OVERVIEW

Nuclear survivability is the ability of personnel, equipment, and systems to survive the effects of a nuclear detonation, including: blast, thermal radiation, initial nuclear radiation, and electromagnetic pulse (EMP). Effective nuclear survivability requires sustained attention throughout the entire life of a nuclear weapon. Also, where an adversary might employ nuclear weapons, U.S. general purpose forces may need to survive and operate through resulting environments and effects in order to meet operational goals. Their ability to do so enhances deterrence by mitigating the advantages of nuclear use and enables DoD to fulfill its missions in the event that deterrence fails. This chapter provides a foundational understanding of elements contributing to nuclear survivability.

GOVERNANCE

The DoD nuclear weapons survivability policy for mission critical systems is established in Department of Defense Instruction (DoDI) 3150.09, The Chemical, Biological, Radiological, and Nuclear (CBRN) Survivability Policy. The policy establishes the CBRN Survivability Oversight Group (CSOG), which is chaired by the Assistant Secretary of Defense for Nuclear, Chemical, and Biological Defense Programs (ASD(NCB)). The Group’s responsibilities include:

- reviewing and monitoring the execution of DoD-CBRN survivability policy;

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1 DoDI 3150.09 was first issued in September 2008 and subsequently updated in 2015; the current version is Change 2, published on August 31, 2018.
ensuring CBRN survivability receives proper emphasis during the development of the defense planning guidance and in the acquisition process during a system’s requirements definition phase consistent with the CBRN threat;

referring recommendations for action to the Under Secretary of Defense for Acquisition and Sustainment (USD(A&S)) or others; and

conducting other responsibilities as outlined in the instruction.

DoDI 3150.09 also establishes the mission-critical system (MCS) designation and mission critical report (MCR) process for DoD systems. It is DoD policy that the MCS components of the force are equipped to survive and operate in chemical, biological, radiological and nuclear (CBRN) environments as a deterrent to adversary use of weapons of mass destruction against the United States, its allies, and interests. The ability of the force to operate in these environments must be known and assessed on a regular basis and MCS must survive and operate in CBRN environments.

The process for reporting those systems is run by the Office of the ASD(NCB). The MCRs identify the mission-critical systems of the Military Departments, Missile Defense Agency (MDA), and the CBRN environments, and assess the current survivability status of their CBRN MCS. Once all the reports are complete, the Military Departments and the MDA review all CBRN MCRs for gaps and limitations in the CBRN survivability of the systems and infrastructure upon which the Military Departments and the MDA rely, and provide a summary of the review to the ASD(NCB). After the MCRs and summary reviews are complete, the Combatant Commanders (CCDRs) review for adequacy in supporting the Combatant Command’s (CCMD) operational, contingency, and other plans, which may require operations in CBRN environments. The Joint Staff reviews the CCDRs’ assessments and provides: (1) an assessment to the ASD(NCB) on the posture of DoD to operate successfully in CBRN environments; and (2) written guidance, if necessary, to the Military Departments and the MDA on which systems should be added to the MCRs.

**STRATEGIC RADIATION-HARDENED ELECTRONICS**

Strategic radiation-hardened (SRH) electronics technology involves components manufactured to allow exceptional resilience to high levels of radiation. SRH electronics are critical to the execution of strategic military systems that must operate in weapon-induced radiation environments.

The overall market for SRH electronics is small compared with that of non-hardened electronics. While commercial space satellites use electronics hardened to the natural space environment, DoD and DOE are the principal customers for electronics required to meet higher levels of radiation associated with man-made radiation environments. Therefore, it is imperative that trusted and assured SRH electronics and technologies that meet the stringent requirements for DoD and DOE use are readily available and accessible.

**STRATEGIC RADIATION-HARDENED ELECTRONICS COUNCIL**

The Strategic Radiation-Hardened Electronics Council (SRHEC) was established to ensure continued U.S. Government (USG) access to SRH electronics. In addition, the SRHEC addresses space-related, radiation-hardened electronics in the event issues arise requiring the support of the Council.
The Council consists of two Council Chairs, Deputy Assistant Secretary of Defense for Nuclear Matters (DASD(NM)) and Principal Director for Microelectronics in OUSD(R&E); an Executive Secretariat (Council-selected), a Technical Execution Lead, Naval Surface Warfare Center (NSWC) Crane; and Council Members from across the USG with equities in SRH electronics.

The SRHEC, via its Executive Secretariat and Technical Execution Lead, conducts periodic, DoD-wide assessments of program needs and requirements for SRH electronics.

