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INTRODUCTION TO WEAPON EFFECTS FOR SHIPS (METRIC)

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Introduction to Weapon Effects for Ships. (Metric)

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FOREWORD

One aspect of ship design that has a significant impact on the operational effectiveness of shipboard weapons systems is the extent to which survivability factors are included in the design phases, and subsequently considered throughout the life-cycle of the ship. Combat survivability must be treated as a design issue no different from other performance characteristics (for example, mobility, maneuverability, seakeeping, stability and control, structural integrity, and so forth) which collectively determine the configuration of a Naval combatant.

The capability of a Naval ship to survive nuclear and non-nuclear weapon (damage) effects depends on the accuracy with which the threat is defined and the deliberateness with which combat survivability, as a design and evaluation discipline, is implemented to meet the threat. Each mission essential space, system and component of a ship must receive dedicated survivability considerations to ensure that an integrated combat entity of the highest survivability is achieved at acceptable levels of cost and performance. Significant advances in the survivability technologies and evaluation methodologies have been made which provide the potential to efficiently achieve this for existing and future ships.

Since a particular passive protection concept may be useful in hardening a system or component against one or more weapon effects, it is necessary that all threat weapon effects be investigated. Factors which must be considered are possible synergistic couplings where combined weapon effects may produce significant increases in ship damage. To realize the balanced survivability design of a Naval ship, therefore, the need exists for the systematic categorization of environmental severity levels for both nuclear and non-nuclear weapons. Equally crucial is the meaningful characterization of controlling design-threat parameters (for example, blast overpressure, fragment kinetic energy, shock velocity, thermal fluence, EMP flux, and so forth) which enter the design equations as additional load factors.

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1. SCOPE .

1.1 Scope. This handbook has been prepared to provide a tutorial on the basic concepts of explosion phenomena and damage effects from nuclear and non-nuclear weapons. It is recommended reading for engineers desiring an introduction to these subjects as they relate to the vulnerability or survivability of ships and mission essential weapons systems, and to passive protection design.

1.2 Introduction. Naval ships must be capable of carrying our their assigned missions and combat roles in man-made threat environments and survive the possible consequences which may result from engaging hostile forces. Viewed in totality, the combat survivability of a warship depends on two distinct but interrelated factors; namely, susceptibility and vulnerability.

l.2.l The first factor, susceptibility, is defined as “the combined characteristics of all the factors that determine the probability of hit of a component, subsystem, or system by a given threat mechanism.” Susceptibility may be characterized as the propensity of a ship’s emissions (intentional and unintentional) to exploitation by threat surveillance sensors, weapon homing seekers, and warhead fuze mechanisms in performing their intended functions of detection attack (weapon launch) targeting, acquisition, and detonation against a ship. Intentional emissions, many of which are unique and readily classifiable, include electromagnetic radiations from on board communications, navigation, and command or control radars, and electro-acoustic radiations from on board sonars. Unintentional emissions (signatures) include radiations and reflections which are inherent to a ship’s configuration and design features, and include: acoustic (radiated noise), radar cross-section, infrared radiance, magnetic, pressure, seismic, and other signatures.

1.2.2 The second factor, vulnerability, is defined as “the characteristics of a system that cause it to suffer a finite level of degradation in performing its mission as a result of having been subjected to a certain level of threat mechanisms in a man-made hostile environment.” Vulnerability may be characterized as the propensity of a ship’s structure (hull, deckhouse, superstructure, hangars) and vital equipments or components to operational impairment as a result of the damage effects from weapon detonations. The level of damage, and degree of impairment, are a function of the following: type of warhead, size of explosive charge, location of the detonation, and a ship’s inherent structural hardness to resist the weapon effects. The first two are directly related to the threat weapon, whereas the last one is directly related to the ship’s design. The weapon hit location or detonation points resulting from “smart” weapons homing-in and exploding on a ship target are related to both the threat weapon; that is, its seeker and homing logic, and also the ship’s signature profile and highlights which are design controllable.

1.2.3 It is seen that ship susceptibility comprises a sequence of signature-influenced engagement events (detection, targeting, attack, seeker lock-on, and warhead detonation), the outcome of which influences the vulnerability of a ship to damage from weapons effects. The interrelations between signature susceptibility and damage vulnerability are, however, complex since the degree of operational impairment to a ship and its mission-essential systems or equipments depends on where weapons hit and explode on the ship and its inherent hardness at such locations.

1.2.4 Survivability design of a Naval ship requires data in the form of design threat parameters, and other quantitative descriptors, which characterize the sensors, seekers or fuzes and the weapons, warheads, or explosives of antiship threat systems. These parameters constitute some of the key inputs to ship design criteria and formulas for determining the type, location, and distribution of passive survivability features. The logic diagram as shown on figure 1 identifies the relationship between "threat" and "ship survivability design", traces the key steps of the process, and relates to the supporting publications in the NAVSEA documentation hierarchy at each node of the process. This handbook addresses only the weapons effects part of the threat environment severity levels (see figure 1).

2. REFERENCED DOCUMENTS

Not applicable.

3. DEFINITIONS

3.1 Definitions. The definitions herein are commonly used terms in ship vulnerability or survivability and in the weapons effects and passive protection disciplines.

3.1.1 Active defense. Active defense is defense provided by a ship's armament system to avoid the effects of a combat environment,

3.1.2 Airblast, Airblast is the shock wave and associated phenomena produced by an explosion in air, resulting in the propagation outward of a sharp pressure front accompanied by subsequent air motion.

3.1.3 Air burst. Air burst is the detonation of a nuclear weapon at such a height that the expanding fireball does not touch the earth's surface when the luminosity is a maximum (in the second thermal pulse).

3.1.4 Angle of impact, Angle of impact is the acute angle between the tangent to the trajectory path and the plane tangent to the surface of the ground or target at point of impact.

3.1,5 Angle of obliquity. Angle of obliquity is an angle, measured in degrees, between the perpendicular to the plate surface and the trajectory of the projectile at the point of impact. This term is generally used when referring to the armor itself.

3.1.6 Armor-piercing (AP) munitions. AP munitions are q unitions such as projectiles and bombs designed to penetrate armor and other resistant targets by means of kinetic energy and the physical characteristics of the warhead.

3.1.7 Areal density. Areal density is defined as the weight of an armor configuration expressed in pounds per square foot (lb/ft^2) of surface area. For example, the areal density of l-inch thick steel armor is 40.8 lb/ft^2.

3.1.8 Back span. Back span is fragments of metal displaced from the back of steel armor as a result of ballistic attack, normally from an area of greater size than the projectile caliber,

3.1.9 Ballistic limit. Ballistic limit, as related to armor, is a measure of the armor's resistance to penetration. Generally, it can be defined as the striking velocity of a kinetic energy fragment or projectile below which partial (rather than complete) penetrations of the armor will predominate.

3.1.10 Ballistic protection system. A ballistic protection system represents some combination of one or more elements made of basic armor materials or composites (in some cases supplemented by nonarmor materials) to form an effective ballistic protection device. This includes installation equipment and hardware.

3.1.11 Basic armor material, A basic armor material is a single material having those properties required to provide a measure of protection against ballistic attack.

3.1.12 Blast-induced pressure. Blast-induced pressure is the force on an object or structure caused by the air blast from an explosion striking and flowing around the object. It is a combination of overpressure (or diffraction) and dynamic pressure (or drag) loadings.

3.1.13 Blast-induced shock. Blast-induced shock is the sudden athwartships motions imparted to an object or structure due to the impulsive nature of a blast (shock) wave striking the object.

3.1.14 Blast wave. Blast wave is a continuously propagated pressure pulse of air in which the pressure increases sharply at the wave front accompanied by strong, but transient winds, resulting from an explosion in air.

3.1.15 Booster (explosive). Booster (explosive) is a quantity of high explosives in which detonation can be more readily initiated (by means of primers) than can the main high-explosive filling. Boosters are used to initiate the main, relatively insensitive high-explosive fillings.

3.1.16 Compact fragments. Compact fragments are fragments produced by the break-up of the casing of specially designed (controlled) fragmentation warheads. Compact fragments are of more uniform size and shape than random fragments.

3.1.17 Complete penetration (Navy criterion) . Complete penetration (Navy criterion) is the condition obtained by projectile impact where the projectile or major portion of the projectile passes completely through the armor.

3.1.18 Composite armor. Composite armor is an armor configuration consisting of two or more different armor materials bonded together to form a protective unit.

3.1.19 Contact burst, Contact burst is a burst occurring when contact-fuzed high-explosive (H.E.) warheads detonate against a ship's structure resulting in very high localized pressure loading over relatively small areas of structure. Effects other than blast pressure may be present; that is, fragmentation, shaped-charge jet, and so forth.

3.1.20 Cube-root law. Cube-root law is a scaling law applicable to many blast phenomena. It relates the time and distance at which a given blast effect is observed to the cube root of the energy yield of the explosion.

3.1.21 Detonation. Detonation is the extremely rapid chemical reaction that occurs in the explosion of high explosives. Detonation is characterized by its propagation through the mass of explosives as a wave, by its great velocity, by the fact that it can be initiated by a shock or blow, and by the extremely high pressures developed,

3.1.22 Diffraction loading. Diffraction loading is the force on an object or structure due to the passage (bending) around and envelopment by a blast wave.

3.1.23 Drag loading. Drag loading is the force on an object or structure due to the transient winds accompanying the passage of a blast wave. The drag pressure is the product of the dynamic pressure and the drag coefficient which is dependent upon the shape (geometry) of the structure or object.

3.1.24 Dynamic pressure. Dynamic pressure is the air pressure which results from the mass air flow (or wind) behind the shock front of a blast wave. It is equal to the product of half the density of the air through which the blast wave passes and the square of the particle (or wind) velocity behind the shock front as it impinges on the object or structure.

3.1.25 Electromagnetic pulse (EMP). Electromagnetic pulse is a sharp pulse of radio-frequency (long wavelength) electromagnetic radiation produced when a nuclear explosion occurs in an unsymmetrical environment, especially at or near the earth's surface or at high altitude. The EMP results from the interaction of the gamma rays and neutrons from the initial nuclear radiation with air particles and atoms. The intense electric and magnetic fields of EMP can damage unprotected electrical and electronic equipment.

3.1.26 Enhanced blast. Enhanced blast is the airblast resulting from the detonation of a chemical high-explosive composition containing powdered aluminum for added oxygen to ensure complete burning of the explosive, thereby yielding a higher peak overpressure and a higher positive impulse for the same weight of explosive. Fuel-air explosive (FAE) mixtures or reactive materials that surround the main explosive may also be used to enhance the blast output of an H.E. warhead.

3.1.27 Explosion. Explosion is defined as multiple, partially confined and unconfined. The following describes each type:

(a) Multiple. Multiple explosion is two or more explosions whose initiation time is such as to cause the blast effects of the various explosions to be cumulative on the response of a structure.
(b) Partially confined. Partially confined explosion is an explosion occurring within or immediately adjacent to a structure. In addition, partially confined explosions may be subdivided into fully-vented explosions where the pressures produced by the accumulation of gases from the explosion are quickly released, and partially-vented explosions where the gas accumulation

will exert pressures in addition to those produced by the shock pressures.

(c) Unconfined. Unconfined explosion is an explosion occurring exterior to a structure such that the blast loads acting on the structure may be classified as: free-air burst, air burst, or surface burst.

3.1.28 Explosive (high-explosive). Explosive (high-explosive) is a chemical compound or mechanical mixture which, when subjected to heat, friction, detonation, or other suitable initiation, undergoes a very rapid chemical change with the evolution of large volumes of highly heated gases which exert pressures in the surrounding medium.

3.1.29 Fallout. Fallout is the process or phenomenon of the descent to the earth's surface of particles contaminated with radioactive material from the radioactive cloud of a nuclear explosion in air.

