within a tolerance. The stringency of the tolerance depends on both the explosive and the charge size/shape. The degree to which detonation shock propagation conforms to an ideal standard is set by the characteristic charge size compared with the shock-triggered reaction length. For a fixed charge size, a thinner reaction zone causes more ideal wave propagation but also greater initiation sensitivity. This inherent tradeoff leads HE designers to sacrifice some wave propagation ideality for greater safety. However, the safer and less sensitive the explosive, the more it must rely on heterogeneity to initiate reaction. And the more reaction is tied to material heterogeneity, the tighter the microstructural tolerances must be to maintain consistent wave propagation behavior.

For example, detonation of LANL's conventional high explosive PBX 9501 (reaction zone = O[10–100] μm) is fairly ideal, and negligible variation is measured between lots. However, the detonation of LANL's insensitive high explosive PBX 9502 (reaction zone = O[100–1000] μm) is much less ideal and lot-to-lot variations in wave propagation are clearly measurable. Thus, in the case of PBX 9502 (but probably not PBX 9501), it is advantageous to tailor calculations to each lot. However, in both cases (and for all explosives), one should always tailor calculations to the actual density and initial temperature if possible.

Detonation Propagation Modeling and the DSD Approach

The ultimate challenge of detonation propagation modeling is to compute the reaction zone length from the material microstructure by first principles. Whether or not existing theoretical tools are adequate, the size of the numerical problem is daunting. Moreover, because our practical concern is only with macroscopic detonation propagation and the thermodynamic properties of the generated gas, we must ask if we really need to compute the problem to a far greater level of detail than the engineering problem requires.

Partly for this reason, current detonation models use a much simpler approach to direct numerical simulation (DNS), which most often represents the spatially averaged reaction rate by an equation. The reaction rate equation is empirically crafted and is calibrated (with varying degrees of success) to a variety of detonation experiments. Even this reduced problem is computationally challenging for supercomputers, the main difficulty being that detonation reaction zones are quite small (typically 10–1000 μm) compared with typical charge sizes of several centimeters. The problem of disparate length scales is partially solved by adaptive mesh refinement, which concentrates grid resolution where it is needed. Even so, a fully resolved DNS remains impractical for 3-D problems.



This diagram illustrates a diverging detonation wave. Energy released downstream of the sonic surface cannot influence the shock but does affect both the following flow and the surrounding environment. D_n is the local wave speed normal to the wave.

A team of LANL and university collaborators developed an alternative approach to DNS, detonation shock dynamics (DSD). DSD is a class of simplified detonation models that retain the most important flow effects while maintaining computational efficiency. DSD treats detonation propagation at the appropriate level of complexity for engineering calculations, while also fully reaping the associated computational efficiency.

Specifically, DSD makes physically based simplifications to the reactive Euler equations (the equations of compressible fluid motion that disregard transport processes like viscosity), exploiting the fact that the flow downstream of a detonation shock passes from subsonic to supersonic in the reference frame of the shock. This creates a condition in which the flow downstream of the sonic surface cannot influence the shock. As such, the sonic surface defines the effective reaction zone length even though the explosive may continue to burn downstream.

Furthermore, the isolation provided by the sonic surface makes a detonation shock a self-contained and self-propelled entity. The self-contained nature of a detonation wave provides the physical justification for a local detonation shock evolution law, called the DSD calibration function, which implicitly encodes information about how the reaction rate and thermodynamic properties of the fluid upstream of the sonic surface affect detonation shock propagation.

DSD is composed of a hierarchy of theories that are distinguished by the form and complexity of the calibration function. In the baseline or zero-order model, detonation waves propagate at a constant speed normal to their current direction—just like acoustic and light waves. Because it is a constant, that speed is equal to the speed of a steady plane detonation. This speed is called D_{cj}, after the scientists Chapman and Jouguet, who are both generally credited with developing the elementary steady plane theory. Constant velocity waves are propagated by Huygens' construction, which evolves a wavefront at a time t by drawing a sphere of radius $D_{cj}\,\mathrm{d}t$ on each point of the wavefront's surface. The wavefront at time $t + \mathrm{d}t$ is the envelope of those spheres in the forward direction. The traditional shock propagation prescription used in hydrocodes advances the wave by this method.

Unfortunately, Huygens' construction is only accurate in regions where the wave is sufficiently planar. Dimensional analysis theory tells us that size has no meaning in itself; rather, everything is big or small only in comparison with something else. In the detonation wave problem, wave planarity is quantified by the local radius of total curvature (the inverse of the total curvature κ), the size of which is judged relative to the local reaction zone length δ. DSD theory indicates that in the simplest nontrivial approximation, the ideality of wave propagation is characterized by the dimensionless product $\eta = \delta\, \kappa$. The smaller η, the more ideal the wave propagation, down to the Huygens limit, for which η to 0.

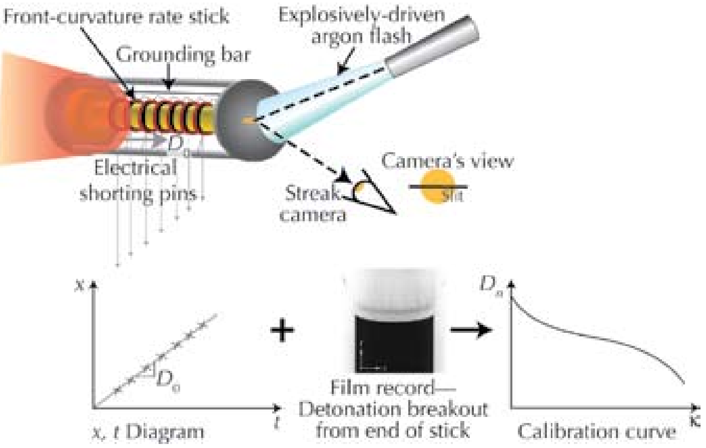
The way this effect arises in DSD theory is that D_n, the local wave speed normal to itself, is a function of the corresponding local value of η. For a given explosive, δ is usually lumped with other material parameters; hence, the first-order (or standard) DSD implementation uses a calibration function that specifies how D_n varies with κ. The second-order (or extended) DSD model can take a variety of forms and strategies, all of which involve more complex calibration functions. For example, one extension uses a 3-D surface of the form $f[D_n, \kappa, dD_n/dt] = 0$. Whatever their formulations, extended models always represent a tradeoff between greater accuracy and greater complexity. The efficacy of such tradeoffs is the subject of ongoing study.

DSD Calibration Experiments

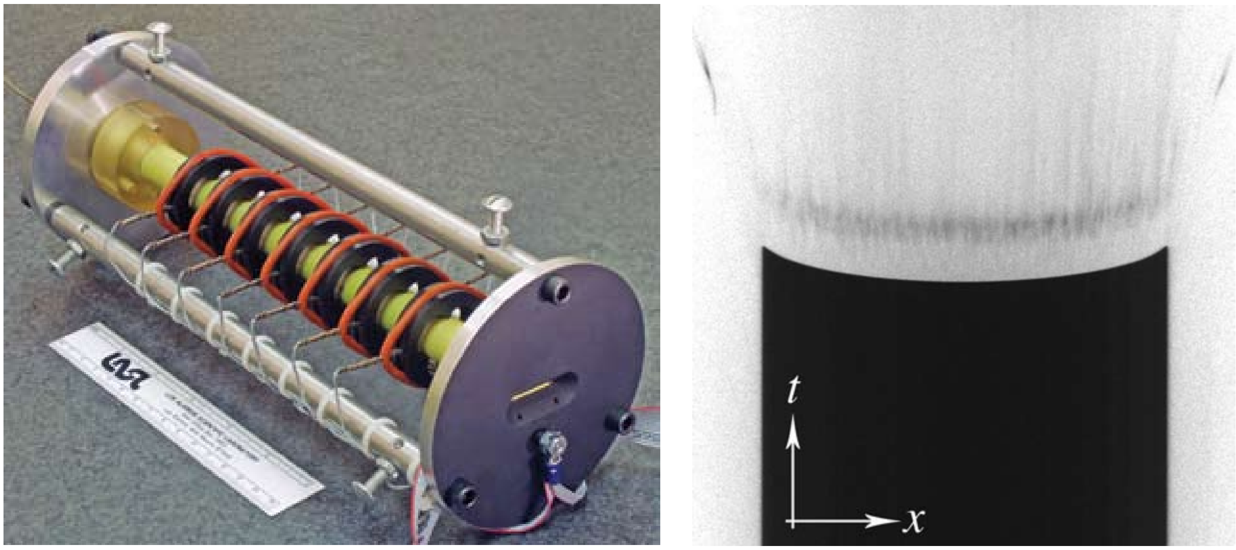
Any test that observes detonation shock propagation can give some information about DSD calibration; however, the most useful known test is the front-curvature rate stick illustrated in the figure at right. After traveling several diameters in a cylindrical charge, a detonation wave approaches a steady speed and a curved equilibrium shape. The detonation speed D_0 in a finite-diameter stick is less than D_{cj} but asymptotically approaches the steady plane value in the limit of large stick diameter. Electrical shorting pins placed at precise locations along the stick length provide an accurate measure of the detonation speed D_0.

The detonation shock shape is measured by a specialized photographic technique. When the detonation breaks through the mirrored charge end, the surface is promptly destroyed and the reflected light signature is attenuated. Because the wave is curved, breakout occurs first at the center and moves outward with time so that the obliterated region is an expanding dark circle. The streak camera records the light cutoff event along a representative diameter. This measurement yields the breakout time as a function of the charge radius, a function of the form $t = f[r]$. Because the wave shape is invariant, the relationship between the breakout time and axial distance is $z = D_0\, t$. Thus, the wave shape is $z = D_0\, f[r]$.

Front-curvature rate stick experiments are usually fired at a variety of stick diameters for each lot/density/temperature combination. Each test yields a detonation shock shape and a point on the diameter effect curve (a plot of the steady axial detonation speed D_0 versus the inverse charge radius). A DSD calibration data set includes the diameter effect curve constructed from all



In a front-curvature rate stick, the downstream charge end is mirrored (in the case of PBX 9502, by polishing the explosive) and is illuminated by a bright light source such as an explosively driven argon flash. A streak camera, the line or slit aperture of which is aligned across the charge diameter, observes the charge end. The flash and explosive are angled so that specularly reflected light points toward the camera. The line image is swept across the film to obtain an (x, t) graph of the breakout event. Data points on the x, t diagram are the wave position as a function of time. Velocity data coupled with breakout data allow us to infer the calibration curve.



This figure shows a photo of an actual experiment and the associated detonation shape record. The photo (*left*) shows an 18-mm-diameter front-curvature rate stick that is designed to accommodate a wide range of initial temperatures. The photo (*right*) shows the corresponding streak camera negative image. The mirror destruction technique gives a very crisp image, a necessity for effective DSD calibration.

tests taken together, plus the collection of wave shapes from the individual experiments. To explore variation with lot, density, and temperature, one must repeat this entire suite of tests for each starting condition—an expensive and time-consuming process.

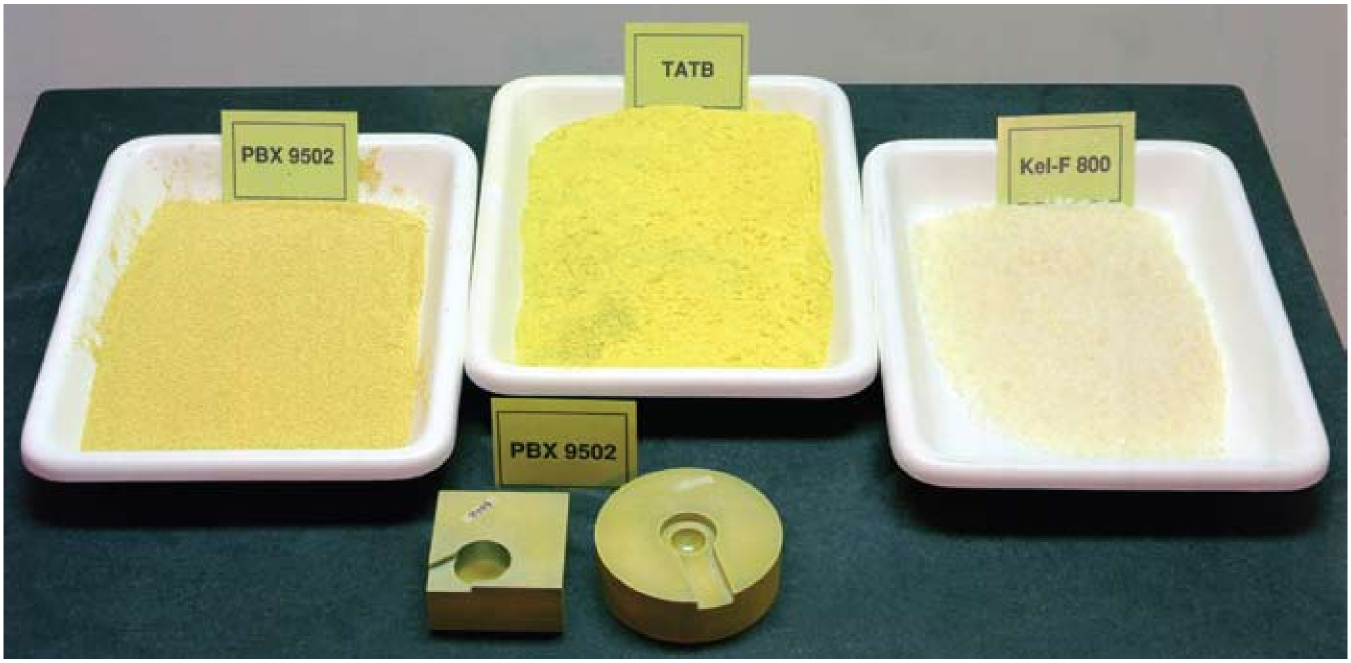
Variability in composition and density is small. If this is not so, then the material is not considered PBX 9502. Consequently, there is no need to explore the effect of composition and density over a wide range. However, the small, unintended density variation in pressed charges does have a measurable effect on detonation propagation, and we find it beneficial to consider density variation along with lot and temperature variations.

PBX 9502 Material Lots

Plastic-bonded explosives usually contain crystalline HE powder held together by 5%–10% of a plastic or rubbery binder. They are designed to create rigid, precise shapes. Most of our applications involve PBX. For easy handling and control of process, PBX and binder are formulated into molding powder, which is composed of nuggets of explosive and binder mixed together in the correct proportion. The molding

Summary of PBX 9502 Rate Stick Tests

Lot number	Material class	Source	Mfg. year	Test year	Age @ test (yr)	Test temp. (ºC)	Diameter range (mm)
79-04	Recycled	LANL	1979	1980	1	–54, 24, 75	6–50
HOL80L890-007	Virgin	Pantex	1980	2006	26	–55, 25, 75	18
HOL85F000E-136	Recycled	Pantex	1985	1992	7	~22	10–50
HOL88H891-008	Virgin	Pantex	1988	1998	10	–55, 25, 75	8–50



From left to right, PBX 9502 molding powder, TATB powder, Kel-F 800 binder; and *front,* PBX 9502 pressed/machined parts.

powder is pressed at high temperature (~100°C) and pressure (~20,000 psi) to form a machinable solid. PBX 9502 contains 95 wt% of the explosive 1,3,5-triamino 2,4,6 trinitrobenzene (TATB) and 5 wt% of a Teflon-like fluoropolymer binder called Kel-F 800.

To conserve TATB, which is expensive, the Pantex Plant developed a process that reformulates machine scraps with equal parts of new material. Such lots are called recycled; all-new material lots are called virgin. The two types of PBX 9502 have different microstructures. Recycled material is finer-grained because TATB crystals that have suffered the machining process are broken and/or internally damaged. In the detonation (as opposed to the shock initiation) regime, experience shows that finer-grained TATB burns faster, yielding a thinner reaction zone and more ideal wave propagation. Thus, recycled PBX 9502 exhibits improved detonation propagation as well as cost savings. Sensitivity is also slightly increased; however, PBX 9502 is so insensitive to begin with that this effect is of no consequence.