NUCLEAR WEAPON EFFECTS SURVIVABILITY AND NUCLEAR WEAPON SYSTEM SURVIVABILITY

Nuclear weapons survivability is comprised of two distinct and overlaying principles—nuclear weapon effects survivability and nuclear weapon system survivability. Nuclear weapon effects survivability applies to the ability of personnel and equipment to withstand the effects of a nuclear detonation; this includes, but is not limited to, the survivability of nuclear weapon systems.

Nuclear weapon system survivability is the ability of U.S. nuclear deterrent forces to survive the entire threat spectrum that includes, but is not limited to, nuclear weapon effects. The range of potential threats include:

- conventional and electronic weaponry;
- nuclear, biological, and chemical weapons;
- advanced technology weapons, such as high-power microwaves and radio frequency weapons;
- cyber attacks;
- terrorism or sabotage; and
- initial and persistent effects of a nuclear detonation.

See Figure 9.1 for a summary of the differences between nuclear weapon effects and nuclear weapon system survivability. An overlap occurs when the threat to the survivability of a nuclear weapon system is a nuclear detonation and associated effects.

Figure 9.2 illustrates the intersection between nuclear effects survivability and system survivability.
NUCLEAR HARDNESS

Nuclear hardness describes the ability of a system to withstand the effects of a nuclear detonation and to avoid internal malfunction or performance degradation. Hardness measures the ability of a system’s hardware to withstand physical effects such as overpressure, peak velocities, absorbed energy, and electrical stress.

Reduction in hardware vulnerability can be achieved through a variety of established design specifications or through the selection of components. (This chapter does not address residual nuclear weapon effects such as fallout, nor does it discuss nuclear contamination survivability.2)

NUCLEAR WEAPON EFFECTS SURVIVABILITY

Each of the primary (e.g., blast, thermal, and prompt radiation) and secondary (e.g., delayed radiation) environments produced by a nuclear detonation cause a unique set of mechanical and electrical effects. Some effects are permanent while others are transient; however, both can cause system malfunction, system failure, or loss of combat capability.

Nuclear Weapon Effects on Military Systems

The nuclear environments and effects that may threaten the survivability of a military system vary with the altitude of the explosion. The dominant nuclear environment refers to the effects that set the survival range between the target and the explosion.3 Low-altitude, near-surface, and surface bursts damage most ground targets within the damage radii, which is principally a function of the yield of the weapon. Also, high-altitude bursts can produce high-altitude electromagnetic pulse (HEMP) effects over a large area that may damage equipment containing vulnerable electronics on the ground and in the air.

Figure 9.3 illustrates the dominant nuclear environments that drive survivability requirements for typical military systems as a function of height of burst (HOB) ranging from exoatmospheric to sub-surface.

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3 The survival range measures the distance from the detonation necessary to survive nuclear weapon effects.
Nuclear weapon-generated X-rays are the primary exoatmospheric threat to military systems. Neutron and gamma-ray effects also create serious problems for these systems but do not drive survivability requirements. At lower altitudes, neutron and gamma-ray effects dominate because the air absorbs most of the X-ray energy. As a result, air-blast and thermal radiation effects usually dominate the survival of systems at or near the surface. However, neutrons, gamma rays, and source-region EMP (SREMP) may also create problems for structurally hard systems that are near the detonation.

SREMP is produced by a nuclear burst within several hundred meters of the Earth’s surface and is localized out to a distance of three to five kilometers from the burst. SREMP can couple into electrical power lines and other long conductors leading to potential damage beyond the localized SREMP field. The final result of the detonation-generated EMP is a tremendous surge of low-frequency electric fields that can couple into a system through designed and unintended antennas, generating a flow of electrical current that overloads and destroys electrical components and renders the equipment nonoperational.

Underwater shock and ground shock are usually the dominant nuclear weapon effects for submerged submarines and buried facilities, respectively. HEMP is the dominant threat for surface-based systems located outside the target zone such as command, control, communications, computers, and intelligence (C4I) facilities or sophisticated electronics associated with ground-based defense systems and equipment.

Survivability requirements vary with the system type, mission, operating environment, and threat. For example, the X-ray, gamma-ray, and neutron survivability levels used for satellites are lower than the survivability levels used for missiles, reentry vehicles (RVs), or reentry bodies (RBs). Satellite levels are usually set so that a single nuclear weapon, detonated in the region containing several satellites, does not damage or destroy more than one satellite. The levels used for RVs, however, are very high because the RV or
RB is the most likely component of an intercontinental ballistic missile (ICBM) or a submarine-launched ballistic missile (SLBM) to be attacked by a nuclear weapon at close range.