3.1.30 Fission. Fission is the process whereby the nucleus of a particular heavy element such as uranium-235 or plutonium-239 splits into (generally) two nuclei of lighter elements, with the release of substantial amounts of energy .

3.1.31 Fluence (integrated flux). Fluence (integrated flux) is the product (integral) of neutron or photon particle flux and time, expressed in units of particles per square centimeter (cm). The absorbed dose of radiation (in rads) is related to the fluence,

3.1.32 Flux (flux density). Flux (flux density) is the product of neutron or photon particle density (that is, number per cubic cm) and the particle velocity. The flux is expressed as particles per square cm/time and is related to the absorbed dose rate.

3.1.33 Fragment-simulating projectile (FSP). An FSP is a projectile of special shape and size designed for ballistic test firings intended to simulate the effect on armor samples of typical fragments from high-explosive shells , usually of larger caliber than the FSP.

3.1.34 Fragmentation, Fragmentation is the shattering of an H.E. bomb or projectile casing into many irregular pieces by the detonation of the explosive payload. Fragmentation also denotes break-up of a hardened AP projectile core into two or more pieces upon impact with a target.

3.1.35 Fusion. Fusion is the process whereby the nuclei of light elements, especially those of the isotopes of hydrogen (deuterium and tritium), combine to form the nucleus of a heavier element with the release of substantial amounts of energy.

3.1.36 Fuze. Fuze is a device designed to initiate detonation in a weapon warhead by an action such as hydrostatic pressure, electrical energy, chemical action, impact, mechanical time, or a combination of these.

3.1.37 Fuze proximity. Fuze proximity is a fuze wherein primary initiation occurs by sensing the presence, distance, or direction of the target through the characteristics of the target itself or its environment.

3.1.38 H.E. projectile, H.E. projectile is a projectile consisting of a shell, high-explosive filler, and detonating device that is designed to cause damage primarily by fragments generated at shell burst.

3.1.39 Homogeneous armor. Homogeneous armor is an armor made from a single material that is consistent throughout in terms of chemical composition, physical properties, and degree of hardness.

3.1.40 Impulse. Impulse is the product of the force (pressure) from the blast wave of an explosion and the time during which it acts on an objective or structure. It is the integral with respect to time of the force, the integration being between the time of arrival of the blast wave and the time at which the force on the element returns to zero.

3.1.41 Initial nuclear radiation. Initial nuclear radiation is the nuclear radiation comprised of highly-penetrating and invisible gamma rays and neutrons emitted within the first minute from the fireball and cloud column of a nuclear explosion in the atmosphere. The transient radiation effects on electronics (TREE) results from the initial nuclear radiation.

3.1.42 Internal burst. Internal burst is a burst occurring when weapons equipped with armor piercing (AP) or semi-armor piercing (SAP) warheads penetrate a ship's outer structure and detonate, by delay-fuze, a large H.E. charge within the confines of the superstructure or hull.

3.1.43 Jet. The definition of jet as it pertains to shaped-charge warheads is as follows:

(a) From a lined charge: The slender, generally fast moving part of a liner after collapse.
(b) From an unlined charge: The central stream of high-velocity gases produced upon detonation.

3.1.44 Jet penetration. Jet penetration is the penetration in armor achieved by a high pressure flow process associated with the functioning of shaped-charge warheads.

3.1.45 Keel shock factor (KSF). KSF is a dimensional index which measures the severity of an underwater shock wave at the keel of a ship from an H.E. weapon detonation.

3.1.46 Kinetic energy projectile. Kinetic energy projectile is a type of projectile that causes damage by the combined effects of projectile characteristics and kinetic energy,

3.1.47 Lethal damage. Lethal damage is the damage to a ship sufficient to sink it or put it out of action (also referred to as ship "kill").

3.1.48 Lethality. Lethality is a measure of the destructive effect of a particular weapon type on a given target under specified attack conditions.

3.1.72 Reflected pressure. Reflected pressure is the total pressure which results instantaneously at the surface when a shock (blast) wave traveling in one medium strikes another medium; for example, at the instant when the front of a blast wave in air strikes the ground or a structure.

3.1.73 Residual nuclear radiation. Residual nuclear radiation is the nuclear radiation, chiefly beta particles and gamma rays, which persists for some time following a nuclear explosion, The radiation is emitted mainly by the fission products and other bomb residues in the fallout, and other materials in which radioactivity has been induced by the capture of neutrons.

3.1.74 Residual primary fragment. Residual primary fragment is a primary fragment possessing residual velocity after penetrating a target material.

3.1.75 Secondary fragmentation. Secondary fragmentation is the fragments produced by spalling from a target material when impacted by primary fragments from a warhead or projectile.

3.1.76 Secondary nuclear radiation. Secondary nuclear radiation is the induced radioactivity in materials irradiated by a primary source of nuclear radiation.

3.1.77 Shaped charge. Shaped charge is an explosive charge with a shaped cavity or liner, usually in the form of a cone or hemisphere; sometimes called a cavity charge or hollow charge. Shaped-charge warheads are designed to penetrate heavy armor.

3.1.78 Shaped-charge effect. Shaped-charge effect is the focusing of a metallic jet or stream of liner fragments from a shaped charge in a specific direction as a means of enhancing penetration capability.

3.1.79 Shock front (pressure front). Shock front (pressure front) is the fairly sharp boundary between the pressure disturbance created by an explosion (in air, water, or earth) and the ambient environment; it constitutes the front of the shock (or blast) wave.

3.1.80 Shock wave. Shock wave is a continuously propagated pressure pulse (or wave) in the surrounding medium which may be air, water, or earth, initiated by the expansion of the hot gases produced by an explosion. A shock wave in air is referred to as a blast wave, because it resembles and is accompanied by strong, but transient, winds, The strong pressure discontinuity of a shock wave is propagated at a velocity equal to or greater than the velocity of sound.

3.1.81 Solid armor. Solid armor is all basic armor materials, composites, and stacked arrangements having no air space between plate elements.

3.1.82 Spaced armor. Spaced armor is an armor arrangement consisting of two or more individual plate elements where each plate is spaced from the adjoining one. Spaced armor is especially effective as a protection system against shaped-charge effects.

3.1.83 Spalling. Spalling results when a layer of plating (or armor) material in the area surrounding a warhead impact location is detached or delaminated from the rear face of the plating.

3.1.84 Stagnation pressure. Stagnation pressure is the total pressure, sum of the incident overpressure and dynamic wind pressure of a blast wave, in the moving air when the air is brought to rest upon impacting an object or structure.

3.1.85 Standoff burst. Standoff burst is an explosion occurring when an H.E. warhead is detonated at distances greater than 300 feet from a ship's superstructure resulting in fragments of various sizes as well as missile debris impacting with ship structure.

3,1.86 Surface burst. Surface burst is the detonation of a nuclear weapon at the surface of land or water and a height above the surface less than the radius of the fireball at maximum luminosity. An explosion in which the weapon is detonated actually on the surface (or within SW . feet of the surface, where W is the yield in kilotons) is called a contact or true surface burst.

3.1.87 Survivability. Survivability is the capability of a ship and its shipboard systems to avoid and withstand a weapons effects environment without sustaining impairment of their ability to accomplish designated missions.

3.1.88 Thermal radiation. Thermal radiation is the electromagnetic radiation emitted from a nuclear fireball as a consequence of its very high temperature; it consists essentially of ultraviolet, visible, and infrared radiations.

3.1.89 TREE. TREE is the damaging effects occurring to individual electronic and electro-mechanical components of electronics systems as a result of exposure to the transient (less than 1 minute) initial nuclear radiation from a nuclear explosion in air.

3.1.90 Trigger shield. Trigger shield is a thin plate spaced in front of the main armor for the purpose of reducing shaped-charge lethality by increasing standoff distance.

3.1.91 Triple point. Triple point is the intersection of the incident, reflected, and merged (or Mach) shock fronts accompanying a nuclear air burst.

3.1.92 TNT equivalent. TNT-equivalent is a measure of the energy released by the detonation of a nuclear weapon, or in the explosion of a given quantity of fissionable material, expressed in terms of the mass of TNT (kilotons or megatons) which would release the same amount of energy. TNT equivalent is also used to relate the explosion energy of different high explosives to equivalent pounds TNT.

3.1.93 Vulnerability. Vulnerability is the characteristics of a ship (or shipboard system) that cause it to suffer a finite level of degradation in performing its mission as a result of having been subjected to a certain level of threat weapon effects in a man-made hostile environment.

4. GENERAL REQUIREMENTS

4.1 Weapons effects and damage environments.

4.1,1 General. Ships and mission-essential combat systems of the U.S. Navy, including the personnel required to operate them, must have capabilities (by deliberate design) to survive and fight during and after exposure to a broad spectrum of weapon damage environments which result from a tactical nuclear or conventional weapon exchange at sea. The variety of generic weapons and warheads which can be employed to damage a ship and its vital spaces, systems, equipments, and personnel leading to operational impairment or incapacitation of mission capability and combat readiness, is shown on figure 2. Antiship weapons with explosive-charge warheads, and this includes both nuclear and non-nuclear (chemical high explosive) types, may be in the form of a bomb, missile, projectile, torpedo, or mine. A special category of antiship weapons encompasses those which do not involve explosives as the means of causing damage to a ship and its mission-essential components and are here termed “non-explosive” type. This includes chemical and biological agents.

4.1.2 The next level of breakdown as shown on figure 2 is in terms of above water and underwater detonations for nuclear warheads; instantaneous-fuzed and delayed-fuzed detonations for conventional warheads; and associated burst types and conditions depending on where the detonation occurs relative to a target. The categorization as shown on figure 2 will facilitate identifying the principal weapons effects and the (direct and indirect) damage environments which result in each case, including possible synergistic coupling between individual effects, The detonation of a nuclear or non-nuclear (chemical) weapon leads to the generation of explosive phenomena. Depending on the medium in which the detonation takes place, the explosion phenomena are manifest as weapons effects. Following the explosion process, there occurs a transition from weapons effects to damage environments which result from the interaction of the weapons effects with the target, and then to impairment or incapacitation which reflects system response to the damage environments. This sequence of occurrences, essentially, represents a transfer of energy from one state to another. The process is shown on figure 3.

4.1.3 It is seen that the weapons effects are inherent to the explosion process as such (air or water) and do not involve interaction with the ship target. The damage environments are obtained as a result of the target being in close proximity or along the path of the propagating or penetrating weapons effects. Operational impairment of a ship’s mission capabilities is a consequence of system response due to the ship’s presence in the damage environments-damage mechanisms come into play as a result of the interactions.

4.1.4 For the generic categories of weapons, burst conditions, and warhead types shown on figure 2, the weapons effects and damage environments crucial to ship vulnerability or survivability are discussed in the sections which follow. Synergistic coupling between individual weapons effects must be considered since the combined effects may be significantly different, even to the extent that an individual effect is enhanced and could prove more damaging than otherwise. The response, and hence damage potential, in terms of impairment or incapacitation of a ship’s structure, materials, systems, equipment, and personnel to weapons effects are also identified and briefly

discussed. The narratives on weapons effects, damage environments, and possible synergisms presented in 4.2 through 4.7 are organized in accordance with the breakdown shown on figure 2.

4.2 Principal phenomena of explosions. Before proceeding with the tutorial discussions on nuclear and non-nuclear weapons effects, a short introduction will first be given on the principal phenomena of explosions, in general, highlighting some of the basic differences between nuclear and non-nuclear or conventional (chemical) explosion phenomena.