We currently have useful rate stick data for the four PBX 9502 lots listed in the table. Lot 79-04 was taken from a much earlier Los Alamos study, which provided extensive speed data but did not measure detonation shock shapes. We have acquired speed and shape data for three other material lots since that 1980 study. One lot, which is usually referred to as 007, is of particular interest because of its longstanding reputation for poor performance.

This table is a virtually complete summary of PBX 9502 rate stick data. There have been no consistent aging studies for experiments of this type; that is, no one material lot has been tested at a variety of ages. However, because no other aging mechanisms have been identified in PBX 9502 other than ratchet growth—a partially irreversible thermal expansion of the bulk material due to the irregular expansion of the constituent TATB crystals—we suspect that the observed differences between material lots have likely been present from the date of manufacture. Note that ratchet growth is not a direct effect of aging, but an avoidable consequence of poorly controlled storage and handling, the effects of which accrue with time only after the molding powder is pressed.

A Strategy for Characterizing Material Variability

DSD implementations use an analytic expression for the $D_n[\kappa]$ calibration function, ideally the simplest one having enough flexibility to accurately capture the range of behaviors exhibited by most explosives. PBX 9502 data is well represented by a function of the form

$$\frac{D_n}{D_{cj}} = 1 - B\kappa\left(\frac{1 + C_1\kappa + C_3\kappa^2}{1 + C_2\kappa + C_4\kappa^2}\right), \qquad (1)$$

where the total curvature κ is positive for a diverging wave, negative for a converging wave, and zero for a plane wave. Equation (1) is a reduction of a more general-purpose and flexible equation. Note that if the wave is planar, Eq. (1) reduces to Huygens' construction, $D_n[\kappa] = D_{cj}$. If the coefficients C_1 to C_4 are zero, then Eq. (1) reduces to a line with slope $-B$. Finite values of C_1 to C_4 allow the curve to bend, as it generally does.

The key insight that allows us to add material variability effects to the existing framework of Eq. (1) is that D_n/D_{cj} does not physically depend on κ alone, but on the product $\eta = \delta\,\kappa$. Consequently, B (as a multiplier to κ) represents a global characteristic reaction zone length. It is distinct from δ (a local quantity that varies across the wave); rather, it represents a typical or average value of δ. The physical importance of η, rather than κ alone, motivates us to rearrange Eq. (1) as

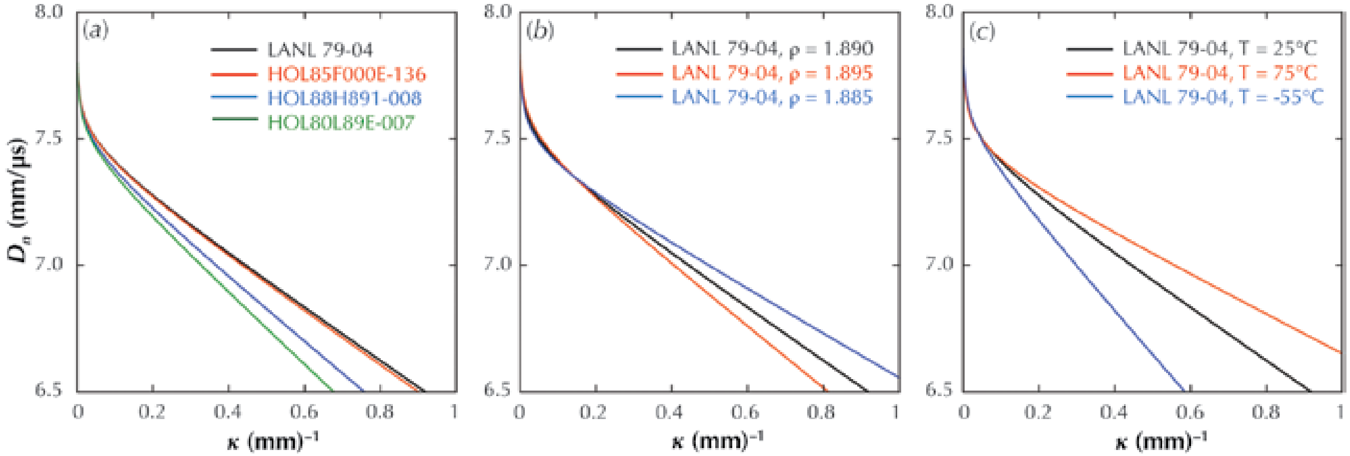
$$\frac{D_n}{D_{cj}} = 1 - B\kappa\left(\frac{1 + c_1(B\kappa) + c_3(B\kappa)^2}{1 + c_2(B\kappa) + c_4(B\kappa)^2}\right), \qquad (2)$$

where $c_1 = C_1/B$, $c_2 = C_2/B$, etc. We argue that D_{cj} and B are the primary controlling parameters, in which case the coefficients c_1 to c_4 are constants that depend only on the nominal PBX 9502 composition. D_{cj} and B are assumed to vary with density and temperature in a relatively simple manner, as follows:

$$\frac{D_{cj}}{D_{cj,ref}} = 1 + c_5\left(\frac{\rho_0}{\rho_{0,ref}} - 1\right) + c_6\left(\frac{T_0}{T_{0,ref}} - 1\right) \qquad (3)$$

and

$$\frac{B}{B_{ref}} = 1 + c_7\left(\frac{\rho_0}{\rho_{0,ref}} - 1\right) + c_8\left(\frac{T_0}{T_{0,ref}} - 1\right) + c_9\left(\frac{T_0}{T_{0,ref}} - 1\right)^2 . \qquad (4)$$



Effect of (*a*) material lot at 1.890 g/cc and 25°C, (*b*) pressed density for lot 79-04 at 25°C, and (*c*) initial temperature for lot 79-04 at 1.890 g/cc. Note that in many cases, all three variations will be present in combination. A poor-performing lot at cold temperature and high density represents the worst-case scenario.

We assume that, like c_1 to c_4, the coefficients c_5 to c_9 are properties of the nominal PBX 9502 composition. The reference values of density and temperature are $\rho_{0,ref} = 1.890$ g/cc and $T_{0,ref} = 298.15$ K.

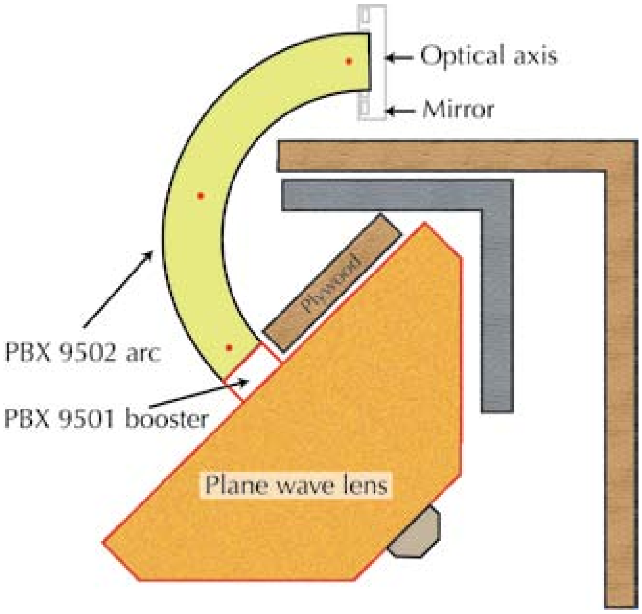
Lacking a direct microstructural parameter to distinguish between HE lots, we characterize material variation effects by B itself. We use a single value of D_{cj} for all material lots because Chapman-Jouguet (C-J) theory tells us that that D_{cj} should not depend on the microstructure. DSD also requires one to specify, as a boundary condition, the angle that the wave makes with the charge edge. This angle depends primarily on the thermodynamic properties of the HE and of any surrounding (confining) materials. Because these thermodynamic relationships, called equations of state, are relatively insensitive to effects other than composition, we assume that a single boundary angle applies for the entire suite of unconfined experiments. Direct measurements of the edge angle support this constraint.

In summary, our method depends on three elements: (D_n, κ)-level DSD theory, the model Eqs. (2–4), and theory- and experience-based assumptions about how the various model parameters should be constrained. All that remains is to use the model to compute all the data sets simultaneously. Each set of calculations composes a single iteration within an overarching nonlinear least squares fitting analysis. After a potentially large computation that depends on the data set size, the optimal model parameters emerge. The three graphs on the previous page show how the (D_n, κ) calibration function varies with lot, density, and temperature. The variation is significant with respect to all three parameters; however, the temperature effect is most prominent because the considered range is large.

Validation Problem Illustrating the Influence of Material Effects

The basic metric of success for the DSD model is how well the calibrated (D_n, κ) curve can reproduce the calibration data set (diameter effect and shock shapes) for each material condition (fixed lot, density, and temperature). We find that the DSD model fits the calibration data to within shot-to-shot repeatability. The success of our material variability extension model is judged by how well it fits the composite data set, compared with how well the basic DSD model fits each data set individually. The result is very successful in that minimal error is added due to the constraints imposed by the material variability extension model. Overall, error is decreased by up to a factor of 4 by using this model as compared with computing all conditions using a nominal calibration.

Unfortunately, faithful reproduction of the calibration data does not tell us how well the model will compute other geometries. The only way to learn that is to perform case-by-case validation experiments. One such experiment has been fielded—the explosive arc (or rib) configuration, which is illustrated in the following figure. The PBX 9502 lot used in this test was HOL85F000E-136—one of the four lots for which we have calibration data. We are therefore able to compute the arc shot using the correct HE lot, density, and temperature.

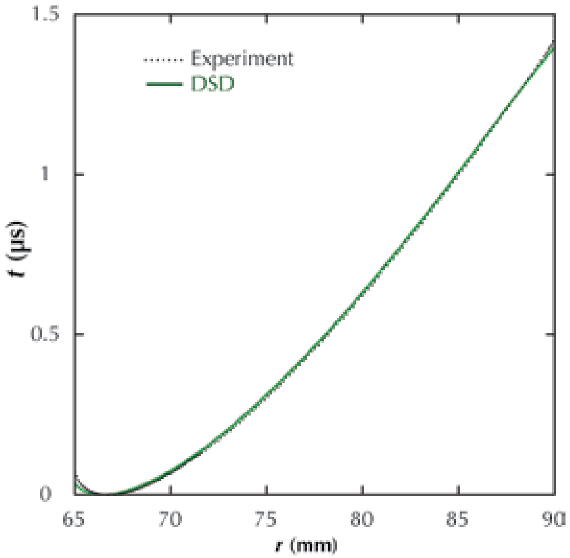


Schematic diagram of the arc experiment. The PBX 9501 booster and PBX 9502 main charge are uniformly initiated by a plane wave lens (PWL). The purpose of the plywood and steel barriers to the right is to keep the PWL detonation products from overtaking the detonation wave on the inner contour. Electrical shorting pins (not shown) are placed along the inside and outside of the arc. Detonation breakout at the end of the arc is observed by essentially the same technique as described for the front-curvature rate sticks.

The calculated arc behavior is compared with the arc experiment in the following table and graph. The table compares the measured and computed speeds along the inside and outside surface of the arc, and the graph compares the shape of the calculated and experimental breakout traces. (Note that the absolute time is poorly defined due to the complexity of the initiation system. For purposes of comparison, therefore, the experimental and computed breakout traces are aligned relative to the first breakout time.) The agreement is excellent on all counts.

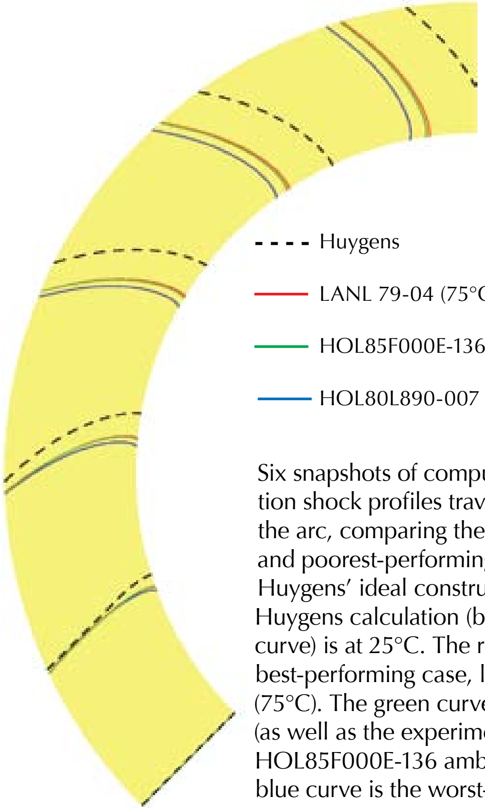
Measured and Calculated Detonation Speeds for the Arc Experiment

	Inner speed (km/s)	**Outer speed (km/s)**
Experimental	7.188	9.953
DSD calculation	7.192	9.958



This graph compares the experimental (black dots) and the computed (green curve) detonation breakout traces for the arc experiment. The comparison is one of shape only (not arrival time). Both waves are aligned at the first breakout time.

The next figure shows a series of arc calculations for a variety of different material conditions. A Huygens calculation at 25°C is also shown for reference. The biggest discrepancy is between Huygens' construction and the three DSD calculations; however, an engineering Huygens calculation would achieve better accuracy by choosing a smaller detonation speed than D_{cj} used here. It is interesting that the best-performing case differs only slightly from the typical; however, the worst-performing case lags significantly at the end of the charge. Our two primary conclusions illustrated by this figure are that the DSD correction to Huygens' construction is large, and one should avoid poor-performing lots at cold temperatures.



Six snapshots of computed detonation shock profiles traveling through the arc, comparing the best-, typical-, and poorest-performing cases with Huygens' ideal construction. The Huygens calculation (black dashed curve) is at 25°C. The red curve is the best-performing case, lot 79-04 hot (75°C). The green curve is a typical (as well as the experimental) case, lot HOL85F000E-136 ambient (25°C). The blue curve is the worst-performing case, lot HOL80L890-007 cold (–55°C).

Future Challenge: Relating Detonation Shock Propagation to the HE Microstructure

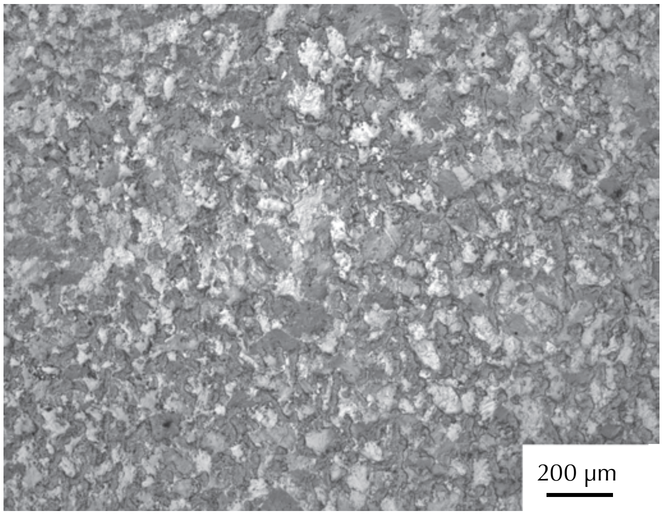
In our current material variability extension model, microstructural effects are buried within the reaction zone parameter *B*. This situation is actually a huge step forward in that we have identified a single experimentally obtainable parameter to characterize how any PBX 9502 lot performs with respect to detonation shock propagation. However, a mystery remains as to how this parameter relates to the complex HE microstructure. To the extent that we can quantitatively answer this question, we will be able to deduce B without having to perform extensive (and expensive) tests for every HE lot. Furthermore, we will be better equipped to custom-tailor the HE microstructure of new HE formulations advantageously.