For a system within the Earth’s atmosphere, the survivability criteria are different. Systems operating at lower altitudes do not have to consider X-ray effects because the range of damaging X-ray effects is typically contained inside the range for the more dominant thermal and blast effects. Outside the range for damaging blast effects, gamma rays and neutrons generally set the survival range for most systems operating at lower altitudes. The survival ranges associated with gamma rays and neutrons are generally extreme compared to air blast and thermal radiation. Two of the most challenging problems in this region are prompt gamma ray effects on electronics, which disrupt or damage sensitive electronics, and the total radiation dose delivered to personnel and electronics.

Between an altitude of 10 kilometers and the Earth’s surface, there is a transition region in which the denser air begins to absorb more of the ionizing radiation resulting in a dominant air-blast environment. Aircraft in this region have to survive combined air-blast, thermal radiation, and nuclear radiation effects.

On the Earth’s surface, air blast and thermal radiation are the dominant nuclear weapon effects for personnel who must be at a safe distance from the range of these two effects in order to survive. As a result, air blast and thermal radiation typically set the safe distance, or survival range requirements for most systems for nuclear weapons with yields exceeding 10 kilotons (kt).

This is not necessarily true for blast-hardened systems such as battle tanks or hardened facilities designed to survive closer nuclear detonations. The very high levels of ionizing radiation associated with a nuclear detonation usually require systems to be at greater distances from the detonation to avoid personnel casualties and damage to electronic equipment. This is especially true for lower yield weapons, where the effects of radiation can be dominant compared to the air blast. For example, a battle tank survives at a distance of less than half of a kilometer from a 10-kt explosion if the only consideration is structural damage to the tank. However, at the same distance ionizing radiation from the detonation may significantly affect the crew and the tank’s electronics.

Because line-of-sight (LOS) thermal effects are easily attenuated by intervening material (e.g., buildings or trees) and have a large variation of effect on the target, they are harder to predict. Traditionally, thermal effects were not taken into consideration when targeting. Advanced computer modeling and simulation of thermal effects are now at a state of maturity that they can be used to assess effects on buildings, personnel, and equipment to first order. Estimates of ignition probability (the likelihood of fire) for buildings in urban environments can also be used to provide higher fidelity estimates of damage and casualties.

**Nuclear Weapon Effects on Personnel**

Several nuclear weapon effects are a threat to personnel. The flash from a nuclear weapon can cause temporary blindness to unprotected eyes, even when not looking directly at the detonation. Thermal radiation can cause burns directly to the skin or can ignite clothing, but only via direct LOS exposure. Initial nuclear radiation (gamma rays and neutrons) can cause an acute dose of ionizing radiation leading to degraded performance, radiation sickness, and death. Residual radiation can cause significant exposure for days to weeks after the detonation. The blast wave can cause immediate casualties to exposed personnel or could damage vehicles.
EMP does not cause injuries directly but can cause casualties indirectly (e.g., via the instantaneous destruction of electronics in an aircraft in flight).

Concepts regarding effects survivability for populated systems must consider the effect of a temporary loss of the “person-in-the-loop” and, therefore, devise ways of overcoming the problem. Hardened structures provide increased personnel protection against nuclear weapon effects. As a rule of thumb, survivability criteria for populated systems are based on the ability of 50 percent of the crew to survive the nuclear event and complete the mission; therefore the equipment should be at least as survivable as the crew, and often more survivable than the crew, depending on mission and overall survivability strategy.

**Nuclear Weapon Effects Survivability Measures**

Increased nuclear weapon effects survivability may be accomplished by timely resupply, redundancy, mitigation techniques (to include operational techniques), and hardening. Because these survivability measures can increase the cost and complexity of a system and support equipment, it is often necessary to consider trade-offs in design and acquisition strategies. However unlikely, it is also important to evaluate the potential consequences of a nuclear attack and adequately mitigate foreseeable risks.

*Timely resupply* is the fielding and positioning of extra systems or spares in the theater of operation that can be used for timely replacement of equipment lost to nuclear weapon effects.

*Redundancy* is the incorporation of extra components into a system or piece of equipment, or the provision of alternate methods to accomplish a function so if one fails, another is available.

*Mitigation techniques* are methods used to reduce the vulnerability of military systems to nuclear weapon effects. These may include, but are not limited to:

- **Avoidance** is the incorporation of measures to eliminate detection and attack. Avoidance techniques are very diverse. For example, avoidance may include stealth tactics that use signal reduction or camouflage.

- **Active defense** is radar-jamming or missile defense systems. Active defense can be used to enhance a system’s nuclear weapon effects survivability by destroying incoming nuclear weapons or causing them to detonate outside the susceptible area of the protected system.

- **Deception** is the employment of measures to mislead the enemy regarding the actual system location. These measures include decoys, chaff, aerosols, and other ways to draw fire away from the target. The effect of deception on production depends on the approach.