4.2.1 An explosion involves a change in the state of matter which results in the rapid and violent release of a large amount of energy within a limited space. This is true for a chemical "high explosive" such as TNT, as well as for nuclear explosives, although the energy is produced in quite different ways. In the case of a chemical explosion, the energy released arises from chemical reactions which involve a rearrangement among the atoms (for example, of hydrogen, carbon, oxygen, and nitrogen) present in the high explosive material. In a nuclear explosion, on the other hand, the energy is produced as a result of the formation of different atomic nuclei by the redistribution of the protons and neutrons within the interacting nuclei. The forces between the protons and neutrons within atomic nuclei are tremendously greater than those between the atoms. Consequently, nuclear energy is of a much higher order of intensity than chemical energy when equal masses of explosive are considered. The energy of a weapon explosion may be divided into three categories: (1) kinetic (or external) energy; that is, energy of motion of electrons, atoms, and molecules as a whole; (2) internal energy of these particles; and (3) thermal radiation energy. The first type of explosion energy is manifest as a mechanical weapon effect, the second as a nuclear radiation effect, and the third as a thermal radiation effect. The sudden liberation of energy from an explosion causes a considerable increase of temperature and pressure so that all the materials present are converted into hot, compressed gases. Since these gases are at very high temperatures and pressures, they expand rapidly and thus initiate a pressure wave called a "shock wave" in the surrounding medium -- air, water, or ground. The characteristic of a shock wave is that there is (ideally) a sudden increase of pressure at the wave front, with a gradual decrease behind it. A shock wave in air is generally referred to as a "blast wave" because it resembles and is accompanied by a very strong wind. In water or in the ground, however, the term "shock" is used because the effect is like that of a sudden impact. The difference in the underlying explosion phenomena is due to the fact that the densities of the propagation media are significantly different in each of the two cases, that of air versus that of water (or earth). Air is significantly more compressible than either water or earth.

4.2.2 Nuclear weapons are similar in some ways to conventional (chemical) high-explosive types insofar as their destructive action is due mainly to blast or shock. Several basic differences between nuclear and chemical explosions which are reflected in the primary weapons effects and their respective intensities follows:

(a) Nuclear explosions can be many thousands (or millions) of times more powerful than the largest non-nuclear explosions.

(b) For the release of a given amount of energy, the mass of a nuclear explosive would be much less than that of a chemical explosive.

(c) Since there is a much smaller amount of explosive material available in a nuclear weapon that is converted into the hot, compressed gases of detonation, somewhat different mechanisms underly the initiation of the blast wave.

(d) The temperatures reached in a nuclear explosion are orders of magnitude higher than in a chemical explosion so that a fairly large proportion of the energy is emitted in the form of light and heat, generally referred to as "thermal radiation."

(e) At the moderate temperatures attained in a chemical explosion, the amount of thermal radiation is comparatively small. Essentially all the energy released at detonation appears as kinetic and internal energy which is almost entirely converted into blast and shock.

(f) A nuclear detonation is accompanied by highly penetrating and harmful invisible gamma rays and neutrons called "initial nuclear radiation," with the ability to propagate over long distances in air. There are no nuclear radiations from a conventional explosion since the nuclei are unaffected in the chemical reactions which take place,

(g) A secondary weapon effect known as "electromagnetic pulse" (EMP) results from the initial nuclear radiation. The detonation of a chemical high explosive can also produce electromagnetic signals, but in comparison provides little consequence to shipboard electronics, The process by which EMP is generated as a result of a nuclear detonation is specified in 4 3.1.1.

(h) The debris and ejects remaining after a nuclear detonation are radioactive, emitting "residual nuclear radiation" over a long period of time.

(i) In the course of their radioactive decay, the fission products from a nuclear detonation emit gamma rays and another type of nuclear radiation called beta particles which give rise to "delayed nuclear radiation. " Beta particles, which are also invisible, are much less penetrating than gamma rays, but like the latter they represent a potential hazard.

4.3 Nuclear weapons effects and damage environments. A distinction is sometimes made between atomic weapons in which the explosion energy arises from fission, and hydrogen (thermo-nuclear) weapons in which the explosion energy arises from fusion. In either case, however, the explosion energy results from nuclear reactions so that both are correctly described as nuclear weapons. The "yield" of a nuclear weapon is a measure of the amount of explosive energy it can produce. It is usual practice to express the yield in terms of the quantity of TNT that would generate the same amount of energy upon detonation. Thus, a l-kiloton nuclear weapon produces the same amount of energy as does 1 kiloton (1,000 tons) of TNT. Similarly, a l-megaton weapon would have the energy equivalent of 1 million tons of TNT. The fission of uranium (or plutonium) or the fusion of the isotopes of hydrogen in a nuclear detonation leads to the liberation of a large amount of energy in a very small period of time. As a result, the fission products, bomb casing, and other

weapon parts are raised to extremely high temperatures, similar to those in the center of the sun. The maximum temperature attained in a nuclear detonation is several tens of millions degrees, compared with a maximum of 9,000°F in a conventional (chemical) detonation. Because of the great heat produced by a nuclear detonation, all the materials are converted into gaseous form. Since the gases, at the instant of detonation, are restricted to the region occupied by the original constituents in the weapon, tremendous pressures will be produced. These pressures are probably of the order of many millions of pounds per square inch. Within less than a millionth of a second after detonation, the extremely hot weapon residues radiate large amounts of energy, mainly as highly penetrating and invisible X-rays. The partition of the energy for the explosion phenomena from a nuclear detonation is shown on figure 4. Most of the energy appears in the X-ray portion of the spectrum, with the second largest appearing in the form of kinetic energy of the weapon debris and ejects. Some smaller portion, probably less than 5 percent total, appears in the form of neutrons and gamma radiation. The X-rays are very quickly absorbed in the surrounding atmosphere heating the air to an extremely high temperature in a very short time. This results in the formation of an extremely hot and highly luminous (incandescent) mass of air and gaseous weapon residues referred to as the "fireball" which causes the thermal radiation and shock front effects. The thermal radiation consists of two components : one in the visible region of the spectrum as a high-intensity light environment, and the other in the infrared region as a high-intensity heat environment. The shock front results in a blast (and blast-induced shock) environment for a nuclear detonation in air, and an underwater shock environment for a detonation in water. The weapon and casing particles lose their momentum very quickly and burn out in very short distances in the air, so there is no weapon effect environment as such from the debris and ejects except as they may be contaminated with nuclear radiation. The neutrons and gamma radiation have the highest intrinsic energy of any portion of the energy partition, usually on the order of 1 million electron volts (Mev) level. The neutrons are particle in nature, whereas the gamma radiation is a true radiant energy (photon radiation). Being of high intrinsic energy the neutrons and gamma rays give rise to the highly penetrating and harmful "initial nuclear radiation." The long-term weapon effects of a nuclear detonation is the persistent radioactivity due to the "residual nuclear radiation" and "delayed nuclear radiation". Using terms and definitions from several references on nuclear weapons effects, which in themselves were found not totally consistent, an attempt was made to synthesize the relevant information into a standardized terminology for this handbook. A summary of the principal explosion phenomena from a nuclear detonation and the associated weapons effects and resulting damage environments which are of critical importance to the vulnerability or survivability of Naval ships is shown on figure 5. From the viewpoint of ship and system survivability design, the damage environments (direct and indirect) which result from the interaction of the weapons effects with the ship target introduce considerations which can be designed against to reduce vulnerability to weapon damage. The controlling parameters which determine the severity, and relative importance, of the damage environments as shown on figure 5 are identified. The fraction of explosion energy received at a distance from a nuclear detonation which determines the severity of the different weapons effects and damage environments depends on the nature and yield of the weapon and the explosion conditions. A typical energy distribution for the weapons damage effects resulting from

a nuclear air burst is shown on figure 6. Therefore, when assessing the vulnerability of survivability of Naval ships and shipboard equipments to the damaging effects of nuclear air bursts, the following "effective weapon yields" as percentages of the actual yield W must be used:

(a) Airblast (and blast-induced shock): 0.50W
(b) Thermal radiation: 0.35W
(c) Residual nuclear radiation: 0.10W
(d) Initial nuclear radiation: 0.05W

In planning for ship and system hardening against nuclear weapons effects, a number of uncertainties exist. For example, it is unlikely that it will be known in advance where or when a weapon will be detonated and the energy yield and type of burst. Naval ships may be attacked by tactical nuclear weapons which are configured and fuzed to detonate either above water (for example, bombs, missiles) at different altitudes, or underwater (for example, depth bombs, mines, torpedoes) at shallow or deep depth. The principal burst types of concern and the dominant weapons effects and damage environments which obtain in each case are briefly discussed, together with associated damage mechanisms and controlling parameters.

4 3.1 Above water detonations. One major type of nuclear weapon burst of interest to ship vulnerability or survivability encompasses above water detonations . These may occur either in the exe-atmosphere at very high altitudes (in excess of 100,000 feet), or in the endo-atmosphere at moderate altitudes (much less than 100,000 feet), or close to the water surface.

4.3,1.1 High altitude (exe-atmospheric) nuclear burst. Above 100,000 feet altitude, the air density is so low that the interaction of the nuclear explosive energy with the surroundings is markedly different from that at lower altitude "air bursts" and, moreover, varies with the altitude. The absence of relatively dense air causes the fireball characteristics in a high altitude detonation to differ from those of an air burst. For example, the fraction of the energy converted into blast and shock is less and decreases with increasing altitude. Two factors affect the thermal energy radiated at high altitude. First, since a shock wave does not form so readily in the less dense air, the fireball is able to radiate thermal energy that would, at lower altitudes, have been used in the production of airblast. Second, the less dense air allows energy from a nuclear explosion to travel much farther than at lower altitudes. Some of this energy simply warms the air at a distance from the fireball and does not contribute to the energy that can be radiated within a short time. In general, the first of these factors is effective between 100,000 and 140,000 feet altitudes, and a larger proportion of the explosion energy is released in the form of thermal radiation than at lower altitudes. For detonations above about 140,000 feet, the second factor becomes the more important, and the fraction of the energy that appears as thermal radiation at the time of the detonation becomes smaller. Although the total energy portion of 85 percent comprising airblast and thermal radiation (see figure 6) remains essentially constant, the partitioning between the two effects differs from the typical 50 percent - 35 percent, depending on the altitude or height of burst. The temperature and pressure in the air at which the detonation takes place influence the distribution. At altitudes above 45,000 feet, part of the energy that would have contributed to the blast wave at

lower altitudes is emitted as thermal radiation. The thermal partition of the energy as a function of weapon yield and burst altitude is shown by the contour lines on figure 7. It is seen that the 35 percent line obtains for yields less than about 20 kilotons and burst altitudes less than 45,000 feet. The dashed portions for yields above 500 kilotons and altitudes above 40,000 feet indicate a region where the data may be applied with somewhat less confidence. Although the total energy emitted as thermal radiation from high altitude bursts is greater than for an air burst closer to sea level (approximately 40,000 feet altitude), about half is re-radiated so slowly by the heated air that it is of no great significance as a cause of damage. The fraction of the explosion energy emitted as nuclear radiation is independent of the height of burst. However, the partition of energy between gamma rays and neutrons received at a distance will vary since a significant fraction of the gamma rays result from interactions of neutrons with nitrogen atoms in the air at low altitudes. Furthermore, the attenuation of the initial nuclear radiation with increasing distance from the explosion is determined by the total amount of air through which the radiation travels. This means that for a given explosion energy yield more initial nuclear radiation will be received at the same slant range on the earth's surface from a high altitude detonation than from a moderately high air burst. In both cases the residual radiation from the fission products and other weapon residues will not be significant at surface level, Both the initial and the residual nuclear radiations from high altitude bursts will interact with the constituents of the atmosphere to expel electrons from the atoms and molecules. Since the electron carries a negative electrical charge, the residual part of the atom (or molecule) is positively charged; that is, it is a positive ion. This process is referred to as "ionization", and the separated electrons and positive ions are called "ion pairs". The existence of large numbers of electrons and ions at high altitudes may seriously degrade the propagation of radio and radar signals. The free electrons resulting from gamma ray ionization of the air in a high altitude burst may also interact with the earth's magnetic field to generate strong electromagnetic fields capable of causing damage to unprotected electrical or electronic equipment over an extensive geographic area below the burst. This phenomena is known as the "electromagnetic pulse" or EMP. The EMP can also be produced in surface and low altitude air bursts but by a different mechanism, and smaller areas beneath the burst point are affected. However, the strongest EMP fields are produced near the burst point by detonation at (or near) the earth's surface, although for bursts at high altitudes, the fields at the surface are strong enough to be of concern. The basic mechanism for EMP is shown on figure 8. The instantaneous (or prompt) gamma rays emitted in a nuclear reaction, and those produced by neutron interactions with weapon residues or the surrounding medium, are basically responsible for the processes that give rise to EMP. The Compton process describes the ionization of air by the gamma radiation. When gamma rays strike air molecules they scatter electrons off in the direction of the gamma radiation leaving the heavier positive-charged nuclei behind. Thus , there is a charge separation in the ionizing region and the electron flow represents a current flow referred to as "Compton currents". If this process occurred with no asymmetries it would be a Focalized. phenomenon and in itself would not radiate any energy. However, in the case of an exe-atmospheric burst, as shown on figure 9, the gamma radiation goes radically outwards from the burst point and can spread over a large distance with no attenuation, except for spherical dispersion. The gamma radiation which is directed upwards, of course, is lost as far as weapon damage effects on the earth's surface are concerned. The gamma radiation which is directed downwards strikes the upper