We can state a priori that a useful microstructure characterization must distill the observed complexity to one or possibly two parameters. The reason is that our experimental methods are integral. Consequently, it is very difficult to deduce how numerous parameters arising from a detailed material description combine to influence the measured outcome, as characterized by D_{cj} and B. On the other hand, the complexity of the HE microstructure ensures that a single effective parameter will not likely be as simple as the mean prepressed particle size. Rather, effective HE microstructural characterization will likely involve the more abstract notion of generalized length scales.

It may seem unlikely that a single parameter could be sufficient to characterize a detonation wave's response to the complex PBX microstructure. But the success of our effort demonstrates that—at least for the four material lots tested—microstructural effects (combined with small density and large temperature variations) are adequately characterized by the single parameter B. The challenge is to relate B to a different single parameter that can be derived from observable attributes of the HE microstructure.

Generally, the finer the TATB powder lot, the smaller B and the more ideal the propagation of an established curved detonation shock. The micrograph of PBX 9502 (upper right) gives some useful information about the range of size scales present in the pressed piece, and our efforts to usefully quantify the HE structure from such micrographs are ongoing. Problems include the fact that the surface appearance depends on the sample preparation, lighting, and magnification.

The finer the prepressed HE powder, the larger the specific surface area s. Previous studies show that the ideality of detonation propagation is at least reasonably correlated with s. Of great interest is the fact that the gas absorption surface area measurement technique does not underestimate the important contribution of the finest particles. Multiplying s by the HE density gives the surface area per unit volume, which is the inverse of a length scale λ. We have previously noted a strong and physically sensible correlation between B and λ for the four tested PBX 9502 lots. Thus, although the size of our data set and the accuracy to which λ has been measured are both limited, the λ scale seems a promising candidate for a distilled, relevant length scale.



Micrograph of the polished surface of a PBX 9502 charge. Although the preformulated TATB powder was composed of distinct polycrystalline particles, this is not very evident in the pressed piece. The deformation, cracking, and general damage to crystals accrued during pressing significantly complicates the task of effective HE microstructural characterization.

Other emerging material characterization techniques involve various forms of penetrating radiography. This class of methods is advantageous because it can measure features throughout the volume of pressed pieces. The challenge for information-rich methods is to distill the many observed details into a single parameter that is highly correlated with B. This metric is impartial—the technique that can best accomplish it will endure.

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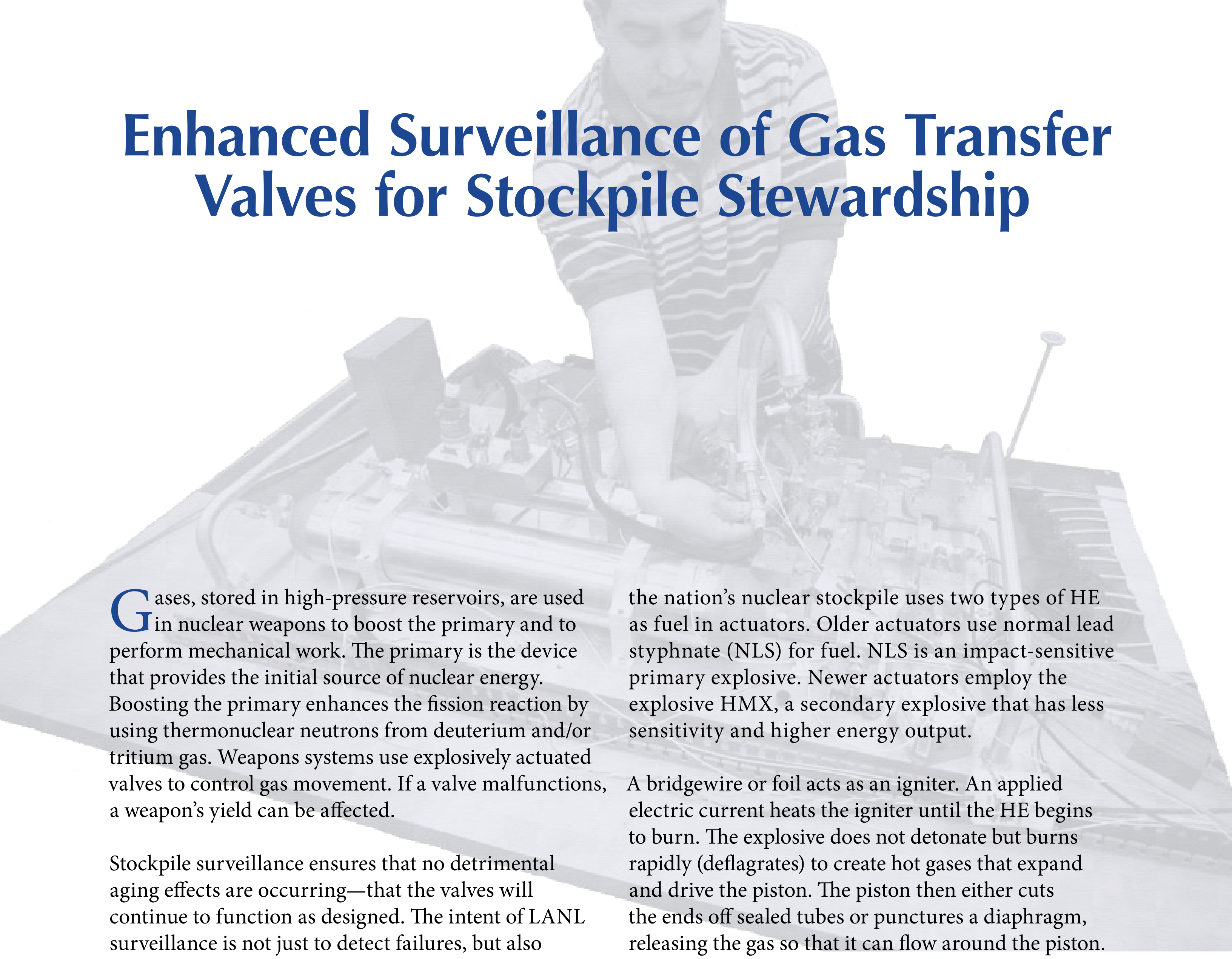
Enhanced Surveillance of Gas Transfer Valves for Stockpile Stewardship



Gases, stored in high-pressure reservoirs, are used in nuclear weapons to boost the primary and to perform mechanical work. The primary is the device that provides the initial source of nuclear energy. Boosting the primary enhances the fission reaction by using thermonuclear neutrons from deuterium and/or tritium gas. Weapons systems use explosively actuated valves to control gas movement. If a valve malfunctions, a weapon's yield can be affected.

Stockpile surveillance ensures that no detrimental aging effects are occurring—that the valves will continue to function as designed. The intent of LANL surveillance is not just to detect failures, but also to detect deterioration before failure occurs. Thus, stockpile reliability is assured.

How Gas Transfer Valves Work

A gas transfer valve opens a flow path between a sealed gas reservoir and a receiving vessel. The receiving vessel may be an expanding bellows that performs mechanical work or a primary that is being boosted.

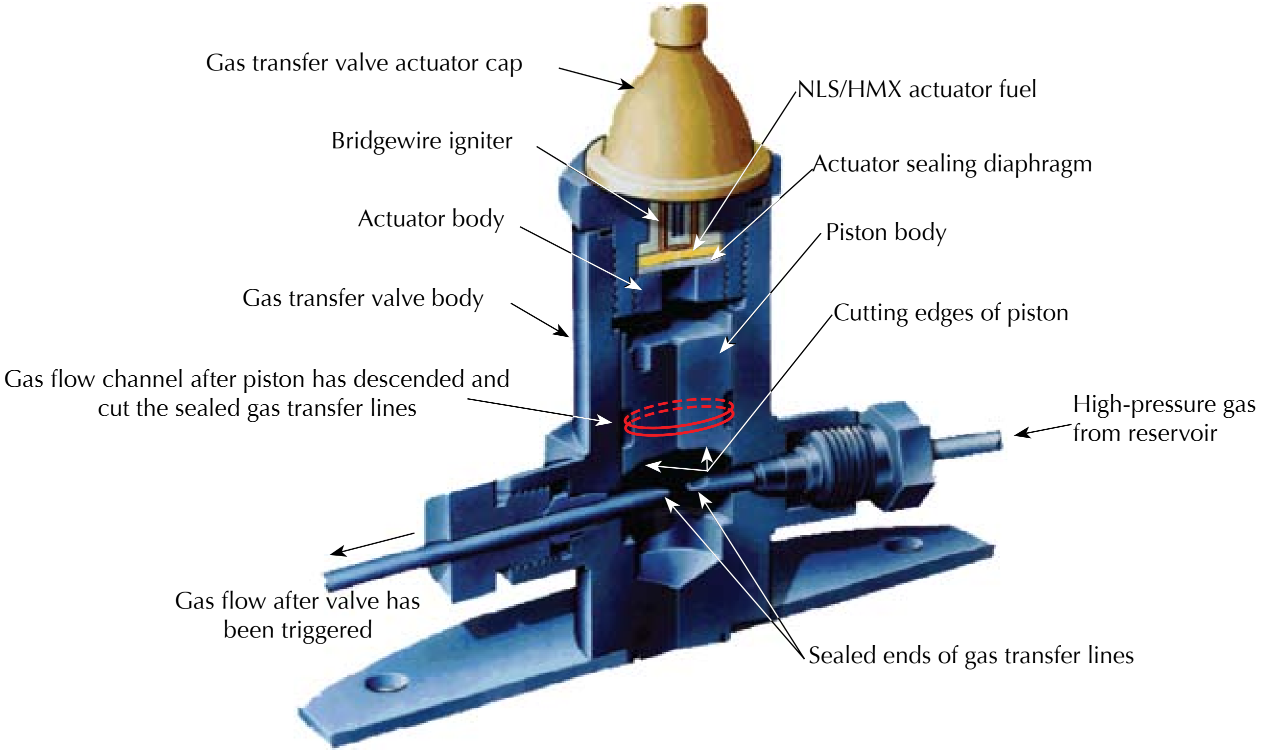
To fully characterize gas transfer valve function, our surveillance team must measure all of the events that occur when a valve functions without disturbing those functions.

Valves consist of a body, a piston, and an actuator. The actuator burns small amounts (125–250 mg) of high explosive (HE) that provide hot combustion gases to move the piston. Currently, the nation's nuclear stockpile uses two types of HE as fuel in actuators. Older actuators use normal lead styphnate (NLS) for fuel. NLS is an impact-sensitive primary explosive. Newer actuators employ the explosive HMX, a secondary explosive that has less sensitivity and higher energy output.

A bridgewire or foil acts as an igniter. An applied electric current heats the igniter until the HE begins to burn. The explosive does not detonate but burns rapidly (deflagrates) to create hot gases that expand and drive the piston. The piston then either cuts the ends off sealed tubes or punctures a diaphragm, releasing the gas so that it can flow around the piston. At the end of its travel, the piston impacts the bottom of the valve body and comes to a halt. Both valve types, ones that cut sealed tube ends and those that puncture a diaphragm, function in the same manner, and therefore the response of the strain gauges and accelerometers that our valve surveillance team uses in surveillance activities is very similar.

Each event that occurs during valve functioning creates small disturbances that are transmitted through the valve body. The surveillance challenge is to acquire and interpret these signals, obtain information about the timing or magnitude of events, and relate the data to performance measures.

A cross section of a gas transfer valve showing the valve's parts and their functions. Upon receiving the external initiation signal, the bridgewire igniter fires and ignites the actuator fuel below. As the fuel burns, gas pressure builds up behind the actuator sealing diaphragm. Once the actuator fuel builds up enough pressure, the actuator sealing diaphragm ruptures, and the sharp pulse of released gas pressure initiates piston travel down the valve body. The actuator fuel continues to burn and expand—continuing to drive the piston downward. As the piston travels down the valve, its sharp bottom edge slices through the sealed ends of the gas reservoir and gas transfer tubes. As the piston comes to rest, the high-pressure gas from the reservoir travels through the machined channel around the outside of the piston and into the gas transfer tube, where it will proceed to perform its intended work.



Valve Function Surveillance

It is insufficient to test valves only for final function, i.e., gas transfer rate. This go/no go test does not measure the valve's performance margin, nor can it detect any incremental aging effects that could result in failure. Other simple measurements are commonly performed such as pre- and post-function bridgewire resistance, pre- and post-function radiography, and measurement of the piston's final position. Although these measurements provide useful data, they do not provide an adequate picture of all the processes involved in valve function.

To fully characterize valve function, our surveillance team must measure all of the events that occur when a valve functions without disturbing those functions. This requires an integrated suite of noninvasive sensors reporting to the data-acquisition system at time scales from microseconds to minutes.

Three measurement types are needed to characterize valve reliability: explosive actuator function (burning explosive), piston travel (moving steel), and gas transfer (moving gas). These measurement types relate to possible aging-related failure mechanisms such as

- explosive deterioration,
- stress relief in the piston or valve body, which can cause a gap to form between the two parts (allowing the actuator gases to flow past the piston) or the parts to bind (the piston becoming locked in place), and
- loss of the gas used as a working fluid.

No single sensor will measure all properties of interest. Therefore, we use a suite of sensors that provides overlapping coverage. This overlap enables us to correlate signals between very diverse types of sensors, which allows a complete characterization of the valve's performance.

Function	Measurement type	Sensor	Measurement parameters
Actuator function	Electrical	Time-resolved digital multimeter for bridgewire resistance change at constant current	• Initial bridgewire resistance, final bridgewire resistance, bridgewire burn-through, firing pulse, and bridgewire heating times • Ignition • Deflagration start and stop • Actuator end cap breakout
	Chemical	Calculated	• Actuator energy
Piston travel	Mechanical	Hoop and axial strain gauges, axial accelerometers	• Piston start and stop • Tube cut or diaphragm puncture • Piston velocity and acceleration
	Electrical	Time-resolved digital multimeter for bridgewire resistance change at constant current	• Piston start • Tube cut or diaphragm puncture
Gas transfer	Thermodynamic	Thermocouples for temperature curve	• Valve body temperature history • Receiving vessel temperature history
		Transducers for pressure curve	• Receiving vessel pressure history • Gas flow rate • Total gas transferred (calculated)

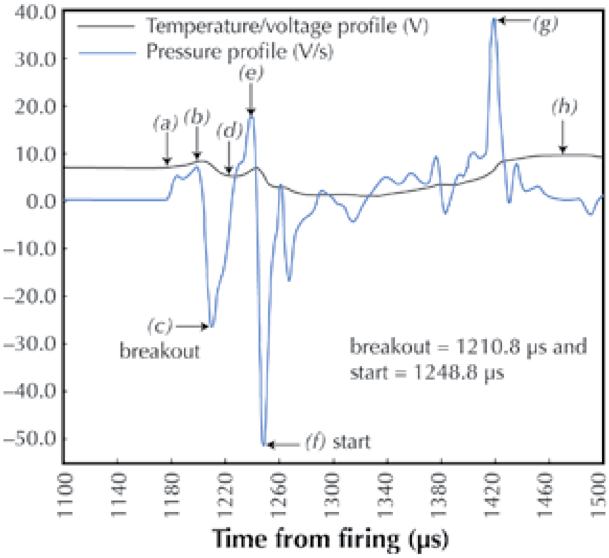
Fast Sensors and Measurements

Bridgewire or foil igniter voltage is the primary diagnostic our valve surveillance team uses to measure actuator performance. Because events occur on a microsecond time scale, data are recorded at 100 ns intervals. A constant electrical current is applied to the bridgewire or foil igniter causing it to heat. Because resistance increases with temperature, the voltage needed to maintain constant current increases. We use our LANL-developed valve-surveillance test system (VSTS) to measure this voltage with good accuracy and speed (sampling 10 million times per second).