- **Hardening** is the employment of any design or manufacturing technique that increases the ability of an item to survive the effects of a nuclear environment. Systems can be nuclear hardened to survive prompt nuclear weapon effects, including blast, thermal radiation, nuclear radiation, EMP, and in some cases, transient radiation effects on electronics (TREE). Hardening mechanisms include shielding, robust structural designs, electronic circumvention, electrical filtering, and vertical shock mounting.

Mechanical and structural hardening consists of using robust designs, protective enclosures, protective coatings, and the proper selection of materials. Electronics and electrical effects hardening involve using the
proper components, special protection devices, circumvention circuits, and selective shielding. Nuclear weapon effects on personnel are minimized by avoidance, radiation shielding protection, and automatic recovery measures. The automatic recovery measures compensate for the temporary loss of the “person-in-the-loop” and mitigate the loss of military function and the degradation of mission accomplishment.

Trade-off analyses are conducted during the acquisition process of a system to determine the method, or combination of methods, most suitable for nuclear weapon effects survivability. The impact of the approach on system cost, performance, reliability, maintainability, productivity, logistics support, and other requirements is examined to ensure maximum operational effectiveness consistent with program constraints.

The nuclear weapon effects survivability of a system can be enhanced when critical elements of the system are reinforced by selecting and integrating technologies that are inherently harder. Threat effect tolerance is the intrinsic ability of a component or piece of equipment to survive some level of exposure to nuclear weapons effects. The exposure levels that equipment can tolerate depends primarily on the technologies it employs and how it is designed.

**NUCLEAR WEAPON SYSTEM SURVIVABILITY**

Nuclear weapon system survivability refers to the ability of a nuclear weapon system to withstand exposure to a full spectrum of threats without suffering a loss of ability to accomplish its mission. Nuclear weapon system survivability applies to a nuclear weapon system in its entirety—all mission-essential assets, the nuclear weapon, and delivery vehicle and platform as well as associated support systems, equipment, facilities, and personnel. Included in a system survivability approach is the survivability of the delivery vehicle, personnel operating the nuclear weapon system, supporting command and control links, and supporting logistical elements.

System survivability drives whether nuclear weapons and forces are non-dispersed, dispersing, or already dispersed. The capability to survive in all states of dispersal enhances both the deterrent value and the potential military utility of U.S. nuclear forces.

**Nuclear Force Survivability**

DoDI 3150.09 establishes policy and procedures for ensuring the survivability of CBRN MCS, which includes all U.S. strategic and tactical nuclear forces, and many U.S. general purpose forces, in CBRN environments.

It is often difficult to separate measures to enhance survivability from those that provide security. Therefore, in addition to the instruction governing survivability (DoDI 3150.09), DoD Directive (DoDD) 5210.41, *Security Policy for Protecting Nuclear Weapons* and its corresponding manual, DoD S-5210.41-M, govern nuclear force security.

For instance, in hostile environments, hardened nuclear weapon containers as well as hardened weapon transport vehicles provide security and enhance survivability during transit. Many of the measures to enhance nuclear weapon system survivability and protect against the effects of nuclear weapons can be the same. Hardening and redundancy, for example as well as threat tolerant designs, resupply, and mitigation techniques apply to both.
Nuclear Command and Control Survivability

Nuclear weapon systems include the nuclear weapons and the associated nuclear command and control. The security and survivability of weapons systems command and control is addressed in DoDI 3150.09, DoDD 5210.41, DoD 5210.41-M, and DoDD S-5210.81, United States Nuclear Weapons Command and Control. These documents establish policy and assign responsibilities and state that the command and control of nuclear weapons shall be ensured through a fully survivable and enduring Nuclear Command and Control System. DoD supports and maintains survivable and enduring facilities for the President and other officials to perform essential nuclear command and control (NC2) functions. The USD(A&S), in conjunction with the Military Departments, establishes survivability criteria for related nuclear weapon equipment. See Chapter 2: Nuclear Weapons Employment Policy, Planning, and NC3 for more information on Nuclear Command and Control.

Missile Silos

The survivability of ICBM silos is achieved through the physical hardening of the silos and through their underground location, which protects against air-blast effects. The geographical dispersal of the missile fields also adds to system survivability by complicating any adversary targeting calculations.

Containers

Nuclear weapon containers can provide ballistic protection as well as protection from some nuclear and chemical contamination. Containers can also provide safety, security, and survivability protection.