earth's atmosphere out to the line-of-sight tangent. This radiation interacts with the air in the absorption layer (altitude of 60,000 to 130,000 feet) and in the absorption process, Compton electrons are produced, Thus, there results an ionized region from horizon-to-horizon depending on the height of burst, and at an altitude of 60,000 to 130,000 feet there is saturation ionization from weapon yields on the order of 1 to 2 megatons. The asymmetry associated with the Compton phenomenon is caused by the earth's magnetic field, which is - relatively strong in the absorption layer. When the Compton currents interact with the earth's magnetic field lines, they tend to spiral or rotate about. This continuous rotation of a vector produces an electromagnetic radiation source. The exe-atmospherically generated EMP shines directly down from the absorption layer onto the surface of the earth from horizon to horizon as determined by the height-of-burst (HOB) altitude. Some idea of the extent of coverage on the earth's surface of high-altitude EMP is shown on figure 10. It shows circles within which the full severity of critical EMP threats will result for bursts over the central part of the U.S. at heights of 60 and 300 miles . Critical EMP levels from exe-atmospheric nuclear bursts are of the order of several tens of thousands of volts per feet, corresponding to intense electric field severities, although of very short duration. There also exist magnetic fields as well. To provide some insight into the operational significance of EMP field strengths of these magnitudes, consider the fact that some Naval FM receivers are disrupted by electric signal strengths of the order of a few microvolt (volts x 10-3). The nuclear EMP is a time-varying electromagnetic radiation which increases very rapidly to a peak and then decays gradually. The time waveform of the EMP signal as a monopulse characterized by rise times of several hundred or a thousand times faster than lightening is shown on figure 11. After reaching its maximum, the strength of the electric field falls off and becomes quite small in a few tens of microseconds. The EMP radiation is by nature a very wide spectrum pulse, distributing energy throughout the frequency regime from a few kilohertz (kHz) to several hundred megahertz (mHz), but principally in the radio frequency (long wavelength) region (see figure 11). The broadband nature of the EMP covers many of the electromagnetic frequency bands of Naval shipboard electrical and electronic systems. In spite of its short duration, the EMP pulse carries a considerable amount of energy, especially if the detonating weapon has a yield in the megaton range. The fleet EMP problems can be summarized as follows. The extensive geographic coverage associated with an exe-atmospheric burst means that EMP energy can spread over thousands of miles on the earth's surface so that a fleet of ships at sea does not have to be targeted as such to have its operational capabilities severely impaired. In fact, one probably would not be able to sense any of the other weapons effects and may not even know that a nuclear detonation has occurred. The second essential point is that the EMP transient can cause serious damage to shipboard sensitive systems by either direct field penetration or by coupling of the energy. As the transient electric field of EMP travels away from the weapon detonation point at the speed of light the radiation can be collected by metallic and other electrically conductive components at a distance just as radio waves are picked up by antennas. The energy can then be converted into large magnitude, short duration currents on the surface of structures. These skin currents do not cause damage as such, but recouping of the strong currents (and high voltages) into interconnecting cables, wave-guides, electrical circuits , and so forth, result in damage to sensitive electrical and electronic

components linked to them. The magnitudes and frequencies of the coupled currents and voltages depend on the shielding (inherent or deliberate) of the wiring and circuitry. This shielding is degraded by the existence of apertures and gaps; for example, openings, structural joints, and so forth, typically found in Naval ship design and construction. The man-machine mix of modern Naval combat systems shows increasing dependence on sophisticated electronics to perform highly complex, nearly instantaneous operations. The increased dependency on shipboard electronics demands miniaturization and denser packaging of components. This means that less energy can be dissipated within the smaller components, and that any unwanted energy picked up and transmitted to them will increase their vulnerability to EMP damage. Mission degradation due to EMP damage can be either permanent or of a short-term nature depending on the type of electronics system and its design. There is another damage effect from nuclear weapon explosions critical to shipboard electronics systems . The initial nuclear radiation, specifically gamma rays and neutrons, can affect materials such as those used in radio and radar sets, gyroscopes, inertial guidance devices, computers, and so forth. The nature commonly applied to these radiation effects is TREE, and includes those effects occurring in electronics systems as a result of exposure to the transient initial radiation from a nuclear weapon explosion. The TREE effect persists for a short time; that is, less than 1 minute; however, the response is not necessarily transient. The response (damage) of electronics systems to TREE depends on the nature of the radiation absorbed and also on the specific component affected, and often on the operating state of the system. The actual damage effects are determined by the characteristics of the circuits contained in the electronics package, the exact components (semiconductors, capacitors, cables, wiring, and so forth) present in the circuits, and the specific construction techniques and materials used in making the components. The TREE phenomenon is not restricted to only exe-atmospheric bursts, but is critical to any above water nuclear burst where the initial nuclear radiation is significant.

4.3.1.2 Air (endo-atmospheric) nuclear burst. If a nuclear detonation takes place at an altitude where there is still an appreciable atmosphere, the weapon residues almost immediately incorporate material from the surrounding medium and form an intensely hot and luminous mass, roughly spherical in shape, called the “fireball.” An air or endo-atmospheric burst is defined as one in which the weapon is detonated at an altitude below 100,000 feet, but at such a height that the fireball (at roughly maximum brilliance in its later stages) does not touch the earth’s surface. For example, in the detonation of a 1-megaton weapon the fireball may grow until it is nearly 5,700 feet (1.1 mile) across at maximum brilliance. This means that the detonation must occur at least 2,850 feet above the earth’s surface if it is to be called an air burst. The quantitative aspects of an air burst depend on its energy yield, but the general explosion phenomena are much the same in all cases. For a nuclear detonation below an altitude of about 100,000 feet, from 35 to 45 percent of the explosion energy is received as thermal energy in the visible and infrared regions of the spectrum. The thermal radiation will travel long distances through the air and may be of sufficient intensity to cause moderately severe burns of exposed skin. In addition, below an altitude of about 40,000 feet, about 50 percent of the explosive energy is used in the production of air shock . At somewhat higher altitudes where there is less air with which the explosion energy can interact, the proportion of energy converted into shock

is decreased whereas that emitted as thermal radiation is correspondingly increased. The exact distribution of energy between air shock and thermal radiation is related in a complex manner to the explosive energy yield, burst altitude, and, to some extent, the weapon design. However, an approximate " rule of thumb for a fission weapon exploded at an altitude of less than about 40,000 feet is that 35 percent of the explosion energy is in the form of thermal radiation and 50 percent produces air shock. Thus , for a burst at moderately low altitudes, the air shock energy from a fission weapon will be about half of that from a conventional (chemical) high explosive with the same total energy release; in the latter case, essentially all of the explosive energy is in the form of airblast. This means that if a 20-kiloton fission weapon is detonated below 40,000 feet altitude, the energy used in the production of blast would be roughly equivalent to that from 10 kilotons of TNT. Regardless of the height of burst, approximately 85 percent of the explosion energy from a nuclear fission weapon produces airblast (and shock) and thermal radiation (and heat). The remaining 15 percent is released as various nuclear radiations, Of this, 5 percent constitutes the initial nuclear radiation, defined as that produced within a minute or so of the detonation. The remaining 10 percent of the total fission energy represents that of the residual (or delayed) nuclear radiation which is emitted over a period of time. The residual radiation is largely due to the radioactivity of the fission products present in the weapon residues (or debris) after the detonation. In a thermonuclear weapon, in which only about half of the total energy arises from fission, the residual nuclear radiation carries only 5 percent of the energy released. Because about 10 percent of the total fission energy is released as residual nuclear radiation, this is not included when energy yield is stated in terms of TNT equivalent. Hence, in a pure fission weapon the explosion energy is about 90 percent of the total fission energy, and in a thermonuclear weapon it is, on the average, about 95 percent of the total energy of the fission and fusion reactions. Just as for the thermal radiation, the initial nuclear radiation from an air burst also penetrates a long distance although the intensity falls off rapidly with increasing distance from the detonation point. The interactions with matter that result in the absorption of energy from gamma rays and neutrons are quite different. Different materials are thus required for the most efficient removal of these radiations. In the event of a moderately high-altitude air burst (above 40,000 feet), the fission products remaining after the nuclear detonation will be dispersed in the atmosphere. The residual nuclear radiation arising from these products will be of minor consequence at the earth's surface. If an air burst occurs nearer the earth's surface, the fission products may fuse with particles of land (or water) resulting in radioactive contamination which can pose a danger to exposed personnel.

4.3.1.3 Surface nuclear burst. A surface nuclear burst is regarded as one which occurs either at or slightly above the actual surface of the earth (land or water). Provided the distance above the surface is not great, the phenomena are essentially the same as for a surface burst. As the height of burst increases to a point where the fireball (at maximum brilliance) no longer touches the earth's surface, there is a transition zone in which the behavior is intermediate between that of a true surface burst and an air burst. In surface bursts, airblast and water shock are produced in varying proportions depending on the energy of the explosion and the height of burst. Most of the material damage caused by a nuclear explosion at the surface or at low

or moderate altitudes in air is due -- directly or indirectly -- to the blast wave which accompanies the explosion. The main characteristic of the blast wave, moving outward at high velocity from the center of the fireball, is that the overpressure (pressure above ambient) rises very sharply at the moving front and falls off toward the interior region of the explosion. In the very early stages, the variation of pressure with distance from the explosion center at a given instant of time is shown on figure 12 for an ideal (instantaneously rising) shock front. Essentially, the pressures at the shock (blast) front are two to three times the already very high pressures in the fireball interior. As the blast wave travels away from its source, the overpressure at the front steadily decreases, and the pressure behind the front falls off in a regular manner. After a short time, when the blast front has traveled a certain distance from the fireball, the pressure behind the front drops below that of the surrounding atmosphere and a so-called "negative phase" develops. This is seen on figure 12 which shows the overpressures at six successive times. For the curves labeled t_1 through t_5 the pressure in the blast wave has not fallen below atmospheric, but for curve t_6 the overpressure at some distance behind the front has a negative value. In this region the air pressure is below ambient, so that an underpressure, rather than overpressure, exists. During the negative (rarefaction) phase, a partial vacuum is produced and the air is sucked in rather than pushed away from the explosion as it is when the overpressure is positive. At the end of the negative phase, which is somewhat larger than the positive phase, the pressure has returned to ambient. The peak values of the underpressure are usually small compared with the peak positive overpressures. With increasing distance from the detonation point both peak values decrease, the positive more rapidly than the negative, and both approach ambient when the peak pressures have decayed to a very low level. The time history of the free-field overpressure at some fixed location (observation point) is traced in the curve as shown on figure 13(a), where p_{om} is the peak overpressure pounds per square inch (lb/in^2) absolute and t_{p^+} is the time duration for the positive phase. The arrival time of the shock front depends upon the energy yield of the detonation and the slant range to the point in question, The overpressure increases sharply from zero to its peak value and subsequently decreases to zero in a short time. This marks the end of the positive (or compression) phase. The duration of the positive phase increases with the energy yield and distance from the detonation. Provided the observation point is at a sufficient distance from the explosion, the overpressure will continue to decrease after it falls to zero so that it becomes negative; that is, less than ambient. After decreasing gradually to a minimum value, the pressure increases until it becomes equal to the normal atmospheric condition and the overpressure is zero again. When the negative phase is ended, the blast wave will have passed the given observation point, With the arrival of the shock front at a given location, a strong wind commences, blowing away from the detonation point. This blast wind is often referred to as a "transient wind" because its high maximum velocity decreases rapidly with time, The wind velocity decreases as the overpressure decreases. The destructive effects of a nuclear blast wave are frequently related to the peak incident (free-field) overpressure which gives rise to a diffraction-type loading upon impacting a flat or curved surface, but there is another important quantity called the "dynamic pressure" which gives rise to a drag-type loading. For a variety of ship structures, the degree of blast damage depends largely on the drag force associated with the strong winds accompanying the passage of a nuclear blast wave. The drag force is influenced by certain characteristics of the structure, primarily size and shape, but also depends