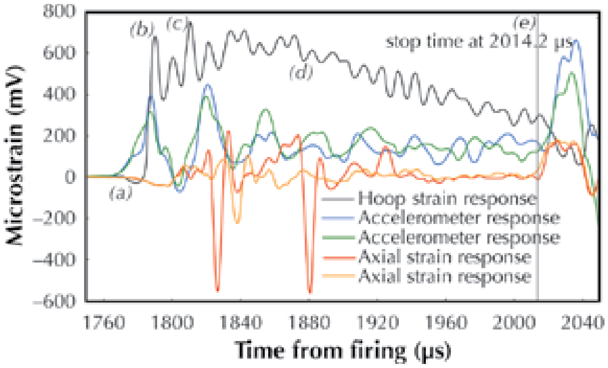
Bridgewire temperature fluctuates distinctively as the actuator functions; for example, temperature increases as the explosive begins to burn, decreases as the piston travels into the cylinder bore, and increases again as the piston reaches the end of its travel (and the explosive continues to burn). Our VSTS nondestructively resolves the timing of the burn sequence and the piston start time. We use the timing of these events to assess actuator performance.

Piston motion is characterized by a combination of strain gauge and accelerometer measurements

A plot of the valve's temperature/voltage profile (black trace) during valve function. The pressure profile (blue trace) is derived from the temperature/voltage profile. The bridgewire temperature increases as current is applied, until the explosive fuel ignites. *(a)* The burning explosive adds heat to the bridgewire, increasing its temperature and resistance and thus the required voltage. *(b)* When gases from the burning explosive generate enough internal pressure, *(c)* actuator breakout occurs by rupturing the diaphragm of the actuator. As the hot gases expand into the cylinder bore above the piston, they cool—reducing the bridgewire temperature and, therefore, the voltage. The burning fuel continues to generate more gases, *(d)* so the pressure and temperature rise once more until *(e)* the piston begins to move—which again drops the temperature and pressure. Eventually the fuel is exhausted, and *(f)* the heating profile returns to that of electrical heating only. At *(g)* the piston stops and the bridgewire burns through like a fuse at *(h)* well after the valve has finished its function.



A plot of strain and accelerometer data. The black trace is the hoop strain response. The green and blue traces are the accelerometer responses. The yellow and orange traces are the axial strain responses. The strain data are a result of pressure increases and decreases on the valve body, and the accelerometer data are a result of vibration and shock response on the valve body. *(a)* As deflagration starts, the pressure builds in the valve. *(b)* Breakout occurs as indicated by the pressure decrease due to an increase in volume. *(c)* Pressure builds up again to move the piston. Pressure then decreases as the piston moves (and allows the volume to increase). *(d)* The piston encounters the gas transfer tube. The axial strain also indicates that the valve has stretched from the encounter. *(e)* The impact response from the accelerometers indicates that the piston has stopped at the end of its travel.



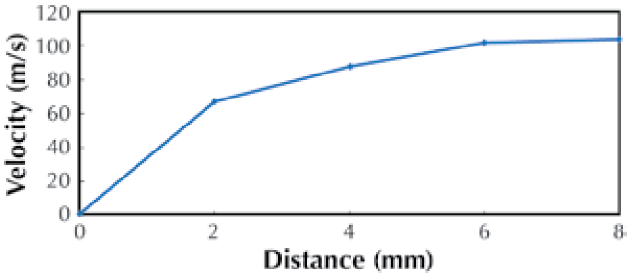
and the piston start time from the bridgewire voltage plot. We apply both axial and hoop strain gauges to the valve body. The axial strain gauges record stretching and the hoop strain gauge records swelling of the valve body as pressure from the actuator

- builds from ignition to breakout,
- decreases at actuator breakout,
- rebuilds to piston start, and finally
- decreases as the piston travels through the cylinder bore.

We also use strain data to resolve the point at which the piston cuts or punctures the gas seal.

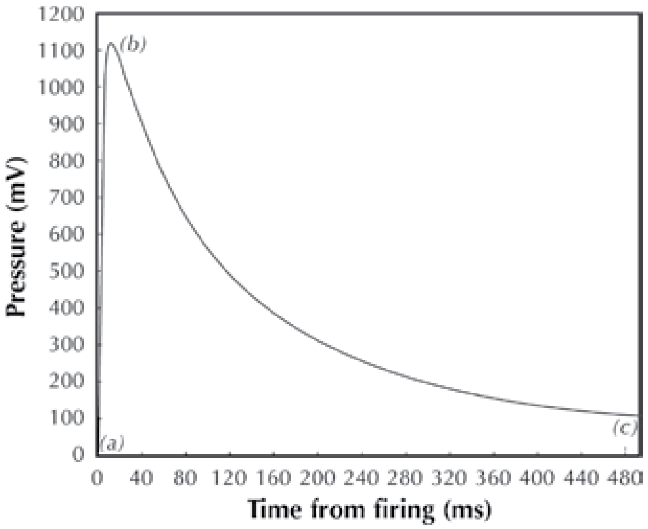
Strain gauges also record the end of piston travel, i.e., when the accelerating piston impacts the bottom of the valve body and comes to a stop. The end of piston travel is characterized by stretching and necking of the valve body, followed by harmonic ringing in cylindrical coordinates (hoop and axial strains 180° out of phase). The strain signals overlap with the bridgewire voltage signals at the beginning of valve function and provide consistent correlation with those signals.

We also place accelerometers on the base of the valve body. Although accelerometers mainly provide data



The incremental piston velocity plot for a gas transfer valve shows the response from five uniformly positioned fine wire pins that our team added to the valve body. Therefore, from the timing of piston events and precision wire placement, we can calculate the piston speed. Piston start is at 0 mm and piston stop is at 8 mm.

A plot of the pressure profile at the gas transfer valve exit port showing a manifold peak pressure of 1125 mV that occured at 11.87 ms. *(a)* Gas is introduced into the transfer tube after valve function. Pressure rise indicates that the transfer tube has been sliced. If the tube is smeared (partial occlusion), our sensors would observe a long rise time from *(a)* to *(b)*. The peak pressure *(b)* is a function of temperature and pressure. The smoothly descending curve from *(b)* to *(c)* indicates that the pressure is equilibrating as it approaches ambient temperature.



at the end of the piston stroke, the axial accelerations also correlate with the axial strains and thus provide overlap and confirmation for those signals.

Strains and accelerations are fast events. Our VSTS records them at 100 ns intervals. Typical function times from ignition to the end of the piston stroke are on the order of 100 µs. From the timing of piston events and the known valve dimensions, our team can calculate piston speed. Typical speeds are on the order of 100 m/s when the piston cuts the seal.

Slower Sensors and Measurements

Gas flow rate and amount are the most easily measured parameters of a gas transfer valve, but require a different suite of measurements at a slower time scale. In order to measure gas flow rate and amount delivered, the pressure, volume, and temperature of the gas system must be known. System volume, determined during test setup, is constant once the valve functions, so our surveillance team must measure only temperature and pressure changes.

We measure temperature changes with thermocouples or thermistors attached to the valve body, pressure manifold, and gas reservoir and with probes inserted into the receiving vessel. We obtain a time history of temperatures from the initial firing signal until system equilibrium at 30 min elapsed time and monitor pressures at the valve exit port and in the receiving vessel.

The pressure curve at the valve's exit port provides information on how fast the gas flows through the valve and, thus, is a key measurement. Flow rate depends on how cleanly the valve opens the seal and how tortuous the resulting flow path is. A short, sharp pressure spike indicates good gas flow. A broad, delayed pulse indicates a poor flow path that requires further investigation. The area under the pressure curve indicates the total amount of gas transferred.

The best measurement of total gas transferred is the equilibrium pressure and temperature in the receiving vessel. The initial measurements are acquired on the millisecond time scale; equilibrium measurements are on the time scale of seconds to minutes.

Nondynamic Measurements

After completing functional tests on the valve, our valve surveillance team performs a series of nondynamic measurements including gas sampling, piston-depth measurement, and metallurgical sampling and hardness testing. Gas sampling will reveal if actuator combustion gases were introduced into the transferred gas, which indicates a leaky piston that may contaminate other weapon system components.

Our surveillance team performs a piston-depth measurement by radiography and confirms it by direct measurement (with the actuator removed). Because the gas must transit an annular groove in the piston to move from the reservoir to the receiving vessel, the position of the groove relative to the sheared gas transfer tubes is critical. If the piston embeds itself too deeply into the valve body or rebounds upward, the annulus will not align properly with the cut tubes and gas transfer will be degraded or prevented.

Metallurgical measurements of the valve body and the piston include microscopic evaluation of polished sections and spot hardness testing. For example, the leading or cutting edge of the piston must be hardened to cut the seal cleanly, but the trailing edge must be ductile enough to seal in the combustion gases. Note that at this time metallurgical measurements are not made of the puncture-type valve.

Our VSTS

LANL scientists created a unique VSTS in order to acquire all of the fast, slower, and nondynamic measurements described in this article. The VSTS provides capabilities for test control, data acquisition, and data analysis for all the valves in the active nuclear stockpile.

Using LabView software, we program test control functions for each valve type and include system pretests, configuration monitoring, and fire signals. Automated interlocks prevent the test from proceeding if pretests fail or pressure manifold valve configurations are not correct for that valve type.

Data-acquisition functions include signal speeds from as many as 10 million samples per second to a few samples per second. We can configure the 52 data channels to received data from strain gauges, accelerometers, thermocouples, thermistors, and pressure gauges.

Analysis functions include data-reduction, filtering, and waveform-interpretation software based on LabView. This system is coupled to an environmental chamber that contains the testing pressure manifold. The pressure manifold contains

- the valve being surveilled,
- a valve simulator with gas reservoir for a complete pretest,
- the receiving vessel, and
- all gauging and instrumentation.

(a) The environmental chamber for our VSTS II. The apparatus in the foreground is our VSTS II showing *(b)* the gas sample bottle, *(c)* the test pressure manifold receiver vessel, *(d)* the valve under test, and *(e)* the source vessel. The system includes pressure transducers and temperature probes for gas volumes and vessel surfaces.

The components of the VSTS II portable test bed unit are *(a)* an industrial-rated computer with custom LabView data acquisition software, *(b)* a flat-panel monitor, *(c)* a keyboard, *(d)* a National Instruments VXI chassis with 48 data channels and 16 digital input/output channels, and *(e)* a custom LANL monitor and control chassis.

The environmental chamber can be programmed to duplicate the temperature of the stockpile-to-target sequences or to test valve functioning at temperature extremes.

A fully functional portable VSTS is also available for off-site testing of radiologically contaminated valves using gloveboxes and gas-handling capabilities.

We test and fully characterize surveillance valves pulled from stockpiled weapon units. We then compare the results from each unit with those obtained from similar but unissued valves as well as the entire tested population. Individual valves with test results that fall outside statistical limits are examined further to determine the cause of the anomaly and assess any impact on the reliability of the stockpile.

Other Applications for VSTS

Explosively actuated mechanisms are used in many devices that require reliable and rapid mechanical functioning. Examples include explosively sheared bolts and cable cutters and other nonweapons applications of explosively actuated valves such as explosive systems and devices used on launch and space vehicles. Many systems in the space program use one-time-use explosive devices for stage separation and release mechanisms. Our VSTS is extremely versatile and can be readily adapted to gather data at a similar level of detail for these types of devices. These data can be used for surveillance, as part of initial product development (to assess the impacts of design changes on component performance), or for final certification and lot acceptance testing. NWJ

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Improving Security Awareness

Many LANL workers routinely work with explosives, nuclear materials, and classified data to support mission-critical weapons research and stockpile stewardship. These elements make the potential consequence of a security lapse severe. Even a minor mistake or lapse in attention can lead to a major security incident.

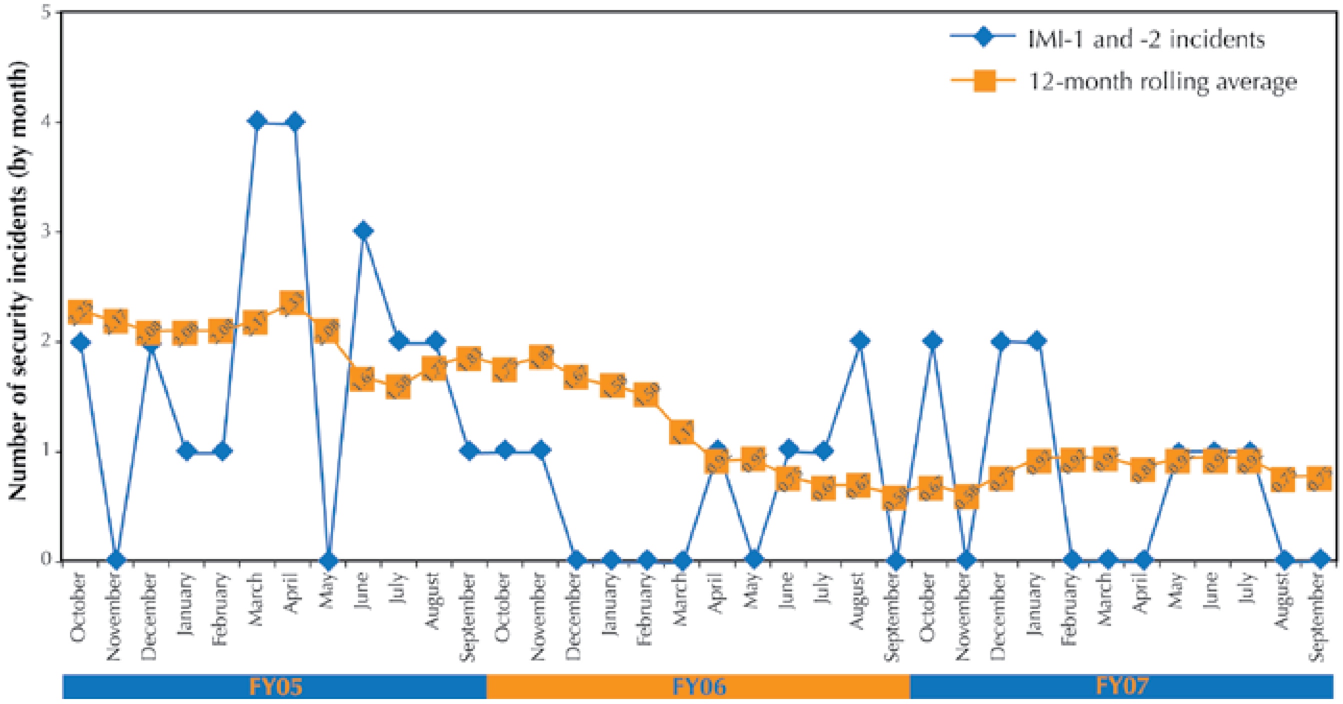
With more than 10,000 workers occupying approximately 11 million square feet of facility space spread across just under 40 square miles, Los Alamos National Laboratory is a large, complex organization. The diverse LANL work force performs work from standard maintenance and support tasks to scientific research that can only be accomplished with the Laboratory's unique facilities and expertise. The complexity and breadth of its operations make the Laboratory a valuable national resource but also create an environment in which security is critically important.

Security is most often associated with physical controls and systems that protect sensitive facilities—the guns, gates, and guards. Workers associate security most closely with physical controls because they are highly visible.

Just as important as the physical control systems are the soft factors—the more subjective elements of the Laboratory's institutional culture related to people, communication, management, and relationships. These more abstract factors often determine the success or failure of any security system. In addition to implementing sound physical controls and pursuing new technologies, the commitment to continuously improving human factors is vital to the Laboratory's security mission.

Security Incident Data

The DOE established a graded incident measurement index (IMI) with four levels of severity. The highest two levels, IMI-1 and IMI-2, represent serious threats to national security and DOE interests. The rate of these severe incidents has declined over the past 2 years.



The Laboratory experienced 22 IMI-1 and IMI-2 incidents in FY05, 7 in FY06, and 9 in FY07 (blue line). The 12-month rolling average (orange line) affords security analysts a better indicator of the Laboratory's ongoing security status. It indicates that we have moved from a rolling average of 2.25 (October of 2004) to our current level of 0.75.