Weapon Storage Vault

A weapon storage vault (WSV) is an underground vault located in the floor of a hardened aircraft shelter. A WSV holds up to four nuclear weapons and provides ballistic protection in the lowered position through its hardened lid and reinforced sidewalls. The United States calls the entire system the weapon storage and security system, whereas the North Atlantic Treaty Organization (NATO) refers to it as the weapon security and survivability system. However, both the United States and NATO denote the entire system by the same acronym, WS3.

Military Standards

The Defense Threat Reduction Agency (DTRA) and its predecessor agencies have developed, and regularly update, military standards (MIL-STDs) designed to aid in the design, development, test, and evaluation of DoD systems subjected to nuclear and EMP environments. These MIL-STDs cover nuclear-generated EMP survivability of aircraft, maritime, and ground-based systems and are developed in coordination with the Air Force and the Navy as well as the broader community of stakeholders. The following are some of the relevant MIL-STDs:

- MIL-STD-1766, Nuclear Hardness and Survivability Program Requirements for ICBM Weapon Systems defines nuclear hardness and survivability requirements and practices for use during the concept exploration, demonstration and validation, full-scale development, production, and deployment phases of the acquisition life cycle of ICBM weapon systems.

- MIL-STD-2169C, HEMP Environment Standard (Classified) defines high-altitude EMP threat environments for system hardness design and testing.
MIL-STD-3023, *HEMP Protection for Military Aircraft* establishes design margin, performance metrics, and test protocols for HEMP protection of military aircraft providing three hardness levels for nuclear EMP survivability. This MIL-STD may also be used for aircraft that support multiple missions. Subsystems of the aircraft required to fully comply with the provisions of the standard are designated as mission-critical subsystems having a HEMP survivability requirement. This approach also allows for consideration of platforms not yet addressed in this standard, such as Unmanned Aerial Vehicles.

MIL-STD-188-125, *HEMP Protection for Fixed and Transportable Ground-Based C4I Facilities Performing Critical, Time Urgent Missions* is in the process of being updated. DTRA is investigating present capabilities and shortfalls of power filters as well as implementing lessons learned from simulated EMP testing.

MIL-STD-4023, *HEMP Protection for Military Surface Ships* establishes performance metrics, test protocols, and hardness margin levels for HEMP protection of military surface ships that must function when subjected to a HEMP environment.

*Satellite System Nuclear Survivability (SSNS) Environment Standard* defines nuclear weapon environment levels for evaluating satellite system performance in nuclear scenarios.

*Comprehensive Atmospheric Nuclear Environments Standard (CANES)* provides detailed nuclear environments for a number of different nuclear weapon-types as a function of height of burst. A supplement to this MIL-STD covers nuclear-disturbed communication environments and nuclear ground burst environments.

**NUCLEAR WEAPONS EFFECTS TESTING**

Nuclear weapon effects testing refers to tests conducted to measure the response of objects to the energy output of a nuclear weapon. Since pausing full-scale nuclear underground testing in 1992, testing has been conducted through the use of simulators; this approach underpins the stockpile stewardship program and the development of nuclear-survivable systems. Test and evaluation of nuclear hardness is considered throughout the development and acquisition process for defense programs. Modeling and simulation play an important role in nuclear weapon effects survivability design and development. Computer-aided modeling, simulation, and analysis complements testing by helping engineers and scientists estimate the effects of the various nuclear environments, design more accurate tests, predict experimental responses, select the appropriate test facility, scale testing, and evaluate test results. Analysis also helps to predict the response of systems that are too costly or difficult to test.

Simulators used to test nuclear weapons effects are usually limited to a relatively small exposure volume and generally used for single event effects (SEE), such as X-ray, neutron, prompt gamma ray, or EMP effects. Free-field EMP, high explosive (HE), and shock tube facilities are notable exceptions because these facilities

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4 Please refer to *Chapter 13: Basic Nuclear Physics and Weapons Effects* for a detailed discussion of nuclear weapons effects themselves.
can accommodate system-level testing in many cases. Additionally, the Army Fast Burst Reactor (FBR) at White Sands Missile Range can perform full-system tests in some cases.

Figure 9.4 lists the types of simulators commonly used for nuclear weapon effects testing. DTRA maintains a Guide to Nuclear Weapon Effects Simulation Facilities and Applications – Support for the Warfighter, currently in the 2020 edition, which includes comprehensive descriptions of all available facilities in the United States for nuclear survivability testing.