on the peak dynamic pressure and its time duration. The dynamic pressure is related to the square of the wind velocity so that changes in the latter will affect the pressure. The dynamic pressure increases suddenly just as the overpressure, when an (ideal) shock front arrives at some point of interest. Then it decreases, but drops to zero some time later than the overpressure, as shown by the curve on figure 13(b), where q_m is the peak dynamic pressure and t_q^+ is the time duration for the positive phase. The dynamic pressure positive phase is thus longer than that of the overpressure. The ratio of the respective positive phase durations depends on the pressure levels involved so that if the peak pressures are high, the positive phase of the dynamic pressure may be more than twice as long as that for the overpressure. At low peak pressures, on the other hand, the difference is only a few percent. By the time the transient wind ceases blowing away from the detonation point, the overpressure is definitely negative (see figure 13); that is, the pressure in the blast wave is less than atmospheric. Hence, air is drawn in and, as a result, the wind starts to blow in the opposite direction (wind reversal), that is, toward the detonation point, but with relatively low velocity. A short time after the overpressure minimum, the wind again reverses direction once more away from the detonation point. The changes in the dynamic pressure corresponding to these wind reversals are indicated on figure 13. The dynamic pressure finally decreases to zero when the blast wave has passed and the ambient atmospheric pressure is restored. Nearly all the direct damage caused by both overpressure and dynamic pressure occurs during the positive overpressure phase of the blast wave. Although the dynamic pressure persists for a longer time, its magnitude is usually so low that the damage effects are insignificant. The direct damage effects w1ll be largely terminated by the end of the ovexpressure positive phase, but the redirect effects, for example, due to fire and flooding, may continue long after the blast wave has passed.

4,3.2 Reflection of blast wave at a surface, So far the discussion has addressed nuclear weapons effects in free space. Nothing has been said about the interaction of a blast wave with either the earth's surface, or on a smaller scale, with a ship's structural envelope (for example, hull plating, deckhouse weather bulkheads, and so forth). When the incident blast wave from a detonation in air strikes a more dense medium, it is reflected off the intervening surface. For a smooth surface, the total reflected overpressure at the surface will be more than twice the peak overpressure of the incident blast wave. The values for the peak reflected pressure will depend on two factors, that is, the strength of the incident wave and the angle at which it strikes the surface. The nature of the surface also has an important effect, but for present purposes the surface is assumed to be smooth so that it acts as an ideal reflector. When the incident blast wave from a nuclear detonation strikes the earth's surface (either land or water) the formation of the reflected wave occurs as shown on figure 14. This shows four stages, corresponding to the successive times t_1 to t_4, in the outward motion of the spherical blast wave originating from an air burst. In the first two stages (t_1 and t_2) the wave front has not reached the ground. In stages three (t_3) and four (t_4), a reflected wave has been produced which is now moving away from the earth's surface as indicated by the respective dashed curves. When such a reflection occurs, an object precisely at the surface not too far from ground zero such as point A (see figure 14), which may be considered as lying within the region of "regular" reflection where the incident and reflected waves do not merge except on the surface, will experience a single pressure increase since the reflected wave is formed instantaneously. Consequently, the overpressure at the surface is generally

considered to be entirely a reflected pressure. The variation of total overpressure with time in this case is shown on figure 15 for an ideal shock front. This is the loading which obtains for ship structural plating which has been impacted by the incident overpressure p from an air burst, but experiences the total Overpressure p_r after reflection of the blast wave. At any location somewhat above the surface (point B, for example), but still in the “regular” reflection region, two separate shocks will be experienced; the first due to the incident blast wave and the second to the reflected wave, which arrives a short time later (see figure 16). When the incident wave reaches point B, at time t_3, the reflected wave is still some distance away. There will, consequently, be a short interval before the reflected wave reaches point B at time t_4. Between times t_3 and t_4, the reflected wave has spread out to some extent, so that its peak overpressure will be less than the value obtained at surface level (see figure 15). In determining the damage effects of airblast on structures in the "regular” reflection region, it may be necessary to consider the magnitude and also the directions of motion of both the incident and reflected waves. After passage of the reflected wave, the transient wind direction near the surface becomes essentially horizontal. The reflected wave travels through air that has been heated and compressed by the passage of the incident wave and as a result, the reflected wave moves faster than the incident wave. Under certain conditions, the reflected wave overtakes the incident wave so that the two wave fronts merge to produce a single front. This process of wave interaction is called Mach or “irregular” reflection. The region in which the two waves have merged is called the Mach or irregular region in contrast to the regular region where they have not merged. The merging of the incident and reflected wave is shown on figure 17. The situation at a point fairly close to ground zero, such as point A on figure 14, is represented on figure 17a. At a later stage farther from ground zero, as on figure 17b, the steeper front of the reflected wave shows that it is traveling faster than the incident wave and is overtaking it. At the stage represented on figure 17c, the reflected wave near the ground has overtaken and merged with the incident wave to form a single front called the Mach stem. The point at which the incident wave, reflected wave, and Mach fronts meet is referred to as the “triple point.” The configuration of the three shock fronts has been called the Mach Y. As the reflected wave continues to overtake the incident wave, the triple point rises and the height of the Mach stem increases (see figure 18). Any object located within the Mach region and below the triple point path will experience a single shock. The behavior of this merged (or Mach) wave is the same as for blast waves in general (see figure 13). At points in the air above the triple point path, two pressure increases will be experienced. The first will be due to the incident wave and the second, a short time later, to the reflected wave. As far as the destructive action of the airblast is concerned, there are two important points to note. First, only a single pressure increase is experienced in the Mach region below the triple point as compared to the separate incident and reflected waves in the region of regular reflection. Second, since the Mach stem is nearly vertical, the accompanying blast wave is traveling in a horizontal direction at the surface; and the transient winds are approximately parallel to the surface. Thus in the Mach region, the blast forces on ship structures and exposed systems are directed nearly horizontal so that vertical surfaces (for example, weather bulkheads) are loaded more intensely than deck structures. The distance from ground zero at which the Mach stem begins to form depends primarily upon the yield of the detonation and the height of burst (HOB) above the ground. These two parameters are important in determining the

extent of blast damage at the surface since they generally define the variation of pressure with distance from ground zero and other critical blast wave characteristics . The variations for air bursts occurring at different heights are most conveniently represented by what are called HOB curves. Such curves have been prepared for various blast wave properties, for example, peak overpressure, peak dynamic pressure, time of arrival, and positive phase duration. Shown on figures 19, 20, 21 and 22 are curves for the case of a l-kiloton nuclear air burst. Values for these and other airblast properties can be determined from the curves for any given weapon yield and height-of-burst by application of appropriate scaling laws; that is, the cube-root Hopkinson laws. In order to calculate the characteristic parameters of an air-blast wave from a nuclear explosion of any given energy if those for another energy are known, appropriate scaling laws are applied. Full-scale tests have shown that cube-root scaling is valid for yields up to, and including, the megaton range. According to this law, if d_1 is the distance from a reference nuclear explosion of W_1 kilotons at which a certain free-field overpressure or dynamic pressure is attained, then for any explosion of W kilotons energy these same pressures will occur at a distance d given by

$$\frac{d}{d_1} = \left(\frac{W}{W_1}\right)^{1/3}$$

This is known as the cube-root or Hopkinson scaling law.

In accordance with the curves shown on figures 19, 20, 21, and 22 the reference explosion has been conveniently chosen as having an energy yield of 1 kiloton, so that $W_1 = 1$. It follows from the above equation that

$$d = d_1 \, W^{1/3}$$

where d refers to a distance (height-of-burst, horizontal distance from ground zero, or slant range) from the point of a nuclear detonation. Thus, for a weapon yield of W kilotons, the peak overpressure p_{om} is found by first calculating a scaled height-of-burst and scaled horizontal distance from ground zero and then interpolating between the appropriate iso-pressure contours shown on figure 19 or 20. In a similar fashion, the horizontal component of the peak dynamic pressure q_m and the corresponding positive phase duration t_p^+ and t_q^+ can be determined using the curves shown on figures 21 and 22, respectively. The cube-root scaling law applies to all the pertinent loading parameters which characterize the severity of a nuclear weapon detonation. The general airblest phenomena resulting from a contact surface burst are somewhat different from those from an air burst described above. In a surface detonation, the incident and reflected shock waves merge instantly and there is no region of regular reflection. All objects and structures on the surface, even close to ground zero, are thus subjected to airblast similar to that in the Mach region below the triple point for an air burst. The free-field overpressure ahead of a moving blast wave resulting from a near-surface nuclear (or chemical H.E.) weapon detonation gives rise to two distinct types of loading environments when it comes in contact with a ship target. One is an airblast-induced pressure loading on ship bulkhead or deck structural plating and ancillary support structures. The other is an airblast-induced

shock loading on shipboard systems and equipments mounted on bulkheads and decks . These two airblast loading environments are discussed separately.

4.3.3 Airblast pressure loads. The phenomena associated with a nuclear (or chemical H.E.) blast wave in air were briefly treated in the preceding sections. The behavior of an object or structure due to the interaction with such a wave is considered in two parts. The first is the forces or "loading" which result from the action of the free-field pressure effects on the structure; the second is the distortion or "response" of the structure to the loading. For an airburst, the direction of propagation of the incident blast wave will be toward the ground at ground zero. In the "regular reflection" region (see figure 17), where the direction of wave propagation is not horizontal, the forces exerted upon structures will also have a considerable downward component. Consequently, in addition to the horizontal loading as for the Mach region, there will also be an appreciable downward force initially. This will cause crushing, for example, dished-in decks on ships, in addition to distortion of vertical bulkheads and hull plating. Details of the interaction of a blast wave with a structure are quite complex and depend on several factors such as geometry of the structure, height of the air burst, and so forth.