Although a common industry metric, analyzing security-incident data by month can be misleading. Such an analysis suffers from too few data points, which can vary greatly without a direct relationship to the Laboratory's overall security culture. The transition from a 1-incident month to a 3-incident month looks far more dramatic than it actually is.

Our security analysts use a statistical practice called the rolling 12-month average to understand the larger context of the security culture at the Laboratory. This averaging smoothes out the spikes that result from the arbitrary bounds of monthly measuring, giving us a more accurate assessment of the Laboratory's ongoing security record. The rolling 12-month average of severe incidents per month has decreased from more than 2 in early 2004 to fewer than 1 at the close of 2006.

The Laboratory aims to achieve the ideal goal of completely eliminating security incidents and strives to meet this goal by sustaining reduced incident rates while continually exploring avenues to drive rates even lower.

The decrease in serious incidents at the Laboratory correlates with the maturation and continued implementation of our Integrated Safeguards and Security Management (ISSM) system. ISSM drives every worker at the Laboratory to integrate safeguards and security measures into his or her work through the five-step process.

1. Define the scope of work.
2. Analyze the security risks.
3. Develop and implement security controls.
4. Perform work within the security controls.
5. Ensure performance.

As workers integrate security awareness into every aspect of their work, they learn to identify and minimize factors that lead to human-caused errors. ISSM is crucial in shaping the security culture of the Laboratory and habits of workers because it reinforces the universal importance of security awareness.

Taking Action to Improve Our Security Status

The Laboratory's reduced incident rate can also be attributed to the following measures.

Incident Analysis and Corrective Actions

The Laboratory's security inquiry program emphasizes causal analysis of incidents, not punishment of the principals. The program also works with the principals' managers to implement corrective actions that address the problems that led to the incident. As a result of the analyses and corrective actions, principals and the Laboratory population benefit from lessons learned.

Deployed Security Officers

Deployed security officers (DSOs), workers with a broad base of security expertise, are assigned to serve as a first-line security resource for managers. DSOs work within organizations throughout the Laboratory. As deployed workers, DSOs are well-versed with the work-specific security needs of their host organizations and can help managers implement ISSM and security policies and procedures into any organization's daily functions. Security expertise, coupled with a deep understanding of the organization to which they are assigned, allows DSOs to effectively address security issues.

Help Desk

The Security Help Desk is an easy-to-find, one-stop resource for workers who need answers. With an emphasis on providing user-friendly service, the Security Help Desk supplies LANL workers with quick and consistent answers about security policies and procedures. It also provides an important data-gathering function that is useful for DSOs and managers.

Communications

The security communications team produces tools focused on increasing security awareness. The team manages the security websites, which provide information and resources and consistently rank among the most-visited LANL web pages. The communications team also produces publications that deliver security information through focused explanations of security topics and case studies of incidents.

Training

Trainers who specialize in security offer courses from general (annual security refresher) to specific (nuclear material accountability). Many courses are delivered in a flexible manner and allow workers to take a course online, by independently reading and signing a document, or attending a live course delivered by an instructor.

Bringing It All Together

Considered alone, any of the above measures may have only a minor impact. However, as the security professionals from each area share data and resources to accomplish mutual goals, the benefits of each measure merge to empower all of the others. Information from incidents, feedback from DSOs, and data gathered by the Security Help Desk drive the development of training, communications, and policies and procedures. As these three tools are reviewed and implemented by LANL managers and workers, they help to identify both deficiencies and best practices in LANL security. These findings then can be used as the basis for further improvements to increase security awareness. As an integrated whole, the Laboratory's soft security elements combine to form a powerful resource for management.

ISSM is a constantly evolving process of incremental improvement. Every LANL worker contributes to the shift in security culture by being constantly vigilant for loopholes, risks, and vulnerabilities. Security culture is defined by the actions and attitudes of each member of that culture. Every worker has a direct stake in the success or failure of security at the Laboratory.

Laboratory workers realize an unlocked door, unauthorized cell phone, or disgruntled coworker can cause a serious incident. In an environment where mistake-free security is of the utmost importance, everyone is responsible for security.

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Nuclear Science Research Contributes to

The US depends on the accuracy of computational modeling to predict the performance of nuclear weapons and certify their reliability. The availability of accurate nuclear data for use in weapons calculations has a dramatic impact on our scientists' ability to use computational tools for these tasks. Refinements to advanced simulation and computing (ASC) computer codes can be made only with precise experimental data obtained at high-energy facilities with the most advanced detectors. Experiments performed at the Weapons Neutron Research (WNR) Facility at the Los Alamos Neutron Science Center (LANSCE) provide these data to assure, in collaboration with weapons designers, the predictability of the US nuclear stockpile.

The WNR Facility at LANSCE provides important contributions to the Stockpile Stewardship Program, especially input to quantification of margins and uncertainties (QMU)—a methodology created to facilitate analysis and communicate confidence in an assessment or certification. QMU is a framework that captures what Los Alamos scientists do and do not know about the performance of a nuclear weapon in a way that can be used to address risk and risk mitigation.

To reliably predict the performance of the fission trigger in a nuclear weapon, we must precisely understand neutron multiplication during detonation.

LANSCE, WNR, and the Nuclear Weapons Program

LANSCE is an accelerator-based multidisciplinary facility that provides extraordinary research opportunities for defense and civilian applications. The 800-MeV proton linear accelerator at LANSCE drives three major national experimental facilities:

- WNR, which employs neutrons with energies between 100 keV and 100s of MeV;
- Lujan Center, which employs neutrons between 0.01 eV and 10s of keV; and
- proton radiography, which employs the direct proton beam.

The WNR Facility is used for basic, applied, and weapons-related nuclear physics research, neutron radiography, neutron resonance spectroscopy, and irradiation testing of industrial components such as integrated circuits. During operations in 2007, LANSCE provided reliable beam for nuclear physics and materials science experiments, operating above 85% beam delivery to all facilities. The accelerator

Predicting and Certifying the Stockpile

enabled WNR to host 117 experiments totaling 1235 days of beam (more days than are in a year by a factor of 3.4 because multiple beam lines are used simultaneously). Fifty four percent of the time was devoted to weapons-related science.

Weapons research experiments at WNR have a direct impact on calculating the potential performance of nuclear weapons and on the diagnostics Los Alamos designs and uses to analyze the performance of nuclear weapons. Data from experiments are evaluated and then incorporated in ASC computer codes for device design. These computer codes are also used to re-analyze data from the nuclear test archive—tests conducted from 1945 to 1992, when underground testing ceased.

One of the primary goals of Los Alamos' WNR experimental campaigns is to amass empirical data that support and/or improve the accuracy of our computational modeling efforts to predict the physical response and performance of weapons-related materials or components. Weapons performance is determined by the two processes that power a nuclear weapon: fission of uranium and plutonium and the thermonuclear fusion process. In order to reliably predict the performance of the fission trigger in a nuclear weapon, nuclear weapons scientists must precisely understand neutron multiplication during detonation. Calculating neutron multiplication in the fission trigger requires three distinct pieces of nuclear information:

- the number of neutrons produced (emitted) by each fissioning nucleus, $n(e_i)$, as a function of the energy of the incoming neutron causing the fission, e_i;
- the energy distribution (spectrum) of these neutrons, $n(e_i, e_p)$, as a function of the produced neutron energy, e_p; and
- the probability that this neutron energy will cause further fission or neutrons will be scattered or captured without causing fission (fission, scattering, and capture cross sections).

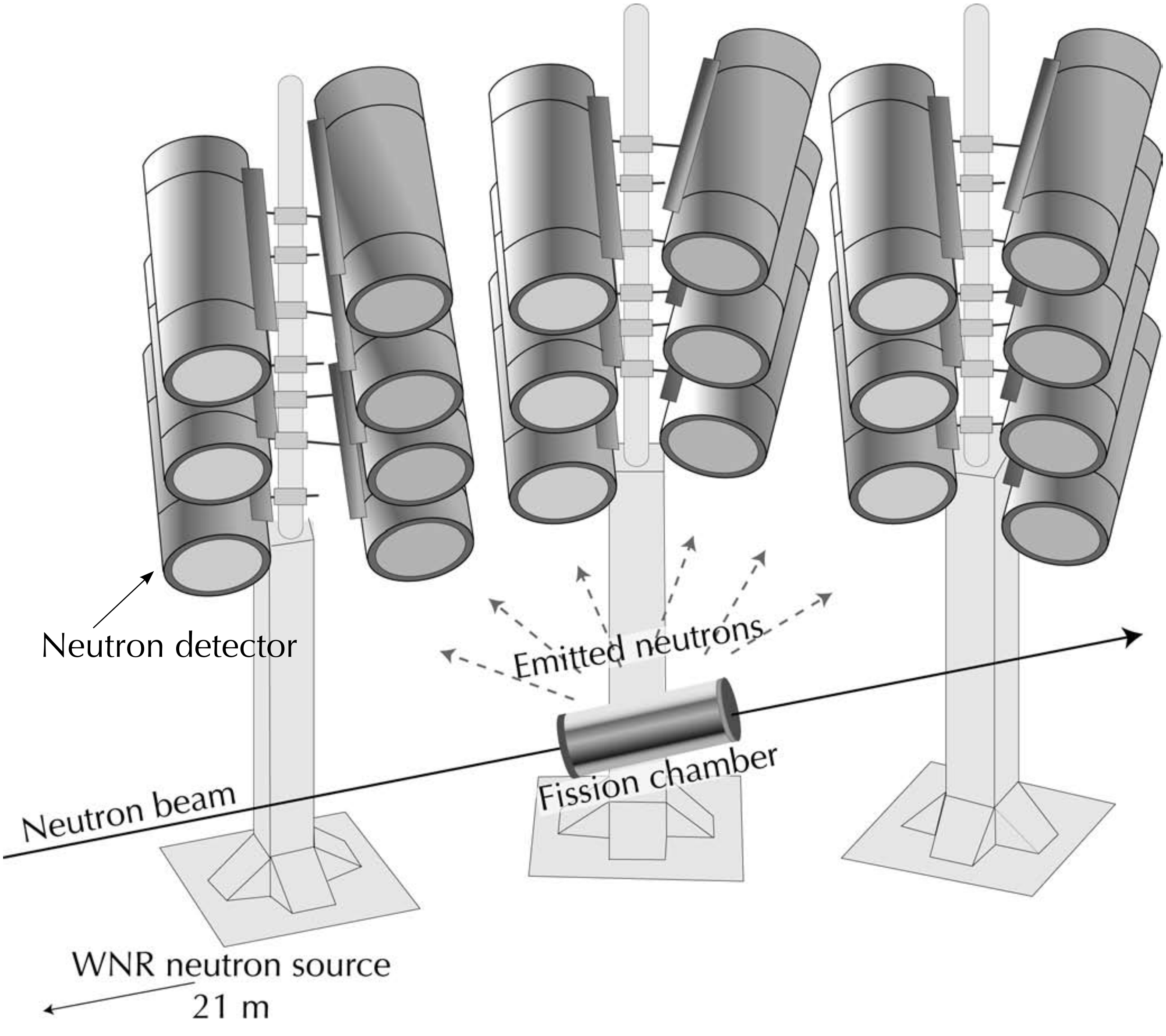
Neutron-Production Measurements

Using the Fast Neutron-Induced Gamma-Ray Observer (FIGARO) detector array, LANL scientists performed extensive neutron-production measurements at WNR. The FIGARO array contains 20 neutron detectors that can, by using pulse-shape discrimination, distinguish between neutrons and gamma rays. The neutrons are detected in coincidence with a signal from a fission chamber that indicates a fission event occurred. The energy of the neutron produced by the fission event is determined by the time between the event signal and detection of a neutron in the FIGARO array (time of flight). The slower a neutron moves, the lower its energy. With the neutron-production measurement data obtained with FIGARO, Los Alamos scientists are able to provide our simulation and modeling teams with the information necessary to improve weapons computational codes.

Measuring Fission Cross Sections

Fission cross sections are used in calculations to determine what effect an incoming neutron interaction will have on the fissile material it encounters. The higher the fission cross section (relative to the cross sections of other processes such as absorption and scattering), the higher the neutron multiplication in a given configuration. This number is an important factor in determining the yield of nuclear weapons.

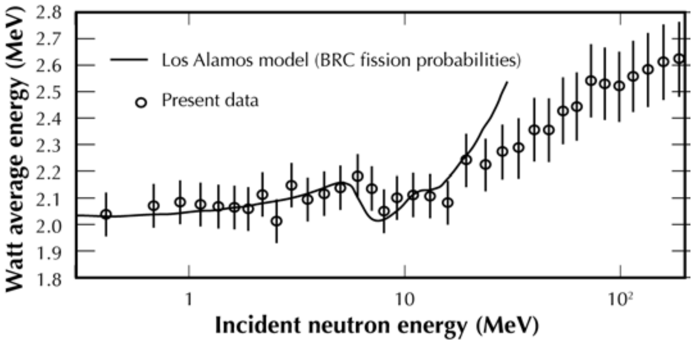
Fission cross sections of fissile materials have been measured numerous times at other facilities. The paramount contributions of WNR to these measurements is that WNR instruments can cover a broad energy range in a single measurement and avoid the systematic errors that accompany changing energies at other accelerator systems. One important example of a measurement at WNR is a detailed measurement of



The FIGARO detector array for measuring fission neutron spectra. A fission chamber is placed in the LANSCE/WNR pulsed neutron beam. A fission signal from the chamber indicates both the time of flight from the neutron source for each incident neutron and the start time for fission neutrons detected in the FIGARO array located 1 m from the fission chamber.

the plutonium-239 fission cross section compared with the uranium-235 cross section that serves as a standard. A gas-filled fission chamber with plutonium-239 and uranium-235 foils is placed in the neutron beam. Then the number of fission events in the chamber is recorded for each neutron energy interval (the neutron energy is determined by time of flight).

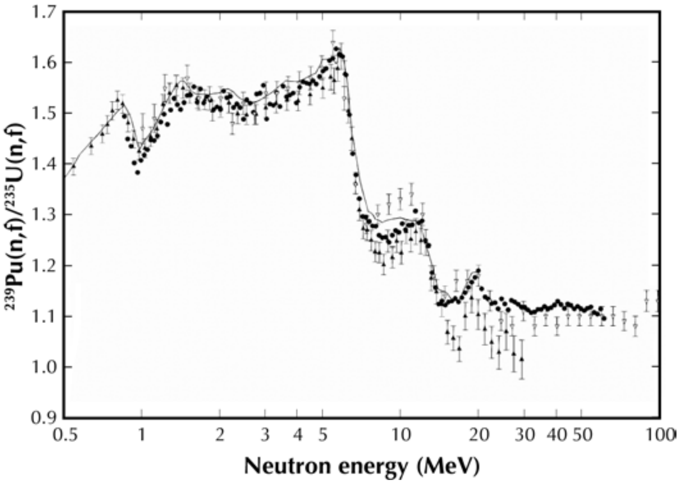
The final values the WNR research team obtained show corrections for several systematic errors. The differences between the previous evaluation of the plutonium-239/uranium-235 fission cross section—the accepted standard in the nuclear science community, which relies on data from the evaluated nuclear data file (ENDF) database—and the data measured at WNR are small, but even these differences have a definite impact on modeling the performance of a fission weapon.



Neutron spectral data (average neutron energy) measured with the FIGARO array compared with a current Los Alamos computer model. The discrepancies at approximately 8 MeV and above 14 MeV demonstrate the need for improved modeling of neutron spectra. BRC stands for Bruyeres Research Center at the Bruyeres-le-Chatel Center of the CEA (the French equivalent of the US DOE).