<table>
<thead>
<tr>
<th>Test Type</th>
<th>Type of Simulator</th>
<th>Test Article</th>
</tr>
</thead>
<tbody>
<tr>
<td>X-ray Effects (Hot)</td>
<td>Low-Voltage Flash X-ray Machines</td>
<td>Components and small assemblies</td>
</tr>
<tr>
<td>X-ray Effects (Cold)</td>
<td>Plasma Radiator</td>
<td>Components</td>
</tr>
<tr>
<td>Gamma Ray Effects</td>
<td>Flash X-ray Machines</td>
<td>Components, circuits, and equipment</td>
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<tr>
<td></td>
<td>Linear Accelerator</td>
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<td></td>
<td>Fast Burst Reactor</td>
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<tr>
<td>Total Dose Gamma Effects</td>
<td>Cobalt 60</td>
<td>Components, circuits, and equipment</td>
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<tr>
<td></td>
<td>Fast Burst Reactor</td>
<td></td>
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<tr>
<td>Neutron Effects</td>
<td>Pulsed Reactors</td>
<td>Components, circuits, and equipment</td>
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<tr>
<td></td>
<td>Neutron Surrogates (i.e., ions)</td>
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<tr>
<td></td>
<td>Neutron Spallation Sources</td>
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<tr>
<td>Blast Effects (Overpressure)</td>
<td>Small Shock Tubes</td>
<td>Components, parts, and equipment</td>
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<tr>
<td></td>
<td>Large Shock Tubes</td>
<td>Small systems and large equipment</td>
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<td></td>
<td>HE Tests</td>
<td>Vehicles, radars, shelters, etc.</td>
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<tr>
<td>EMP</td>
<td>Pulsed Current Injection (PCI)</td>
<td>Point of Entry (POE) Systems</td>
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<td></td>
<td>Free Field</td>
<td>Aircraft and vehicles</td>
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<tr>
<td>Thermal Effects</td>
<td>Thermal Radiation Source (TRS)</td>
<td>Equipment</td>
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<tr>
<td></td>
<td>Flash Lamps and Solar Furnace</td>
<td>Large components</td>
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<tr>
<td></td>
<td></td>
<td>Components and materials</td>
</tr>
<tr>
<td>Shock Effects (Dynamic Pressure and Overpressure)</td>
<td>Large Blast Thermal Simulator (LBTS)</td>
<td>Equipment, Large components, Systems</td>
</tr>
</tbody>
</table>

**Figure 9.4 Simulators Commonly Used for Effects Testing**

**X-ray Effects Testing**

X-ray environments are the most challenging to simulate in a laboratory. Historically, UGTs were performed principally to study X-ray effects. Existing X-ray facilities only partially compensate for the loss of nuclear explosive testing, and opportunities for improving the capabilities of X-ray facilities are both limited and costly.

Because X-rays are rapidly absorbed in the atmosphere, they are only of concern for systems that operate in space or at high-altitude. Additionally, the X-ray environment within a system is a strong function of the distance and orientation of the system with respect to the nuclear burst.

X-ray effects tests are usually conducted using flash X-ray machines (FXRs) and plasma radiation sources. FXRs are used to simulate the effects from higher-energy hard (hot) X-rays whereas plasma radiation sources are used to simulate the effects from lower-energy (and longer wavelength) soft (cold) X-rays.
FXRs store large amounts of electric energy, which is converted into intense, short pulses of energetic electrons. The rapid discharge of this much energy in a short time period results in power levels ranging from billions to trillions of watts. The electrons are normally accelerated into a metal target that converts a small portion of their energy into a pulse of X-rays. The resulting photons irradiate the test specimen. The output characteristics of FXRs depend on the design of the machine and vary considerably from one design to the next. Radiation pulse duration ranges from 10 to 100 nanoseconds and output energies range from a few joules for the smallest machines to several hundred kilojoules for the largest.

X-ray effects testing usually requires a machine capable of producing high power with an output voltage of around one million volts. The resulting radiation tends to resemble the hard X-rays and gamma rays that reach components inside enclosures. Lower output voltages are needed to produce the warm X-rays that are important to many internal component responses. The machine’s output energy and power usually determine the exposure level and test area and volume. Most X-ray tests in small FXR machines are limited to components and small assemblies. Larger machines can be used for electronic boxes and sub-assemblies.

Soft X-ray effects testing is designed to replicate surface damage to exposed components in exoatmospheric applications and is normally performed with a plasma radiation source (PRS). The PRS machine generates cold X-rays by driving an intense pulse of electric energy into a bundle of fine wires or a gas to rapidly compress a plasma column into a hot, dense plasma that radiates both thermal X-rays and intense-line radiation from highly excited ions. The energy of the photons produced by the PRS is a function of the wire material or gas and tends to be in the 1 to 14 kilo-electron-Volt (keV) range. These X-rays have very little penetrating power and deposit most of their energy on the surface of the exposed objects. The exposure level and test volume depends on the size of the machine. Test objects are normally limited to small material samples and components.