4.3.3.1 Diffraction loading. When an airblast wave strikes a structure, reflection occurs off the incident face. As a result the overpressure builds up rapidly to at least twice, and generally several times, the free-field value of the incident wave front. This reflected pressure is controlled by several factors such as the peak free-field overpressure of the incident wave, and the angle between the normal to the wave front and that to the incident face. The pressure increase is due to the conversion of kinetic energy of the air behind the wave front into internal energy as the rapidly moving air is decelerated at the incident face. The reflected blast front propagates back into the surrounding air and the high pressure region expands outward towards regions of ambient pressure. As the wave front moves forward, the reflected overpressure on the incident face of the structure drops rapidly to the free-field level, plus an added drag force due to the wind (dynamic) pressure. At the same time, the air pressure wave bends or "diffracts" around the structure so that it eventually becomes engulfed by the blast wave and approximately the same pressure is exerted on all sides and the top. The incident face, however, is still subjected to wind pressure although the back face is shielded. The stages of the diffraction process described above are shown on figure 23 for the case of a box-like structure with no openings. Events (a) through (e) show an incident wave normal to a face, and events (f) through (i) show a wave incident to a corner of the structure. The pressure differential between the front (incident) and back faces will have a maximum value when the blast wave has not yet completely engulfed the structure as shown on (b), (c), and (d) or (g) and (h). This pressure differential will produce a net lateral (translational) force tending to move the structure bodily. This force is known as the "diffraction loading" because it occurs during the time the blast wave is being diffracted around the structure. The nature and extent of the response will depend upon the size, shape, weight, and rigidity of the structure and its mode of attachment to some contiguous deck. When the blast wave has engulfed the structure, (see figure 23(e) or (i)), the pressure differential is small and the loading is due almost entirely to the drag pressure exerted on the front face. The actual pressures on all faces of the structure are in excess of the ambient atmospheric pressure and will remain so, although decreasing steadily until the positive phase of the blast wave has ended (see

figure 13). Hence, the diffraction loading on a structure without openings is eventually replaced by an inwardly directed pressure; that is, a compression or squeezing action, combined with the dynamic pressure of the blast wave. In a structure with no openings, the loading will cease only when the overpressure drops to zero. The structural damage caused during the diffraction stage will. be determined by the magnitude of the loading and its duration. The loading is related to the peak (free-field) overpressure in blast wave and is consequently an important factor. If the structure has no openings, the duration of the diffraction loading will be roughly the time required for the wave front to move from the incident face to the back of the structure, although the wind loading will continue for a longer period. The size of the structure will thus affect the diffraction loading. For numerous slender structures, for example, masts , tripods, quadrapods, truss-type supports, and so forth located topside on Naval ships, the diffraction period is so short that the corresponding diffraction loading is negligible. If the structure (for example, ship deck-house) exposed to the blast wave has any openings, windows, doors, or panels, which fail in a very short time, there will be a rapid venting and equalization of the pressure between the inside and outside of the structure. This will tend to reduce the pressure differential while diffraction is occurring. The diffraction loading on the deckhouse as a whole will thus be decreased, although the loading on interior bulkheads and partitions will be greater than for an essentially closed structure; that is, one with few openings. This latter effect will result because of confinement of the airblast pressure as would occur in the case of armor-piercing or shaped-charged warheads which are designed to first penetrate and then explode inside a ship’s deckhouse or hull. If the structure has many openings, the crushing action due to the pressure differential between outside and inside, following the diffraction stage, will not occur.

4.3.3.2 Drag loading. During the overpressure positive phase, and for a short time thereafter, a structure will be subjected to the dynamic pressure (drag) loading (the drag pressure is the product of the dynamic pressure and the effective drag coefficient) caused by the transient winds behind the blast front (see figure 13). Under non-ideal conditions, a dynamic pressure loading of varying level may exist prior to the maximum overpressure (or diffraction) loading, Like the diffraction loading, the drag loading, especially in the Mach region, is equivalent to a lateral (translational) force acting upon the structure exposed to the airblast. Except at high blast overpressures, the dynamic pressures at the incident face of a structure are much less than the peak overpressures due to the incident wave and its reflection. However, the drag loading persists for a longer period of time compared to the diffraction loading, which is effective for only a small fraction of a second even for a large structure. It is the effect of the duration of the drag loading on structures which constitutes an important difference between nuclear and high explosive detonations. For the same peak overpressure a nuclear weapon will prove to be more destructive, especially for structures which respond to drag loading. This is because the positive phase duration for the blast effects of a conventional H.E. detonation is much shorter than for a nuclear detonation; that is, milliseconds versus seconds. As a consequence of the longer duration for the same overpressure, nuclear weapons cause more damage to drag sensitive structures than might be expected from the peak overpressure alone. However, when comparing the relative environment severity levels for nuclear and non-nuclear weapons effects, the peak overpressures resulting from conventional H.E. detonations are significantly higher because of the closer distances and

the localized nature of the detonations. In analyzing the structural response of ship deckhouses, hangars, hulls, and shipboard equipments and supporting elements, it is convenient to consider two categories of structures: diffraction-type and drag-type. As the names imply, the former would be affected mainly by diffraction (overpressure) loading and the latter by drag (dynamic pressure) loading. For structures of practical interest in Naval ship design, the relative importance of each type of loading in causing structural damage will depend upon the type of structure as well as on the characteristics of the blast wave.

4.3,4 Airblast-induced shock. The high temperature, high pressure expansion gases generated by the detonation in air of a nuclear (or chemical) weapon results in an outwardly moving blast wave. A primary loading environment which arises from the interaction of the blast wave with a structure, for example, a ship deckhouse, is due to pressure: First, the free-field incident overpressure which strikes a surface, for example, structural bulkheads or decks; the reflected pressure which results from diffraction or the sudden change in kinetic energy of the air particles in the incident blast wave; and, the dynamic (drag) pressure due to the high velocity winds accompanying the detonation. These pressure loads are characterized by an amplitude or level, and a time constant referred to as the positive phase duration. For nuclear bursts the time constant is of the order of a second, and for conventional H.E. bursts of the order of milliseconds. Another equally important airblast loading has come to be recognized as blast-induced shock. Blast-induced shock damage was observed in the full-scale ship tests Operations CROSSROADS and SAILOR HAT. The interaction of a piece of equipment (for example, missile launcher, fire-control director) located topside on a ship with the impulsive loading of airblast results in a shock response. The severity of the shock depends on several factors: blast pressure loading, natural vibration characteristics of the system, its inherent shock resistance, the mounting and foundation design, and so forth. For the case of low-altitude air bursts, the blast wave causes a shock loading predominately in the horizontal (athwartship) direction due to the Mach effect (see figure 17). The resulting shock motions, that is, sudden accelerations and high velocities, experienced by the shipboard equipments would, therefore, be horizontal, and any vertical component of motion would result 'from mechanical coupling. Thus , the blast-induced shock environment is different from underwater shock where the resultant shock motions imparted to the same equipments are predominantly vertical, and any horizontal motions are due to coupling. However, for an air burst occurring almost directly above a ship, for example, a proximity fuzed missile warhead containing a large H.E. charge, so that it experiences blast effects in the region of regular reflection (see figure 17), the induced shock motions would be very much like those from underwater shock. There are several distinguishing features between the blast-induced shock produced by a nuclear air burst and a conventional air burst. A nuclear blast wave is planar and expansive in dimension so that it eventually envelopes the entire ship, whereas an H.E. blast wave is more curvilinear and of much smaller dimension so that the loading environments it creates are localized. This results in the fact that nuclear (free-field) overpressures, at practical ranges, are of the order of one fifth the levels for conventional H.E. airblast. However, the positive duration for nuclear airblast is typically 1 or 2 seconds while that for H.E. airblast is of the order of milliseconds, so that the resulting positive impulse for the former is generally greater by factor of about 400-500. For a nuclear detonation the predominate blast-induced shock on shipboard equipments

is that transmitted through their foundations. This is due to the large elasto-plastic deformations of the bulkheads and decks, on which equipments are mounted, caused by the blast wave hitting the side of a ship. For a conventional detonation, the predominant blast-induced shock loading is caused by the incident overpressure acting directly on the equipments; little, if any, shock motion would be transmitted through foundations because of the localized nature of the airblast. However, for equipments located inside the deckhouse or hull, lateral deformations of the weather bulkhead plating could impart shock motions through equipment foundations. Depending on how internal equipments are mounted and their orientation to a propagating blast wave will determine the nature of the shock response. It is clear that shock sensitive equipments mounted inside a ship's deckhouse or hull would experience no direct blast-induced shock loading from H.E. airblast, except in the case of a delay-fuzed, penetrating weapon designed to detonate internally or on contact.

4.3.5 Underwater detonations. The rapid expansion of the hot gas hubble formed by an underwater nuclear detonation results in a shock wave being propagated in all directions through the water medium. The shock wave is similar in general form to a blast wave in air, although it differs in detail. Just as in air, there is a sharp rise in overpressure at the shock front; however, the peak free-field overpressure does not fall off as rapidly with distance in the water. Hence, the peak values in water are much higher than for an explosion of equal intensity in air. For example, the peak overpressure at 3,000 feet from a 100-kiloton burst in deep water is about 2,700 lb/in^2 compared with a few lb/in^2 for an air burst. On the other hand, the duration of the shock wave in water is shorter than in air; that is, on the order of a few hundredths of a second compared with about a second or more for a nuclear detonation and tens of milliseconds for an H.E. detonation. When the peak pressure from an underwater detonation is high, the velocity of the shock front is greater than the normal speed of sound. The pressure wave thus propagates as a spherical wave originally at speeds much faster than that of sound. As the pressure wave propagates away from the point of detonation, the pressure decays in an exponential fashion so that at lower free-field overpressures the shock front velocity becomes less, dropping rapidly to the sound velocity just as in air. In the meantime the gas bubble begins to expand in size while the pressure in the bubble gradually decreases. This expansion overshoots the equilibrium condition between hydrostatic (local ambient) pressure and gas pressure. After reaching a maximum radius with a minimum pressure considerably below ambient, the pressure differential brings the outward motion (expansion) to a stop, and the bubble begins to contract at an increasing rate. The inward motion (contraction) continues until the compressibility of the gas in the bubble, which is insignificant in the phase of appreciable expansion, acts as a powerful check to reverse the motion abruptly. The inertia of the water together with the elastic properties of the gas and water thus provide the necessary conditions for an oscillating system, and the bubble does in fact undergo repeated cycles of expansion and contraction. The sequence of underwater explosion events described above (see figure 24) shows the time history of the initial shock wave and two bubble pulses where T and T are the periods of the first and second pulses, respectively. At each minimum (each recompression), additional pressure pulses are emitted which are not shock waves and which become weaker with each oscillation. However, they still represent important dynamic loads for ship structures. The first such bubble pulse can have a peak pressure of 10-15 percent of the shock wave peak overpressure.

During the bubble pulsation process, the gas bubble migrates upward because of the influence of gravity, with the maximum migration occurring during the pressure minima. When the shock wave in water strikes a relatively rigid, submerged surface such as the hull of a ship, positive (compression) reflection occurs as in air. However, when the water shock wave reaches the upper surface (air interface), an entirely different reflection phenomenon occurs. As a result of the shock wave meeting a less rigid medium (air), a reflected wave is sent into the water, but this is a rarefaction of tension wave (that is, negative pressure) of short duration. At a point below the surface the interaction of the negative reflected wave with the direct positive wave produces a decrease in the water shock pressure. This is referred to as the “surface Cutoff". The idealized variation at a given target location of the shock overpressure with-time following an underwater detonation, in the absence of bottom reflections, is as shown on figure 25. This idealized wave shape is called the “acoustic approximation” where the initial shock wave and the negative reflected wave are assumed to travel at the same speed. In actual practice, however, the acoustic approximation is modified depending on the conditions of the detonation. Essentially, passage of the reflected (negative) wave through water which has been disturbed by the direct (positive) shock wave results in a less sharp surface cutoff than the ideal shown on figure 25. Typical underwater pressure pulses observed from experiments are shown on figure 26; their deviation from the “acoustic approximation” is noted. The time interval between the arrival of the direct shock wave at a particular underwater target and that of the cutoff, signaling the arrival of the reflected negative wave, depends on the shock velocity, burst depth, target depth, and the distance from burst point to target, These three distances determine the lengths of the paths traveled by the direct (positive) and reflected (negative) shock waves reaching the target. If the target is close to the surface, for example, a shallow ship bottom, then the time elapsing between the arrival of the two shock fronts will be small and the cutoff will occur soon after arrival of the shock front. A surface ship may then suffer less damage than a deeper submerged target (a submarine) at the same distance from the detonation because of the resultant venting of shock energy. Certain effects connected with the sea bottom may be important, particularly in shallow water. One of these is bottom reflection of the primary shock wave. Unlike the reflection from the air-water interface, the bottom reflection is a compression wave which increases the pressure in regions it traverses, The total pressure experienced by a ship’s hull now includes a positive reflected pressure, in addition to the initial shock pressure and the negative reflected pressure. The characteristics of the overall pressure pulse will be dependent on the magnitudes and signs of the various pressures and the times of arrival of the two reflected components. These quantities are determined by the three distances mentioned in connection with figure 25 and the water depth, as well as by the explosion yield and the nature of the bottom. In deep water, where bottom (and other positive) reflections are not significant, the initial shock wave and the negative surface reflection are generally the roost important features of the pressure disturbance from an underwater detonation.