CROSS SECTIONS

When a neutron encounters a nucleus, many types of interactions can take place, depending on the neutron's energy. Inside fissionable material such as in reactor fuel or a nuclear weapon, a neutron can be absorbed by a nucleus, subsequently emitting a gamma ray; it can scatter, producing a secondary neutron at a lower energy; or it can cause the nucleus to fission (split apart), releasing several more high-energy neutrons. Each one of these reactions has a specific probability that physicists define through the effective area the nucleus presents to the incoming neutron for each type of interaction. The larger the area, the higher the interaction probability. Cross sections are measured in barns (b), a unit of measure equal to 10^{-24} square centimeters. A typical fission cross section will be on the order of several barns for an incoming neutron at an energy of a few million electron volts. The cross section determines the effective area that the neutron "sees" (relating to this reaction) as it approaches the nucleus and subsequently, the reaction probability.



Ratios of measured plutonium-239 fission cross section using a fission chamber in the WNR beam, to that of the uranium-235 cross section, which serves as a standard. The full points are the plutonium-239/uranium-235 ratios from data taken at WNR. The line is an accepted evaluation of previous experimental results in the ENDF database (ENDF/B-VI). The measurements improve the nuclear weapons community's knowledge of the fission cross sections and enable more precise calculations of weapons performance.

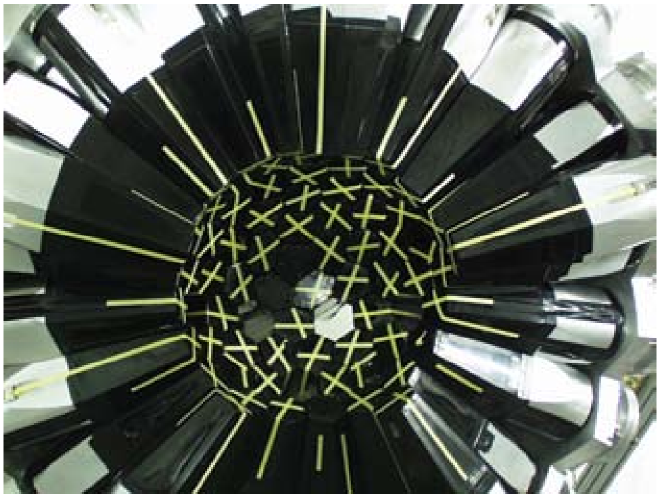
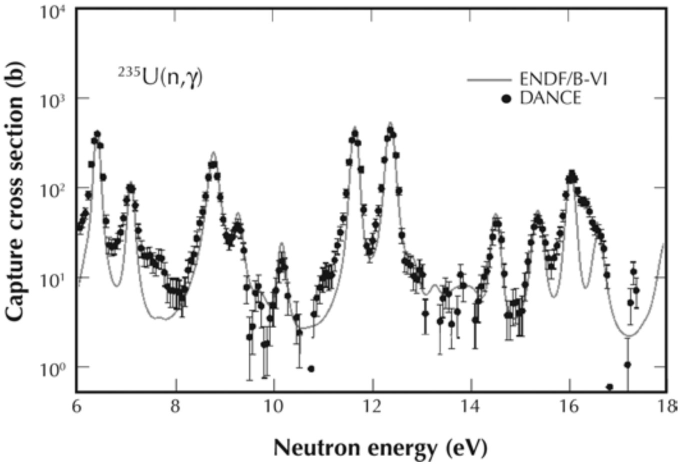


Photo of the DANCE detector system. The DANCE system is used to measure neutron capture cross sections by measuring gamma-ray emissions in a large detector array.



Measurements of capture cross sections of uranium-235 at DANCE compared with a previous evaluation in the ENDF/B-VI database. Accurate measurements of this cross section are required for accurate weapons performance simulations.

Measuring Capture Cross Sections

A complementary, but no less important, factor that determines the performance of a fission weapon is the capture cross section—the probability that a neutron will be captured in the nucleus without producing fission and its associated energy. Los Alamos scientists measure capture cross sections with the Detector for Advanced Neutron Capture Experiments (DANCE), an array that surrounds the target and detects almost all of the gamma rays emitted when a neutron hits the target nucleus. Gamma rays emitted when a nucleus undergoes fission differ when compared with those emitted when a nucleus captures the neutron. This difference enables us to measure the capture cross section.

When our WNR research team superimposed the capture cross section data from a DANCE experimental series over a previous ENDF evaluation, they saw that the results generally agreed. They also saw that the older evaluation in the ENDF database must be modified in specific energy intervals to reflect the more precise measurements obtained with the DANCE detector. Accurate measurements of capture cross sections are required for accurate weapons performance simulations.

Thermonuclear Yield Cross Section

Thermonuclear yield is produced by the fusion of deuterium (a stable isotope of hydrogen) and tritium (a radioactive isotope of hydrogen). Tritium is produced in a thermonuclear weapon by a reaction between a neutron and lithium-6 (one of the stable isotopes of lithium) embedded in the weapon. The production rate of tritium (cross section) in this reaction is crucial in determining the amount of tritium available for fusion, which determines the thermonuclear yield. To date, the nuclear science community does not precisely know this cross section. In the incident-neutron-energy range relevant to weapons physics (a few million electron volts), this cross section is considered to be uncertain by as much as 30%.

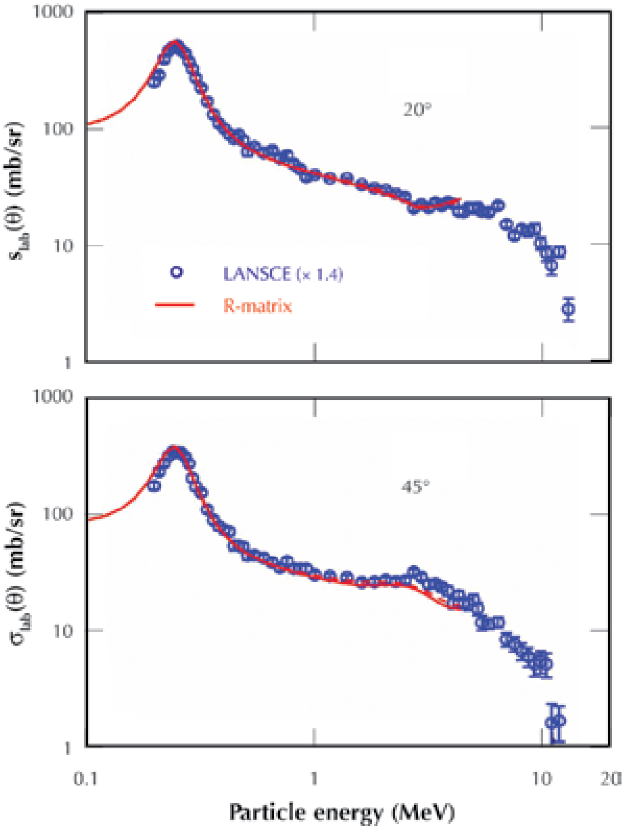
At WNR, LANL scientists completed an experimental series to determine this cross section. Our experiments used a sandwich of silicon detectors to detect both reaction products (tritium particle + alpha particle) using the energy produced in the reaction to identify the reaction as a function of the incident neutron energy. In order to improve nuclear models that predict other important reactions that impact the fusion process, WNR scientists measured the direction of the tritium when it was emitted. Our scientists are currently analyzing these data. The analyses are expected to be complete by the end of FY08. The fact that the model calculations (R matrix) fit our recent WNR experimental data so well gives us confidence about the model's applicability to other reactions and energies that have not been measured but are required for weapons calculations.

Radiochemical Weapons Diagnostics

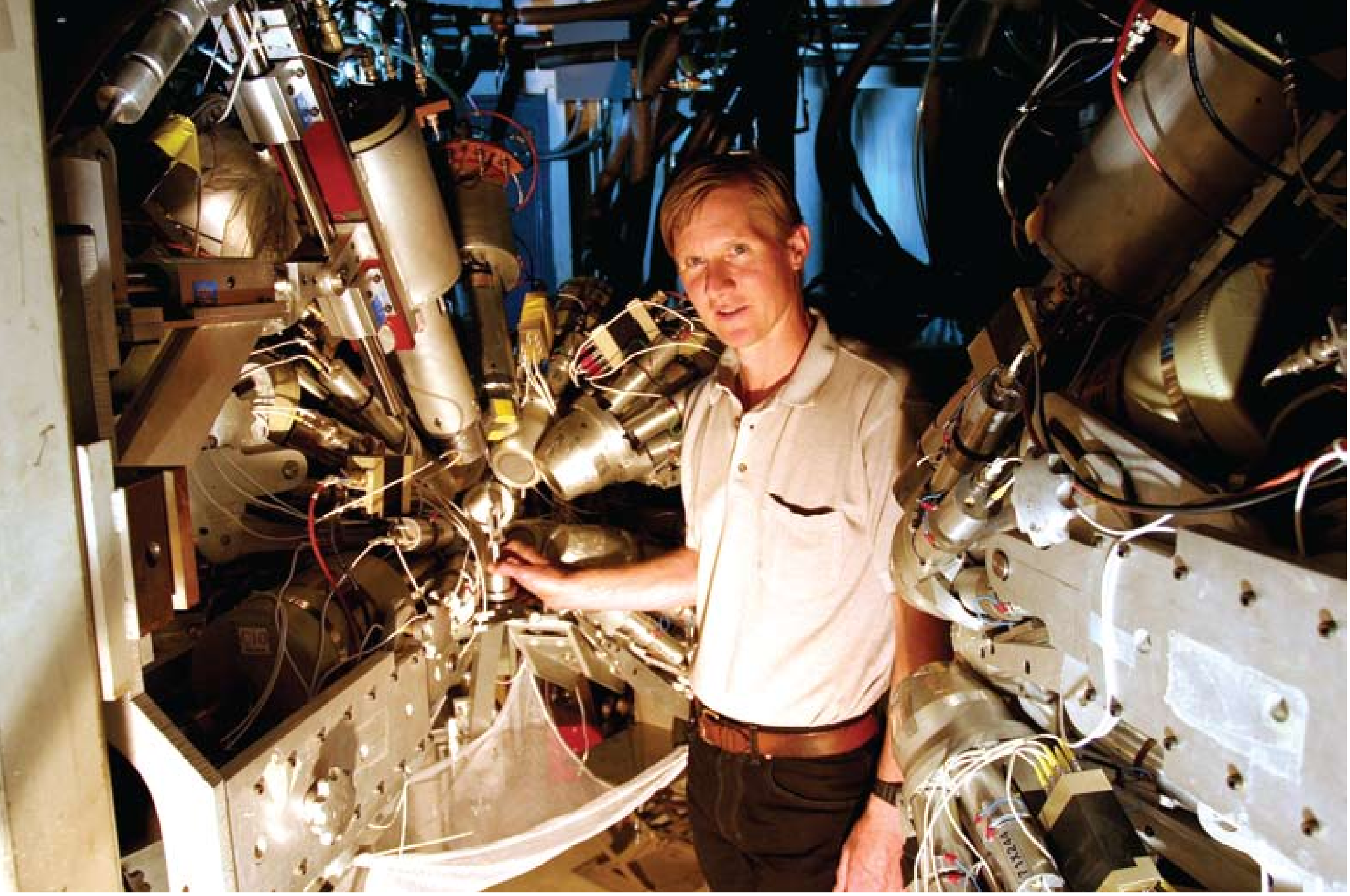
Many past nuclear tests incorporated different isotopes (radiochemical tracers) in components of nuclear weapons to determine the performance parameters at those locations. These tracers serve as weapons diagnostics. If LANL scientists can precisely determine the cross sections for these reactions, we can benchmark weapons calculations by comparing the calculated ratios of these isotopes with the measured ones. In the past, if calculations did not agree with experimental data, it was difficult to determine whether the culprit was a problem in the weapons code or poor-quality nuclear data.

Two dominant types of reactions change the incorporated isotope to one with a higher or lower mass. One reaction is the emission of two neutrons ejected by an initial high-energy neutron. For example, iridium-192 undergoes an n,2n (one neutron in, two neutrons out) reaction and becomes iridium-191. Low-energy neutrons are often captured, e.g., iridium-192 will become iridium-193 with a n,γ (one neutron in, none out, only a gamma-ray is emitted) reaction. The interplay between the various reactions in a nuclear weapon is very complex. At an initial stage of explosion, many high-energy neutrons will convert iridium-192 into iridium-191, but as the neutrons slow down (as a result of collisions with nuclei), the iridium-191 can capture 1–2 neutrons and turn into iridium-192 or iridium-193. To interpret the radiochemical activation results, LANL scientists need to know cross sections (both n,γ and n,2n) of several adjacent, isotopically speaking, iridium isotopes.

LANL researchers performed iridium isotope cross section measurements at the Germanium Array for Neutron-Induced Excitations (GEANIE) detector system at WNR. GEANIE is an array of 26 high-resolution gamma-ray and x-ray detectors that view a sample bombarded with neutrons. Researchers from Los Alamos and Lawrence Livermore National Laboratories collaborated to construct this detector specifically to investigate neutron reactions at the center of a nuclear weapon—reactions that are difficult to study by any other means.



Using a sandwich of silicon detectors at four laboratory angles (two angles, 20° and 45°, are shown here), WNR scientists measured relative triton (nucleus of tritium) differential cross sections (the probability that an emitted tritium particle goes out at a specific angle θ) and compared them with current calculations (red line). LANL WNR experiments measured a total of 650 data points for both tritons and alpha particles at 8 angles. The experiment provides data required for thermonuclear yield calculations.



The GEANIE detector views gamma rays from an encapsulated plutonium-239 sample as it is bombarded with neutrons from the WNR source. GEANIE has also been used for plutonium-239(n,2n) cross-section measurements, a very important weapons diagnostics issue.

Summary

In 1992, US policy dictated that nuclear weapons scientists and designers move from underground testing to computational modeling to predict nuclear weapons performance and certify their reliability. At Los Alamos, our researchers have constructed the most sophisticated high-performance computing resources in the world to model the physics of a nuclear detonation. However, the nuclear weapons community cannot achieve the goals of the Stockpile Stewardship Program without precise (first principles) knowledge of how the materials we use to fabricate nuclear weapon components react to the high-energy conditions they will experience.

Los Alamos scientists, in collaboration with Lawrence Livermore scientists, conceived and built detectors such as FIGARO, DANCE, and GEANIE for use at the high-energy beam line at WNR and have begun to obtain and analyze the resulting data. It is only through the interaction of all three elements of stockpile stewardship—world-class high-performance computing, weapons design advanced simulation computational codes, and first-principles nuclear/materials science research—that the nuclear weapons community can certify to the nation that our nuclear stockpile is reliable.

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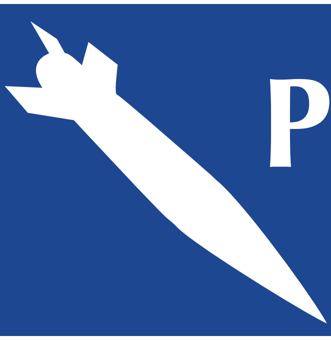


Predicting Nuclear Weapons Effects

Our changing national security environment has shifted nuclear deterrence strategies away from massive retaliation toward potential limited use of nuclear weapons that have specific effects and result in minimal collateral damage. Simultaneously, the rise of rogue nations caused the US to assess, attempt to respond to, and mitigate the effects of potential nuclear devices that might be used on our homeland.

The DoD's 2001 Nuclear Posture Review (NPR) concluded that a strategic posture that relies solely on offensive nuclear forces is inappropriate for deterring potential adversaries. The New Triad, established in the NPR, consists of nuclear and nonnuclear strike capabilities and defenses and a robust, responsive infrastructure supported by enhanced intelligence and adaptive planning capabilities. The New Triad provides a balance of capabilities suited for the emerging threat environment and provides military options that are credible to enemies and reassuring to allies.