Coated optics used in satellite and missile defense interceptors can be sensitive to damage from fairly low cold X-ray fluencies. The surfaces of reentry vehicles and reentry bodies of nuclear warheads can be damaged by the rapid vaporization of surface materials. The sublimation of surface materials can result in an off-axis dynamic input, also known as a blow-off impulse. The high fluencies required for blow-off impulse testing limits the test object sizes to small material coupons. Figure 9.5 shows the electromagnetic spectrum for radio waves, infrared radiation, visible light, ultraviolet radiation, X-rays, and gamma rays.

Figure 9.5 Electromagnetic Spectrum

5 A coupon is a small sample of the material under test that has been prepared in such a way that its failure mechanism will be representative of the larger production pieces.
The National Ignition Facility (NIF) located at the Lawrence Livermore National Laboratory (LLNL) uses high-energy laser beams to create plasma-radiating sources that generate cold-warm X-rays for component-level testing. Larger test objects can be subjected to blow-off impulse testing using light-initiated high explosives (LIHE) or magnetically driven flyer plates and only simulate the pressure pulse seen by the overall system. A nascent blow-off simulation technique called direct laser impulse (DLI) uses lasers and transparent surface coating to efficiently generate impulse on surfaces.

Currently, there are a number of pulsed-power facilities used to generate X-ray environments. NNSA operates the LIHE, Saturn, and Z facilities at Sandia National Laboratories (SNL) and the NIF at LLNL. DoD operates the Modular Bremsstrahlung Source (MBS), Pithon, Short Pulse Gamma, and Double Eagle at the DTRA West Coast Facility in California. These facilities are currently in various states of readiness and are under review for replacement based on predicted future test and evaluation needs.

**Gamma Dose-Rate Effects Testing**

All solid-state components are affected by the rapid ionization produced by prompt X-rays and gamma rays. Gamma dose-rate effects dominate TREE in non-space-based electronics and the effects do not lend themselves to strict analyses because these are usually nonlinear and are very difficult to model. Circuit analysis is often helpful in bounding the problem, but only active tests have proven to be of any real value in replicating the ionizing effects on components, circuits, and systems.

Two machines used for gamma dose-rate testing are FXRs and linear accelerators (LINACs). The FXRs used for gamma dose-rate effects tests operate at significantly higher voltages than FXRs used for X-ray effects tests and produce X-ray radiation that is equivalent in photon energy to the prompt gamma rays produced by an actual nuclear explosion.

LINACs are primarily used for component-level tests because the beam produced by most LINACs is fairly small in size and of relatively low intensity. LINACs produce a pulse or a series of sub-nanosecond pulses of highly energetic electrons. The electron pulses may be used to irradiate test objects or to generate bremsstrahlung radiation.\(^6\)

LINACs are restricted to piece-part size tests and are typically operated in the electron beam mode when high-radiation dose rates are required. The biggest drawbacks to the use of LINACs are their low temporal fidelity, small exposure volume, and relatively low-output intensity.

Most dose-rate tests are active; that is, they require the test object to be powered up and operating for testing. Effects such as component latch-up, logic upset, and burnout, can only occur using active testing. Tests must be conducted in a realistic operating condition and the test object must be continuously monitored before, during, and after exposure.

SNL operates the High-Energy Radiation Megavolt Electron Source (HERMES) pulsed-power facility to simulate prompt gamma environments at extreme dose rates for NNSA. DoD currently operates smaller gamma ray facilities used to test systems at lower levels, including the Pulserad 1150 and the Short Pulse

\(^6\) **Bremsstrahlung** is literally “braking radiation.” It is caused by the rapid deceleration of charged particles interacting with atomic nuclei and produces electromagnetic radiation covering a range of wavelengths and energies in the X-ray regions.
Gamma at the DTRA West Coast Facility in California, the Pulserad 958 and linear accelerator (LINAC) at Hill Air Force Base (AFB) in Utah, and the LINAC Facility at White Sands Missile Range in New Mexico.

**TOTAL DOSE EFFECTS TESTING**

The objective of total dose effects testing is to determine the amount of performance degradation suffered by components and circuits exposed to specified levels of gamma radiation. A widely used simulator for total dose effects testing is the cobalt-60 (Co60) radioactive isotope source. Other sources of radiation, such as high-energy commercial X-ray machines, LINACs, and the gamma rays from nuclear reactors, are also used for testing.