4.3.5.1 Burst depth categories. No clear demarcation exists in terms of height-of-burst for the different categories of above water nuclear detonations (exe-atmospheric, endo-atmospheric, high altitude, and air bursts); so too here there are no well-defined depths for underwater detonations (see 4.3.1). This is because the primary controlling parameter is weapon yield,

which can be any reasonable value. Empirical classifications for the different underwater depth categories have been developed; these are shown on figure 27. As expected, the controlling parameter is the weapon yield W in terms of kilotons TNT equivalent. The classifications shown have been tested for yields as large as 30 kilotons, and they are probably valid for yields of up to about 100 kilotons. The depth bounds for the "contained" and "no spray dome" classifications were derived from H.E. tests, but have not been confirmed by nuclear tests . Therefore, they are to be interpreted as "containment possible" and "possible limiting depth for spray dome formation", respectively. The following explosion phenomena were used to empirically establish the bounds for the depth classifications as shown on figure 27:

(a) Near-surface burst. The layer of water above the burst is vaporized by the explosion. The surface phenomena for this type of burst and the associated hazards (damage environments) are unknown. The radiological hazard of the base surge is considered to be unimportant compared with the airblast and fallout.

(b) Very shallow burst. The gas bubble vents early during the first expansion cycle (see figure 24); that is, when the bubble pressure is greater than ambient, and fission products are blown out at that time.

(c) Shallow burst, The gas bubble vents late during the first expansion cycle after the bubble pressure has dropped below ambient, and fission products are blown in.

(d) Deep bursts. The depth of burst is equal to or greater than the radius of the fully expanded gas bubble, but not as deep as the very deep burst described below.

(e) Very deep burst. The explosion is at sufficient depth that the gas bubble breaks up, becomes a vortex ring, or loses its identity before reaching the surface.

For purposes of highlighting the salient weapons effects of underwater nuclear detonations and the resulting damage environments of importance to ship structure and shipboard equipment vulnerability, attention is focused on two depth regimes of practical interest. These correspond to shallow and deep bursts, and are chosen to illustrate the principal damage effects or environments which occur. To fix ideas, for a weapon yield of 20 kilotons "shallow burst" implies a depth regime of about 200 to 500 feet, and "deep burst" a depth regime of about 500 to 1500 feet.

4.3.5.2 Shallow burst. For underwater nuclear detonations of principal concern to Naval ship vulnerability or survivability, the explosion phenomena and weapons damage effects or environments apply equally well to conventional H.E. weapons of equal yield except for the (nuclear) radiation effects. The initial underwater shock wave is followed by one or more oscillatory bubble pulses emitted during the contraction phase as the explosion bubble approaches its minimum diameter. Almost coincident with attainment of minimum diameter, the bubble will migrate upward in nearly a step fashion due to buoyancy forces, remaining at the shallower depth until the minimum of the second oscillation has occurred when it will move upward again (see figure 24). If a rigid surface such as the underside of a ship's hull (or ocean bottom) is in the vicinity of the explosion, the bubble will tend to migrate toward this surface. If

contact is made with the ship's underside, a portion of the bubble can collapse upward striking the hull and producing a spiked loading condition analogous to a water hammer effect. The resulting damage effects or environments are of two general types. One is the direct effect of the shock wave on a ship's hull and the other is the indirect effect on equipments located not only within the hull envelope, but also those mounted on the deck and superstructure, The shock wave impacting on the hull can cause severe stressing of the framing and rupture of the hull plating under a severe loading condition. The shock energy transmitted vertically through the deck levels will impart sudden motions to sensitive ship machinery and combat equipments. The principal shock motions experienced will be in the vertical direction; however, due to mechanical coupling there could also be some horizontal motion. Depending on the severity of the shock loading and on the inherent shock hardness of system components located topside on the deck and superstructure, these could experience significant structural damage and operational impairment. Another important damage effect can result from the direct shock waves impacting on the underside of a ship's hull. Depending on a standoff distance and the location along the keel at which the detonation occurs, a near-resonance excitation known as "whipping" may be induced in which the main hull girder vibrates in beam-like modes. The occurrence of resonance vibrations depends upon the natural frequencies of the girder structure relative to the bubble pulse frequencies. The resulting vibratory motions can be so extreme as to cause severe damage due to plastic deformations ("hinging") of the main hull girder and rupture of the hull plating and reinforcing structure. This would undoubtedly result in flooding of vital spaces and loss of ship mobility. For a relatively shallow weapon explosion where the gas bubble vents during the first expansion cycle, the action of the underwater shock wave on the hull of a ship is usually terminated by the surface cutoff (see figure 25). This occurs when a wave of negative (or zero) — pressure reflected from the water surface reaches the hull. If the cutoff time, that is, the difference in arrival times between the direct and surface-reflected waves, is short compared to the duration of the shock wave, then less than half of the shock energy will be delivered to the ship bottom before cutoff. An underwater nuclear detonation produces a shock wave of duration which is much greater than the cutoff time. In that case energy is not the determinative factor of shock severity. A better measure of the underwater shock severity for nuclear attack is "bodily velocity", which is given by the ratio of the impulse in the free-water pressure pulse at the bottom of the ship to the mass of the ship, This translates to the following formula:

$$v_b = \frac{2p}{pc} \cos \theta$$

where:

v_b is the peak bodily velocity (feet per second)
p is the peak incident overpressure for the initial shock wave (lb/in^2)
pc is the acoustic impedance-of seawater (lb/in^2 per feet per second)
0 is the angle of incidence measured as the ratio of burst depth (D) to slant range (R)

For the case of a conventional H.E, underwater detonation, on the other hand, the cutoff time is long compared to the shock wave duration so that the full energy in the shock will be delivered to the ship bottom. In that case energy is determinative of shock severity and “shock factor” is the applicable measure for the resulting shock response. Although the major portion of the shock energy from a shallow underwater nuclear detonation is propagated through the water as a shock wave, a considerable amount of energy is transmitted through the air-water interface as a blast wave in air. The particular mechanism will depend on weapon yield and depth of burst; however, one or more blast waves will generally follow. The shallower the depth of burst for a given yield, or the greater the yield for a given depth, the more severe will be the airblast. Although the airblast can cause direct damage to a ship’s superstructure, it could also capsize a ship. Of the three structural response variables (displacement, velocity, and acceleration) which characterize the motion of the bodies subjected to shock loading, whether from underwater or airblast-induced shock, velocity has been found to be the most meaningful for quantifying the shock motions of shipboard equipments and for correlating the motions with observed damage from at-sea tests; for example, operations CROSSROADS, SAILOR HAT, and so forth. On the other hand, the more meaningful variable for quantifying the shock response of ship structure (for example, hull, deck, superstructure plating and stiffening members) subjected to shock loading is displacement (strain). Another phenomenon of shallow underwater nuclear detonations is the “base surge,” a doughnut-shaped gigantic wave (or cloud) which surrounds the hollow explosion column near its base. The visible base surge is essentially a dense cloud of small water droplets much like the spray at the base of high waterfalls, but having the property of flowing almost like a homogeneous fluid. From the weapons (damage) effects standpoint, the importance of the base surge lies in the fact that it is likely to be highly radioactive because of the fission (and other) residues present either at its inception or dropped into it from the radioactive cloud. Because of its radioactivity, the radioactive base surge may represent a hazard for a distance of several miles, especially in the downward direction. The necessary conditions for the formation of a base surge have not been definitely established, although it is reasonably certain that no base surge would accompany bursts at great depths. In an underwater nuclear explosion, much of the thermal radiation and initial nuclear radiation are absorbed within a short distance from the point of detonation. The energy of the absorbed radiations will merely contribute to heating of the surrounding water. Depending on the depth of burst, some of the thermal and nuclear radiations will escape through the air-water interface, but the intensities will generally be less than for an air burst. However, the residual nuclear radiation, that is, that emitted after the first minute, now becomes of considerable significance since large quantities of water in the vicinity of a shallow detonation will be contaminated with radioactive fission products. Underwater detonations also generate relatively slow, outward-moving surface waves with certain characteristics which become more pronounced when the detonation occurs in shallow rather than deep water. The energy- in the surface wave motion has been estimated to be between 2 and 5 percent of the weapon yield. Water wave damage is possible to ships located moderately near to surface zero. In certain instances, capsizing may occur.

4.3.5.3 Deep burst. The deeper a nuclear detonation takes place, the greater the containment of the explosion phenomena and the mitigation of the resulting weapons effects because of the increased ambient pressure and water volume with depth. Some of the weapons damage effects which occur for shallow bursts would be of lesser severity. The base surge, and particularly the radioactive base surge, would be contained to a varying degree depending on weapon yield and burst depth. The surface radioactivity would be operationally insignificant within an hour or so from the time of a deep burst, and in some instances may be faint enough as to escape detection. Also there would be little venting of the shock energy at the air-surface interface and, hence, no airblast of any significance would result from the venting. Because of this, however, the underwater shock effects could be of greater severity, but up to a point as seen from the equation for bodily velocity (see 4.3.5.2). The burst depth (D) and the standoff distance (R) control the shock severity. For purposes of this handbook, the intent here is to highlight a unique weapon effect of deep bursts which does not cause mechanical damage as such but can result in a serious operational impairment (incapacitation) of a ship's mission capabilities. Somewhat analogous to the EMP from above water nuclear detonations which can damage and seriously impair the functioning of vital shipboard electrical and electronics systems, there occurs the intense acoustic reverberation known as "blue-out" due to the propagation in the ocean volume of the shock wave resulting from deep nuclear (or H.E.) explosion. It is known that even the relatively low-level acoustic waves from an active (pinging) sonar can, under certain conditions, result in high reverberation levels which can seriously degrade underwater surveillance and communications operations. The volume reverberation caused by a propagating shock wave is order of magnitude greater in intensity and expanse; the time duration of this reverberation may also prove serious. Depending on the prevailing oceanographic conditions, the reverberation can become trapped in the naturally-occurring acoustic paths of the ocean and propagate over long distances of up to several thousand miles. Although the intense "blue-out" environment may not cause physical damage as such to a ship or its mission-essential underwater systems, it can cause serious operational problems of a transient nature.