The DOE, through the NNSA and in partnership with the DoD, is responsible for ensuring the US has a safe, secure, and reliable nuclear deterrent. NNSA is responsible for transforming the Nuclear Weapons Complex into a responsive infrastructure that supports specific stockpile requirements and maintains the essential US nuclear capabilities needed for an uncertain global future. In addition, the US nuclear deterrent will transition from one that relies on deployed forces to one that relies more heavily on weapons' capabilities.

Nuclear deterrence and homeland security demand high levels of nuclear weapons effects (NWE) expertise and predictive capability. Los Alamos National Laboratory played an important role in the national NWE strategy and is an important participant in efforts to rebuild a strong NWE program.

Our nation's NWE expertise has always been centered in the DoD. Within the DoD, the Defense Threat Reduction Agency (DTRA) and its predecessors have been responsible for NWE research and development of predictive tools. The US Strategic Command (USSTRATCOM) used those predictive tools in military planning.

DOE/NNSA and three of its national laboratories (LANL, Sandia National Laboratories [SNL], and LLNL) also had key roles in the following related areas:

- designing weapons and analyzing output,
- developing high-fidelity computational codes and high-performance computing platforms,
- applying existing expertise to specific NWE issues such as defeat of hard and deeply buried targets, defeat of chemical or biological agents, defeat of electromagnetic pulse (EMP), and fireball dynamics,
- maintaining and employing underground and aboveground experimental test facilities for certification and validation of codes and designs, and
- assessing and verifying the survivability of nuclear and nonnuclear components in hostile and fratricide radiation environments.

Reversing the Trend

During the 1990s, and particularly after the collapse of the Soviet Union, the capability for predicting NWE started to deteriorate within DoD and DOE because the end of the cold war created the misperception that nuclear weapons were no longer needed. With a few exceptions, most of the initiatives to reverse this trend have been unsuccessful.

Among the successful attempts to revitalize the capability for predicting NWE have been those spearheaded by the Nuclear Survivability Steering Group (NSSG), a study by the Defense Science Board (DSB) task force on the NWE national enterprise, and the DOE Advanced Simulation and Computing (ASC) Program. In 2001, a joint panel of NNSA and DoD experts chartered the NSSG. The purpose of the NSSG was to advise the NNSA Assistant Deputy Administrator for Research, Development, and Simulation on high-level matters affecting the Defense Program's ability to ensure the nuclear survivability and lethality of the stockpile and to provide interfaces with customers and stakeholders in the Office of the Secretary of Defense, the armed services, DTRA, and USSTRATCOM.

Since its inception, the NSSG has played a pivotal role in maintaining active communication between the DoD and DOE stakeholders in nuclear survivability and effects. In coordination with the NSSG, Los Alamos, SNL, and LLNL met in 2002 to assess the state of the NWE enterprise and NNSA's future role in that effort. This assessment, coordinated through LANL's Nuclear Survivability Campaign (Campaign 7), determined the need for a program to rejuvenate and steward NWE capabilities and that the three laboratories, in coordination with DTRA and USSTRATCOM, have important roles in this mission. These roles are further strengthened by the emerging needs of homeland security and nuclear deterrence.

The ASC Program allowed the national laboratories to develop, verify, and validate a new suite of advanced simulation tools in the absence of nuclear testing. These simulation tools must run on modern, massively parallel supercomputing platforms and have been extensively validated against existing nuclear data. These tools can create modern baselines of existing systems and can model outputs and effects in new weapons systems. Simulation tools also allow assessment of weapon outputs and environmental effects in the immediate vicinity of a weapon.

In January 2004, the Undersecretary of Defense commissioned the DSB task force on NWE test, evaluation, and simulation to provide a comprehensive evaluation of DoD processes for ensuring successful

DEFINITIONS

agent defeat—Destroying a chemical or biological agent's ability to be used as a weapon.

certification—Certifying that the nuclear weapons in the US stockpile are safe and reliable.

chemical or biological agent—Material that can be weaponized with the goal of having major health effects on large numbers of people.

code validation—Validation demonstrates that a predictive model duplicates experimental data. The reliability and performance of computer models of all stockpile materials must be supported with experimentally validated data and physics models of all stockpile materials at the accuracy required for certification.

fratricide—Unintentionally causing an offensive nuclear weapon to malfunction (thereby preventing its intended performance) as the result of another offensive weapon being detonated nearby.

hard and deeply buried targets—Military facilities (e.g., command and control or weapons storage) installed at depths intended to evade the effects of conventional and/or nuclear attack from the surface. In addition to deep burial, such facilities may also have engineered features designed to absorb shock waves and mitigate their effects.

hostile environment—The region surrounding a nuclear detonation that is caused by an enemy ballistic missile defense. Elevated radiation; strong EMP, shock, and blast effects; and high quantities of explosion-generated debris characterize this region.

nuclear weapon output—Energy in x-rays, gamma radiation, and neutrons produced by a nuclear weapon.

shock loading—Forces and deformation on a target that are produced by passage of shock waves.

survivability—Ability of a nuclear weapon to perform as designed in a hostile environment without significant degradation in reliability.

operation of a nuclear weapon in a hostile nuclear environment. The DSB's 2005 report identified the need for the DoD and the DOE to define and support a national enterprise for NWE modeling, simulation, test, and evaluation. Consequently, DTRA and NNSA signed a memorandum of understanding to coordinate these measures and create the integrated set of capabilities envisioned in the national enterprise model.

Initially, DTRA and NNSA made little progress. As a result, another DSB task force was convened to investigate and evaluate national NWE requirements and identify the modeling and simulation capabilities and the experimental facilities required to support those needs.

NNSA's responsibility is to design, provide, and test nuclear sources for NWE tests. DoD and NNSA share responsibilities for several nuclear weapons issues by means of a memorandum of agreement, including the following.

- Hard and deeply buried target defeat—predict weapon energy transfer into the ground for various devices and penetration depths, propagation of ground shock through complex, heterogeneous geologic media, and response of underground facilities to ground shock.

- Agent defeat—predict thermal and radiation environments in a chemical or biological agent storage facility, container and agent response to those environments, turbulent agent sweep up and mixing within a rising fireball, and the effects of these events on the agent itself.

- Nonideal air blast—predict weapon output into air and propagation of shocks in complex settings (e.g., due to topography or urbanization), particularly for devices at low yield or nonideal height of burst.

- Primary and secondary fire—predict fire ignition and spread from nuclear detonations and resultant collateral damage, particularly in urban settings.

- Dust cloud, fallout—predict transport of bomb and activated target debris to low and high altitudes and the subsequent fallout. Focus on heavily debris-laden plumes, chemical or biological agent-containing plumes, and complex terrain and weather. This prediction includes activation of the surrounding materials, particularly in urban settings.

- High-altitude nuclear effects and EMP—develop high-fidelity capability to predict EMP environments over the full range of EMP time scales at all altitudes and the response of infrastructures to the EMP environment. This capability involves designing specialized warheads and analyzing responses of a variety of targets (e.g., interaction with the Earth's radiation belts) relative to the warhead's design.

In addition to these effects, survivability of nuclear and nonnuclear components is a major activity in NWE studies. Nonnuclear refers to nuclear weapons components outside the nuclear physics package, e.g., arming, firing, and fuzing systems components.

Nuclear deterrence and homeland security demand high levels of nuclear weapons effects expertise and predictive capability.

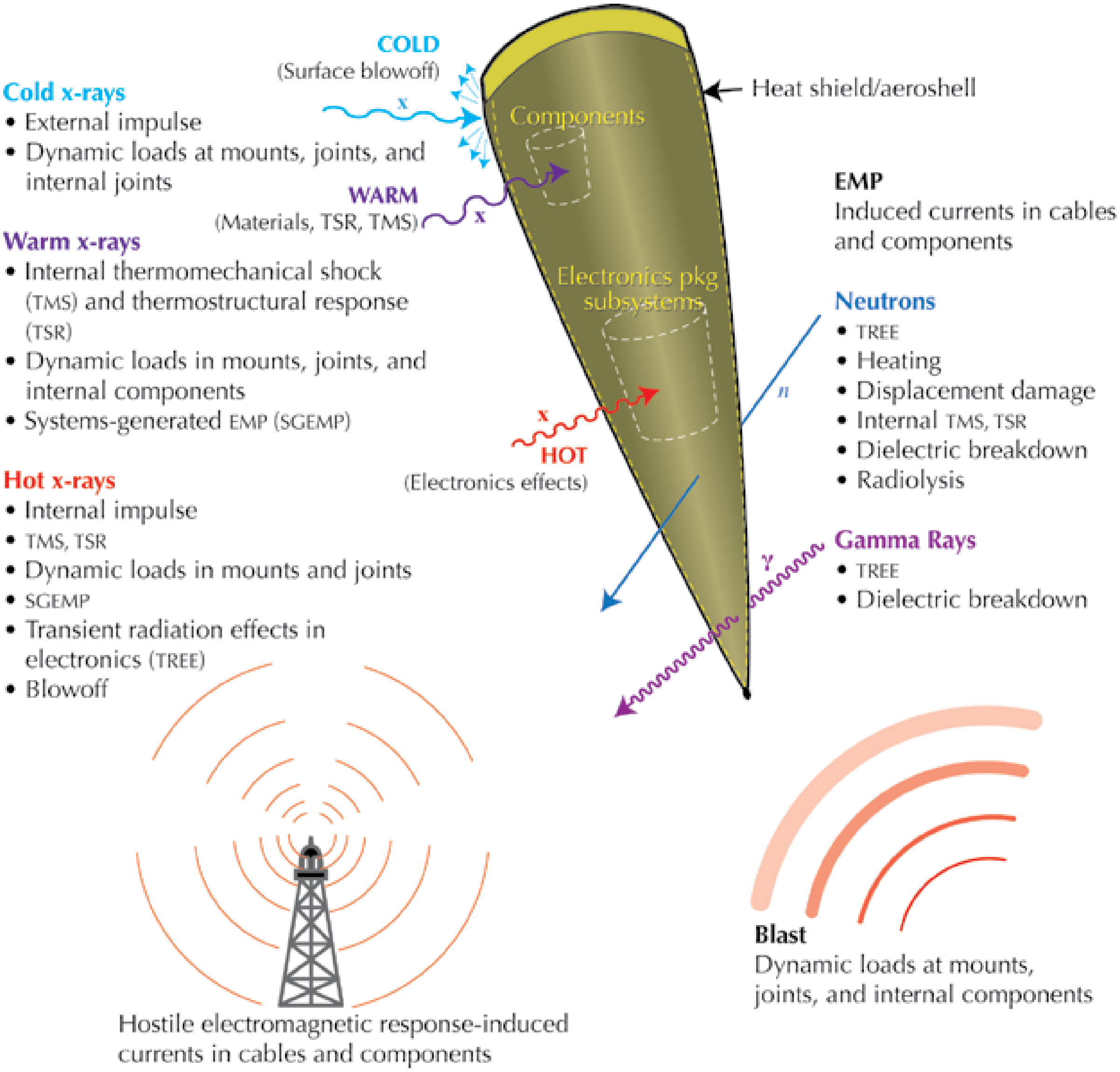
Ensuring Nuclear Survivability

Increased emphasis on stockpile life extension requires reevaluating the role of nuclear survivability within the stockpile surveillance program. New strategies must be developed so that survivability can be monitored and maintained over the lifetimes of weapon systems. These strategies must be consistent with the constraints of the stockpile surveillance program, meet stringent nuclear survivability requirements, and can be supported by existing industrial and/or governmental sources.

The Laboratory's extensive long-term nuclear survivability program ensures the reliable operation of US nuclear weapons, principally submarine- and silo-based strategic missiles. The environments associated with a potential adversary's nuclear-armed ballistic missile defense systems include: nuclear radiation and associated phenomena such as neutrons, x-ray and gamma photons, and blast. These environments can produce fissile material heating, damage to critical components, thermostructural response, external and internal EMP, and acceleration loads. The program's success requires understanding the

- operation and output of nuclear weapons,
- interactions of radiation with individual weapon components and major assemblies, and
- sensitivity to material properties, particularly as they age.

Extending the planned service life of a nuclear weapon in the stockpile (from 15–20 years to many decades) and restricting underground nuclear testing altered certification and verification procedures. The vulnerability and hardening program involves an interactive combination of analysis and simulation experiments, a database of past experiments, and computer analyses. The purpose of this program is to ensure the survivability of components and systems in environments that can impose traumatic effects, typically radiation-induced interactions. The success of this program is contingent upon close cooperation with production plants, aeroshell and reentry systems designers, weapons systems electronics designers, and the military.



General vulnerability phenomena and their effects on the reentry body.

Coordinating with Other NWE Groups

A key factor in resurrecting the nuclear weapon design and effects program is coordination with other organizations that have NWE interests or missions. To this important end, both the NSSG and the DSB task force on the NWE national enterprise must work together. Another important coordinating body is the Weapon Effects Strategic Collaboration (WESC). WESC recently replaced the NWE Users Group that was chartered in 2004 by NNSA, USSTRATCOM, DTRA, and the UK's Atomic Weapons Establishment to prioritize, plan, and conduct technical reviews of NWE work.

WESC has four main tasks:

- assemble a community of NWE managers, users, and developers to share information on technologies, gaps, and plans,
- aggregate and prioritize requirements and identified capabilities defined by the user community,
- recommend accreditation standards for NWE simulation codes and models, and
- coordinate NWE programs.

Five subgroups, each focusing on a specific technical area, provide detailed input to WESC. Los Alamos is represented in each subgroup. NNSA and DTRA are working to coordinate the NWE programs that bring ASC and other resources together. Collaborations with the UK are coordinated through joint working groups. As an example, Los Alamos and DTRA are investigating development of an effective response to urban nuclear threat, including optimized resource allocation and a comprehensive risk management strategy. Using a model-based approach, validated with appropriate testing, this exercise focuses on improving and/or developing models spanning fundamental phenomenology (e.g., weapons output and effects) through systems-level and operations models. A comprehensive risk management strategy will ensure the underlying capabilities are maintained, including the translation from fundamentals to system-level domain to support gaming, exercises, and training as well as the maintenance of expertise with respect to response operations at the military and civilian levels.

NWE is vital to the Laboratory's role in addressing evolving national security issues. Through active planning and coordination with other agencies, the Laboratory promotes an effort that sustains long-term stewardship of NWE capabilities.

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The Radiation Protection Program—Working with Radiation Safely

Los Alamos National Laboratory has fostered many scientific centers of excellence. It is no surprise that the Radiation Protection Program is a center of excellence in the field of health physics given LANL's emphasis on worker safety and its missions in stockpile stewardship, weapons manufacturing, physics research, and numerous other activities that use radioactive materials and radiation generating devices.

Health physics is the science and practice of protecting individuals and populations from the harmful effects of radiation. It also includes studying the effects of ionizing radiation and energy emitted from radioactive materials on humans and their environment. Health physicists recognize that LANL's diverse operations present some intriguing technical challenges and, consequently, some of the most serious radiological safety hazards in the DOE Complex.

Many of the Lab's health physicists work in the Radiation Protection (RP) Division, which focuses on the safety and health of Laboratory workers and visitors. Specifically, the RP Division's mission is to ensure radiological work is conducted safely within requirements established by Occupational Radiation Protection (10 CFR 835) and enforced under the Price-Anderson Amendments Act.

RP Division has 260 professionals dedicated to this mission. Approximately two-thirds of RP workers are deployed to facilities where they provide on-site monitoring and surveillance, hazard assessment and work control, and incident and emergency management. RP Division also has centralized services to

- monitor, measure, and assess radiation doses,
- calibrate, repair, and maintain radiation monitoring instruments,
- report and retain radiation exposure records,
- provide radiological engineering support, and
- develop and deliver training for all LANL radiological workers.

Why is Radiation Hazardous?

The discipline of health physics includes studying the effects of radiation on people. Studies of human populations exposed to radiation, animal studies, and research on tissues and cells have taught us about radiation hazards. This knowledge is captured in national and international standards, which are then incorporated into regulations and requirements for worker, public, and environmental protection.