**NEUTRON EFFECTS TESTING**

The objective of most neutron effects testing is to determine the amount of performance degradation in susceptible parts and circuits caused by exposure to a specified neutron fluence at a specified pulse width. Neutron effects on electronics can be simulated using a number of platforms including the FBR at White Sands Missile Range, the pulsed Annular Core Research Reactor (ACRR) located at SNL, the Ion Beam Laboratory surrogate source located at SNL, or the Los Alamos Neutron Science Center (LANSCE) neutron spallation source located at Los Alamos National Laboratory (LANL). Other platforms exploiting nuclear fusion reactions such as the NIF at LLNL and the Z Facility at SNL are currently being investigated for neutron sources, as are techniques using Dense Plasma Focus (DPF); these could potentially provide pulsed neutron capability for future effects testing.

**AIR-BLAST EFFECTS TESTING**

The military relies more on structural analyses for determining air-blast effects than on testing. This is because of the confidence engineers have in computer-aided structural analyses and the difficulty and costs associated with air-blast testing. Exposed structures and equipment like antennas, radars, radomes, vehicles, shelters, and missiles that have to be evaluated for shock and blast effects are usually subjected to an evaluation consisting of a mix of structural analyses, component testing, or scale-model testing. The evaluation may also include full-scale testing of major assemblies in a HE test or in a large shock tube.

Shock tubes vary in size from small laboratory facilities to large, full-scale devices. The Army Large Blast Thermal Simulator (LBTS) was refurbished for blast in 2018 and is undergoing refurbishment for thermal; it can accommodate test objects as large as a helicopter. The LBTS replicates ideal and non-ideal air-blast environments. Shock tubes have the advantage of being able to generate shock waves and over-pressures with the same positive phase-time duration as the actual nuclear blast environment.

HE tests were conducted by the Defense Nuclear Agency, the DTRA predecessor, at Stallion Range located at White Sands Missile Range. These tests were used to validate the survivability and vulnerability of many systems before the LBTS became operational. The explosive source was normally several thousand tons of ammonium nitrate and fuel oil (ANFO) housed in a hemispherical dome. The test objects were placed around the dome at distances corresponding to the desired peak overpressure, or dynamic pressure of an ideal blast wave. HE tests produced shock waves with fairly short positive duration corresponding to low-yield nuclear explosions. HE test results needed to be extrapolated for survivability against higher yield weapons and for non-ideal air-blast effects. Structures composed of heat sensitive materials, such as fiberglass and aluminum,
which lose strength at elevated temperatures, are normally exposed to a thermal radiation source before the arrival of the shock wave.

**ELECTROMAGNETIC PULSE EFFECTS TESTING**

There are two general classes of EMP effects tests: injection tests and free-field tests. An injection test simulates the effects of the currents and voltages induced by HEMP on cables by artificially injecting current pulses onto equipment cables and wires. Injection tests are particularly well-suited for the evaluation of interior equipment that is not directly exposed to HEMP.

A free-field test is used to expose equipment, such as missiles, aircraft, vehicles, and radar antennas, to HEMP. Most free-field HEMP testing is performed with either a broadcast simulator or a bounded wave EMP simulator. Both types of simulators use a high-power electrical pulse generator to drive the radiating elements. In the broadcast simulator, the pulse generator drives an antenna that broadcasts simulated EMP to the surrounding area. Objects are positioned around the antenna at a range corresponding to the desired electrical field strength. The operation of the equipment is closely monitored for upset and damage. Current and voltage measurements are made on equipment cables and wires to determine the electrical characteristics of the EMP energy coupled into the system.

In the bounded wave simulator, the pulse generator drives a parallel plate transmission line consisting of a horizontal or vertical curtain of wires and a ground plane. The test object is placed between the wires and the ground plane. The energy travels down the line, passes the test object, and terminates in a resistive load. As the pulse passes the test object, it is subjected to the electric field between the lines. Some simulators locate test instrumentation in a shielded chamber below the ground plane.

Free-field EMP simulators are available at the Patuxent River Naval Air Station in Maryland and at White Sands Missile Range in New Mexico.

**THERMAL RADIATION EFFECTS TESTING**

The majority of thermal radiation effects testing is performed with high intensity flash lamps, solar furnaces, or rocket nozzles using liquid oxygen and powdered aluminum, called a thermal radiation source (TRS). Flash lamps and solar furnaces are normally used on small material samples and components. A TRS is used for larger test objects and have been used in conjunction with the large HE tests. LBTS features a thermal source that is also being refurbished that allows test engineers to examine the combined effects of thermal radiation and air blast.

**SHOCK TESTING**

High-fidelity tests exist to evaluate systems for survivability to nuclear underwater and ground shock effects because, for these factors, conventional explosive effects are very similar to those from nuclear weapons. Machines such as hammers, drop towers, and slapper plates are used for simulating shock effects on equipment. Explosives are also used for shock testing. The Navy uses explosives on floating shock platforms (barges) to simulate underwater shock and subjects one ship of each class to an explosive test at sea. The Army and the Air Force employ similar methods.