LANL has the on-site capabilities and expertise to control, manage, and minimize radiological safety hazards.

Although we use radiation in medical diagnosis and treatment (e.g., x-rays or radiation therapy), it can harm people depending on how much radiation, what type, how it is delivered, how quickly it is delivered, the physical and chemical form of radioactive material, and each individual's response to the radiation. Radiation can induce chemical changes and cause damage to cells, tissues, organs, and systems in the body. Detrimental effects of radiation include tumors, leukemia, and cancer. Radiation can harm specific organs (e.g., inducing cataracts); can harm blood, gastrointestinal, or central nervous systems in severe cases; and can modify genetic material, possibly affecting future generations. In most cases, however, it is impossible to determine whether such effects were caused by radiation or some other natural means.

The unit of measure for determining radiation dose on the human body is rem, which takes into account the amount of energy absorbed by human tissue and the biological effects of different types of radiation. We receive approximately 350 mrem/year from natural background (including radon, other terrestrial sources, and cosmic radiation). Severe effects of radiation have been observed only at relatively high radiation doses (100s of rem). Of course, regulatory dose limits are set far below levels at which any detrimental effects have been observed. The established dose limit for radiological workers is 5000 mrem/year (5 rem), and the dose limit to general employees and members of the public is 100 mrem/year.

Although we don't know whether radiation is harmful at low doses, for safety's sake we assume that any dose is detrimental. Therefore, we control doses to levels that are as low as reasonably achievable (ALARA). DOE facilities must maintain an ALARA program and apply ALARA principles when managing radiation doses. ALARA principles require that there must be a commensurate benefit from any dose incurred (e.g., the benefit the nation receives from having medical isotopes developed must be worth the risk of having some workers receive a small radiation dose). Similarly, the diagnostic benefit gained from a typical chest x-ray is generally worth the risk of receiving a 10-mrem radiation dose. ALARA principles also require that radiation doses be kept as far below the established limits as practicable and that they be managed, measured, and tracked closely.

Most radiation doses incurred by LANL workers are anticipated, planned, and controlled, but events involving radiation and unplanned exposures do occur. Fortunately, the instances of workers receiving high doses are very rare. LANL maintains appropriate emergency response capabilities and participates in aggressive investigation, causal analysis, corrective action, and reporting to learn lessons from such events and to prevent recurrence.

Controlling Radiation Hazards

When determining the appropriate controls to put into place, radiation protection professionals must consider

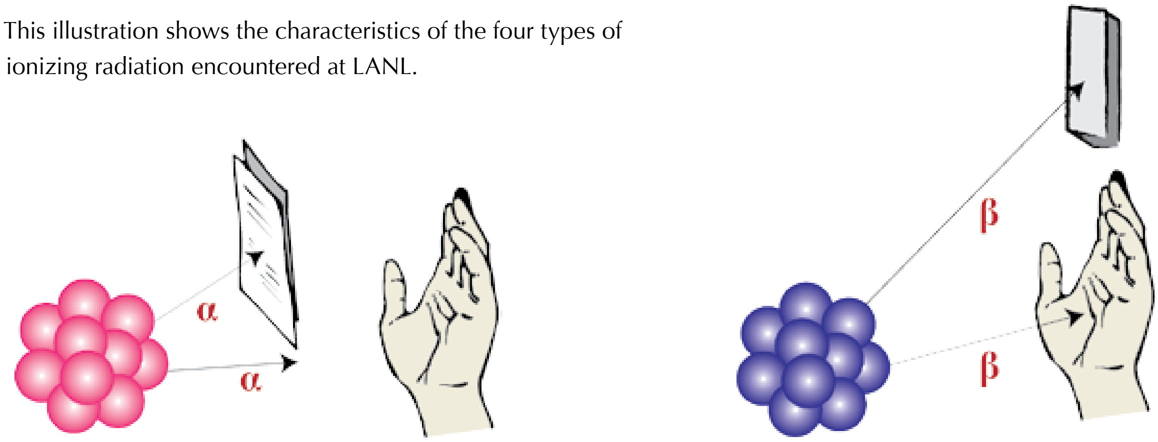
RADIOLOGICAL OPERATIONS

LANL operations encompass 20 active nuclear facilities and more than 170 buildings with radiological hazards. The Laboratory also has inactive radiological facilities and sites that contain legacy radiological contamination and are being prepared for decontamination and decommissioning (D&D).

Current radiological activities include:

- research, development, production, and testing associated with nuclear weapons,
- radiochemistry and metallurgy with radioactive materials,
- fabrication of radioisotope thermoelectric generators and heat sources,
- accelerator-based nuclear physics research and applied technologies,
- activation product and mixed fission production and analysis, including hot cell work,
- materials science and testing involving radioactive materials and accelerators,
- dynamic testing with radioactive materials,
- tritium research and applications,
- applications of x-ray devices, other radiation generating devices, and radioactive sealed sources,
- biomedical research using radiotracers and irradiators,
- nuclear criticality experiments,
- research, development, and applications in support of nuclear fuels,
- work in support of nonproliferation, counterterrorism, and homeland security,
- on-site and off-site emergency response,
- transportation of radioactive material,
- liquid and solid radioactive and mixed-waste treatment and storage,
- D&D of facilities and sites,
- environmental restoration, and
- miscellaneous research, development, testing, or operations involving ionizing radiation and/or radioactive materials.

This illustration shows the characteristics of the four types of ionizing radiation encountered at LANL.



Alpha particles
- Range—short
- Shield—paper
- Penetration—negligible
- External hazard—none

Beta particles
- Range—medium
- Shield—aluminum, glass
- Penetration—moderate
- External hazard—skin, eyes

ALARA principles and whether the potential exposure is from external or internal sources. Typically, external radiation hazards are present with radioactive materials or radiation generating devices (e.g., x-ray machines) that emit penetrating radiation. Photon (gamma rays and x-rays) and neutron radiation can penetrate and harm the entire body. Beta radiation is considered low penetrating and can cause damage to the skin or lens of the eye. External radiation is typically controlled by minimizing time of exposure, maximizing the distance from the source, and using shielding to reduce exposure rates. Work at the Los Alamos Neutron Science Center (LANSCE), for example, generally results in external radiation hazards.

Radiation can also cause harm from internal sources. Radioactive materials can be taken into the body through inhalation, ingestion, absorption through skin, or directly through a wound. Alpha emitters (plutonium and transuranic nuclides) are generally the most harmful internal radiation hazards, often collecting in specific organs/systems and causing localized damage. Internal radiation hazards are controlled by preventing radiation from entering the body through the use of engineered controls and personal protective equipment (PPE).

HOW DO WE MEASURE DOSE?

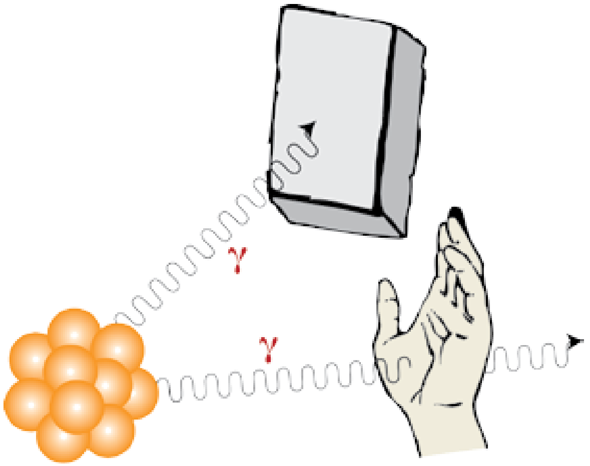
LANL workers can be exposed to occupational radiation hazards in two primary ways: external sources of radiation and radioactive materials taken into the body. One of our unique challenges is measuring radiation dose using dosimetry.

External dosimetry uses dosimeter badges to estimate radiation dose to the whole body, skin, lens of the eye, and extremities from external sources. The Health Physics Measurements Group issues dosimeter badges to individuals who access radiological areas or perform radiological work. Dosimeters are returned regularly for analysis.

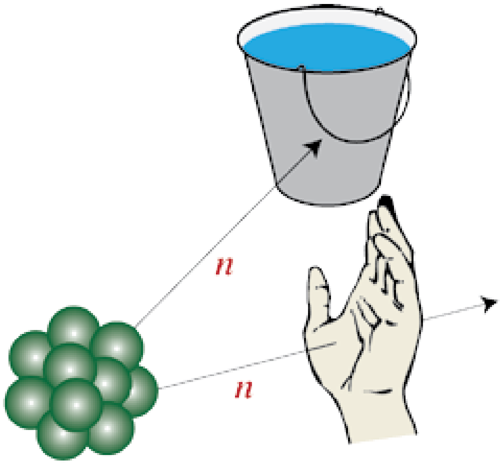
Different types of dosimeters are required for LANL's diverse external radiation hazards.

Internal dosimetry is the direct measurement of radioactive materials in the body (in vivo) or the analysis of excreta (in vitro or bioassay) to estimate dose to the whole body and specific organs from internal sources.

An in vivo measurement is a whole body or chest count that directly measures radioactivity in the body with specialized equipment. In vivo results are analyzed to determine the nuclide and amount of radioactive material in the body.



Photons (gamma rays & x-rays)
- Range—long
- Shield—lead
- Penetration—high
- External hazard—whole body



Neutrons
- Range—long
- Shield—water, cement
- Penetration—high
- External hazard—whole body

Two Radiological Control Challenges: LANSCE and the Plutonium Facility

Each type of radiological material and activity has a unique set of hazards. LANL addresses these hazards with facilities, controls, and programs to ensure the safety of the worker, the public, and the environment. The Radiation Protection Program maintains the capabilities, functions, systems, and expertise to meet this broad spectrum of radiological control challenges.

For example, the LANSCE accelerator, associated facilities, and other energetic radiation generating devices require a full suite of unique health physics capabilities and controls. Because of the relatively high external dose rates and the high-energy radiation, these facilities require robust engineered controls (e.g., shielding and interlock systems), formal access control procedures, unique instrumentation (to detect x-rays and pulsed radiation fields), and specialized external dosimetry. Controls associated with normal operations prevent significant worker dose. Off-normal operations, maintenance on the accelerator or targets, and handling materials that have been in the accelerator beam have the potential to deliver significant worker doses.

In vitro measurements involve the worker providing bioassay samples (typically urine or feces), which are analyzed using methods customized for the radionuclide. The Health Physics Measurement Group estimates the amount of material taken into the body and the resultant dose based on physiological models that depend upon the radionuclide, physical form, and individual factors.

Wound counting quantifies the intake of radioactive material that may be absorbed directly into the bloodstream through a wound.

Both external and internal dosimetry are prescribed for an individual based on the type and number of radiation hazards expected for the area and the type of work, as detailed in facility-specific dosimetry matrices. Dose assessment can be complex and require several measurements over time to confirm and assign a dose. The resulting worker dose becomes an official record and is reported to the worker and DOE annually.

Workers wearing PPE conduct a drum-out operation at a LANL nuclear facility. A drum-out involves removing contaminated items from a glovebox and placing them into a drum using special equipment and techniques to avoid spreading contamination. The headphones worn by the radiological control technician are for the purpose of monitoring the response from an instrument that detects contamination.

The radionuclides produced at LANSCE are used for medical and other research purposes. They must be retrieved, packaged, and handled at another LANL facility for shipment to medical facilities. These activities and others dealing with mixed-fission products require a different suite of controls, including real-time dosimetry, special handling equipment and facilities (remote handling and hot cells), and a comprehensive and aggressive ALARA program that includes work planning, limits on the amount of time a worker can be exposed, and dose tracking. Moreover, these activities require unique health physics expertise in the areas of high-energy dosimetry, instrumentation, and shielding; management and control of a full spectrum of highly radioactive nuclides; and work management in high-radiation fields.

The Plutonium Facility handles plutonium and other transuranic nuclides. Because these nuclides pose significant internal hazards, there is great emphasis on controlling radiological materials using confinement (e.g., fume hoods), containment (e.g., gloveboxes, glovebags, and packaging), ventilation, PPE (e.g., anticontamination clothing and respiratory protection), and a comprehensive contamination control program (monitoring for airborne radioactivity and surface contamination on equipment, areas, and people).

Activities involving plutonium or other transuranic nuclides can also pose an external radiation hazard, requiring a corresponding suite of controls that enable the work. Such controls include shielding in many forms, remote handling, and automation. Unique health physics expertise is required in the areas of instrumentation and internal dosimetry capable of measuring alpha emitters, design and application of engineered controls, and air monitoring and contamination control.

Can We Work with Radiation Safely?

The answer is yes. LANL has the on-site capabilities and expertise to control, manage, and minimize radiological safety hazards. Radiation safety concepts, policies, procedures, and training are deeply ingrained in the Laboratory's radiological workers. LANL maintains programs to meet all radiation protection needs, and management is committed to supporting these programs and implementing radiation protection requirements. Although radiological workers incur some risk, overall the Laboratory works safely with radiation as a necessary part of executing critical national security missions.

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Backward Glance

The S-Site Burning Grounds

Los Alamos Scientific Laboratory's Group GMX-3, which had the mission of developing high explosives (HE) systems, operated S-Site from approximately 1948 to 1972. At S-Site, workers fabricated HE to required shapes by casting, pressing, or machining.

Residue from casting or machining, portions cut off from pressings, and pieces that were unsound, damaged, or defective because of operator error became scrap HE. In destructive testing, performed for reasons such as safety tests or mechanical tests, pieces of explosives were not detonated but broken up, crushed, or made useless in another way. Where operations such as casting and destructive testing were performed, 32-gallon galvanized iron or steel garbage cans were designated as HE scrap cans. A trained scrap disposal crew removed the cans or their contents, took the scrap HE to the burning grounds, and disposed of the scrap by burning.

The burning grounds were located well away from any operating buildings. Two types of facilities were located at the burning grounds—three filter beds with their basket-washing building and three burning pads (also known as burning slabs). Both the filter beds and the burning pads were used for disposal of scrap HE.

Many S-Site buildings where HE was fabricated were equipped with inside drains that fed through the wall into concrete sumps that contained filter baskets. The baskets collected the HE scrap that a stream of water washed down to the sumps.

The HE scrap disposal crew removed wet filter baskets from the sumps and placed them onto a specially equipped truck. The truck had a hydraulic lift on the back and a watertight bed covered with steel plate that was carefully welded so that HE could not lodge in the crevices. Workers drove the truck to the basket-washing building, where they inverted the baskets over a concrete basin and then washed out the remaining HE. The basin connected to a diverter that could be arranged to feed any one of three open channels that led to each of the three filter beds. The flow of water carried HE waste to a filter bed, a concrete basin lined with firebrick and filled with sand. Water-borne waste filtered through the sand and left the HE waste on the surface.

The natural process of evaporation and use of waterproof electric-heating elements in the sand reduced the water content in the waste HE until it would readily burn. Workers ignited the HE in the filter bed by pouring a very small amount of gasoline on scrap paper and then initiating an electrical squib (ignition device) from the basket-washing building. The disposal crew loaded any unburned HE residue from the filter beds into HE scrap cans, transported the cans to the one of the burning pads, and then reburned the residue with scrap HE.

The three burning pads were fenced, cleared squares of land 100 ft on a side with a rectangular gravel-covered pad of approximately 40 ft × 60 ft within each square. Land around each burning pad was cleared of trees and vegetation to a distance of 200 ft or more to prevent accidental fires. The disposal crew unloaded scrap HE from the truck, spread it on the gravel pad, and built a burning train 4-ft to 6-ft long of selected HE chunks. At the end of the train farthest away from the HE to be burned, a pile of scrap paper was stacked and wet with a small amount of gasoline. Personnel, protected by a barricade and at a safe distance, fired a squib that ignited the paper and the HE.

After the bulk of the HE burned and only a very small fire remained, the HE disposal crew would leave and return later to make sure the burn was complete. The scrap disposal process ended after the crew washed the truck and the empty scrap cans.

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