4.3.6 Synergistic considerations for nuclear weapons effects. So far little has been said about the possibility of ship structure, shipboard equipment, and crew personnel receiving multiple or combined types of damage (injury) from a single weapon explosion. Being exposed to multiple damage environments would be a common occurrence in the case of nuclear weapons (and to some extent for conventional H.E. weapons). Multiple damage (injury) may be experienced simultaneously or be separated in time by orders of seconds, minutes, and even days in the case of residual nuclear radiation (radioactive fallout). This depends on the sequence and time duration of the individual explosion phenomena and associated weapons effects. The multiple-type damage (injury) would be the consequence of synergistic coupling between individual effects which could result in more severe damage environments than the component effects. Some of the salient aspects of coupling between individual nuclear effects and the damage implication for ship structure, equipments, and personnel are discussed. To aid in identifying possible synergism between nuclear effects which might prove quantitatively (or qualitatively) different from individual effects in terms of damage environments, it would be helpful to summarize the principal events. The timing and sequence for the principal expansion phenomena and weapons effects or damage environments resulting from a nuclear explosion are shown on figure 28. Also shown are the relative durations for each. To

preclude cluttering of the figure, only those events which take place within the first couple of seconds from the time of detonation are shown. Following earlier statements, the blast event could be generalized to include shock for the case of underwater bursts, and leave out the EM? damage environment for that domain. The first, almost instantaneous, indication of a nuclear detonation in air is a flash of brilliant light accompanied and followed by intense heat, both of which are part of the effective (or prompt) thermal radiation emitted from the heated air of the fireball within the first minute (or less) following the explosion. The initial nuclear radiation produced by the gamma rays and neutron particles may continue after the thermal radiation has ceased. This initial radiation produces the electromagnetic pulse (EMP). Coincident with the explosion is the production of debris and ejects which eventually become radioactive as a result of nuclear radiation effects. Then, surface and water shock will arrive followed very soon by the airblast (and sound) wave. As the fireball rises, strong afterwinds will be experienced. Early radioactive fallout will follow which may continue for several hours. The final events involve late-time effects and resulting damage environments such as delayed radioactive fallout which may persist for days or weeks, and blackout. The gamma radiation is comprised of two parts as shown on figure 28. First, the prompt gamma rays which together with the neutrons produced during a period of 1 minute after detonation comprise the initial nuclear radiation. This radiation effect produces the electromagnetic pulse (EMP) which can-cause serious damage or impairment of modern shipboard electronics and electrical systems. Second, the delayed gamma rays which together with other explosion phenomena (neutron, alpha, and beta particles) comprise the residual nuclear radiation resulting in radioactive fallout. The injurious effects of nuclear radiations on people range from radiation sickness to serious systemic changes. The weapons effects or damage environments discussed above also obtain in the main for the case of underwater nuclear explosions, but with certain caveats. The difference in properties of the two media, air versus water, is reflected in the relative severity (and hence importance) of the various weapons effects and not in whether they occur at all. For example, water shock resulting from an underwater detonation is of principal importance in causing shock damage to inadequately-designed structural components and vital systems. Also, if the detonation occurs at a shallow enough depth so that the shock energy vents at the air-surface interface, a certain amount of energy will be manifest as airblast and its attendant damage effects (including blast-induced shock). The severity of this vented airblast is dependent on weapon yield and burst depth but in general can be considered of secondary importance for underwater detonations . For above water nuclear detonations, airblast is of primary importance as a damage environment for ship structure and exposed equipments. As in tile previous case, the airblast induces a shock damage environment as a primary effect but one which is quite different than that of underwater shock. In a similar vein, the thermal radiation effects (visible and infrared) from an above water nuclear detonation create damage environments which would certainly prove more critical than those in water. As another example, the EMP which is of great significance for nuclear air bursts would be of no consequence for underwater detonations. Two thermal pulses generally occur in a nuclear explosion as shown on figure 28. From an air burst at altitudes below about 100,000 feet, the thermal radiation is emitted from the fireball in two pulses. However, the first pulse is quite short and carries roughly 1 percent of the total radiant energy and is, therefore, of no consequence. The second pulse is of longer duration and,

hence, is of some significance in causing damage to structural materials such as aluminum by degrading their mechanical properties; for example, the modulus of elasticity and ultimate strength. The duration of the effective thermal pulse from a l-kiloton air burst is about 0.4 second whereas from a 10-megaton explosion it is more than 20 seconds. With increasing altitude the character of the thermal radiation pulse changes. At altitudes above 100,000 feet there is only a single thermal pulse and its effective duration depends on the height of burst and energy yield of the explosion; for example, the duration is of the order of 1 second or less for weapons in the megaton range. For explosions above about 270,000 feet, the pulse length is somewhat longer. Thermal radiation can cause serious ship damage by accidentally igniting combustible materials carried on board, for example, highly flammable hydrocarbon fuels. Any spreading fires may, in turn, cause cook-off of sensitive shipboard munitions such as missiles and projectiles which could result in a succession of detonating warheads, subsequently leading to widespread blast, fragments, and more fires. Thermal radiation is also capable of causing severe skin burns and eye injuries to exposed personnel at distances at which fuel ignition or weapon cook-off may not occur. Thermal radiation can, in fact, be an important cause of injury to personnel from both direct exposure and as the result of fires, even at greater distances than other nuclear weapons effects. Subsequent to the (effective) thermal pulse from a nuclear detonation, the shock wave occurs next in the sequence of weapons effects. In an overall sense, the airblast (including blast-induced shock) and underwater shock environments, both of which result from the shock front phenomenon, cause the most serious damage to a ship and its vital equipments. They are, therefore, two of the more critical damage environments to be considered in any assessment of ship vulnerability or survivability and requirements for passive protection design. A coupling may occur between the underwater shock and the vented airblast or induced-shock environments in the case of a shallow nuclear burst. The resulting damage environment can prove to be more severe than either of the individual ones. The underwater shock loading transmitted up through the hull structure would manifest itself as sudden vertical motions imparted to vital internal machinery and topside combat systems or equipments. There would almost simultaneously occur athwartships motions of these same components imparted by the induced shock of the airblast resulting from venting of the detonation. The timing of the two events and the severity of the resultant synergism would, of course, depend on several controlling factors, such as warhead yield, depth of burst, and ship standoff from the point of detonation. There also exists an important coupling between the thermal effects and the airblast-induced shock effects resulting from a nuclear weapon detonation which could prove critical. The thermal radiation pulse from a nuclear detonation heats any exposed ship structure or system in its path. The temperature rise caused by such heating can lead to serious problems for temperature-sensitive materials. Of the metals commonly used in ship construction (for example, deckhouses, helo hangers, exposed equipment foundations, and so forth), the aluminum alloys are particularly vulnerable to the thermal radiation because of their low thermal tolerance and relatively low mechanical strength. The loss in mechanical strength could cause an aluminum load bearing element to fail prematurely. If the element does not immediately fail, it may do so when the blast (pressure) loading arrives due to its weakened state. Nuclear airblast can, therefore couple with thermal effects to drastically influence the damage caused to shipboard aluminum structures. The steel alloys used in ship construction are much less vulnerable to a similar degradation of mechanical properties and, hence,

on ultimate load-carrying capacity. However, the high temperatures which result from thermal radiation may induce thermal stresses in structural plating or support elements made of steel (or aluminum), and these stresses alone can cause or contribute to premature failure. The stresses resulting from the subsequent blast pressure, added to the thermal stresses, would contribute to failure. In nuclear airblast there are two components of the induced shock loading (motion) experienced by exposed equipments (see 4.3.4). One is due to the blast pressure acting directly on the piece of equipment (for example, radar antenna, missile launch box), and the other is that transmitted through the equipment's foundation. Nuclear airblast having a large incident front can cause severe elasto-plastic deformations of the decks on which equipments are mounted and these translate to shock motions transmitted through the foundations. This situation is not viewed as a case of synergistic coupling between individual weapons effects or damage environments, but rather one in which there are two components of the same loading. Other cases of so-called synergistic coupling (for example, EMP-induced heating and nuclear radiation heating) are insignificant. Thus, the two instances of synergistic coupling between individual nuclear weapons effects or damage environments of real significance to ship survivability design are the high-temperature heating of structural materials due to the thermal pulse followed by the blast-induced pressure and shock loading transmitted to equipments located topside on a ship followed by the blast-induced shock loading caused by the vented alrblast in the case of an underwater burst.

4.3.7 Nuclear injury effects on personnel. The three principal nuclear weapons effects or damage environments which result in personnel casualties are: blast (shock), thermal radiation, and nuclear radiation (initial and residual). There is the possibility of shipboard personnel receiving multiple types of injury, which would be a common occurrence in the advent of a nuclear war at sea. Multiple injuries may consist of any combination of blast, thermal radiation, and nuclear radiation effects which might be received nearly simultaneously or be separated in time as specified in 4.3.6. In synergistic or combined injuries, the interaction of the various forms of personnel trauma can result in enhanced delayed mortality,

4.3.7.1 Blast mechanical injury. Blast injuries to shipboard personnel may be direct or indirect. A direct blast injury is caused by the sudden change in environmental pressure due to the blast overpressure acting directly on the exposed body. Although the human body is relatively resistant to the crushing forces of the blast overpressure, the sudden pressure differences may cause serious injury. Anatomic localization of such injury occurs predominantly in air-breathing organs such as the lungs, gastroenteric tract, ears, and prenasal sinuses. An indirect blast injury may be caused by blast-energized debris striking exposed personnel or by translational impact of personnel against rigid objects due to the blast winds, Other miscellaneous indirect injuries to shipboard personnel could be caused by blast-induced fires and the high concentration of dust circulated by the blast winds.

4.3.7.2 Thermal radiation injury, Thermal radiation is composed of energy in the ultraviolet, visible, and infrared regions of the spectrum and travels in a straight line at the speed of light; it is emitted within periods of a few milliseconds to several tens of seconds. Upon detonation of a nuclear weapon, exposed personnel will sustain skin burns at distances that may be

larger than those at which injury occurs as a result of blast overpressure or nuclear radiation. Burns may be produced directly by absorption of radiant energy by the skin or indirectly by heat transference through clothing or by ignition of clothing. The severity of skin burns is related to the degree of elevation of skin temperature and its time duration. Pain, a familiar warning sensation, is useful in alerting an individual to evade the thermal pulse but the amount of pain experienced is not related to burn severity. The severity of skin burns can, however, be measured according to the following classifications: first degree, second degree, and third degree burns. Another injurious effect on personnel of the thermal radiation from a nuclear explosion is that on the eyes. Exposure of the human eye to the bright flash of a nuclear explosion produces two possible injuries: flashblindness and retinal burns. Flashblindness (dazzle) is a temporary impairment of vision which lasts several seconds to minutes, and is caused by the saturation of the light-sensitive elements in the retina of the eye. It is an entirely reversible phenomenon which will normally blank out the entire visual field of view with a bright after-image. Flashblindness normally will be brief, and recovery is complete. A retinal burn, on the other hand, is a permanent eye injury that occurs whenever the retinal tissue is heated excessively by the focused image of the nuclear fireball within the eye. The underlying pigmented cells absorb much of the light and raise the temperature in that area. Retinal burns can be produced at great distances from a nuclear explosion because the probability of eye burns does not decrease as the square of the distance from the detonation as is true of many other nuclear damage effects. For example, explosion yields greater than 1 megaton and at heights of burst greater than about 130,000 feet may produce retinal burns as far out as the horizon on clear nights. When personnel have adequate warning of an impending nuclear burst, closing or shielding of the eyes will prevent flashblindness and retinal burns.

4.3.7.3 Nuclear radiation injury. The injurious effects of nuclear radiations (gamma rays, neutrons, beta particles, and alpha particles) on shipboard personnel represent a phenomenon that is completely absent from conventional high-explosives. Serious radiation injury may result from either the initial radiation or the residual (delayed) radiation. Gamma rays and neutrons resulting in various proportions from the initial nuclear radiation are responsible for biological injury to personnel. Individuals exposed to whole body ionizing radiation may show certain symptoms of radiation sickness. The time interval to onset of these symptoms, their severity, and duration generally depend on the amount of radiation absorbed. Within any given dose range, the injurious effects that are manifested can be divided into three time phases. During the initial phase of radiation absorption, individuals may experience nausea, headache, dizziness, and a generalized feeling of illness; the severity of these symptoms increases with increasing doses. During the latent phase, exposed personnel will experience few, if any, symptoms and most likely will be able to perform operational duties. The final phase is characterized by frank illness that requires hospitalization after exposure to the higher doses; this phase is consummated by recovery or death. The importance of residual nuclear radiation as a source of injury to shipboard personnel depends upon the necessity for military operations in or near areas of local radioactive fallout, Time of arrival, weathering, and decay of the deposited fallout all result in a constantly changing rate of external protracted exposure in contrast to the almost instantaneous exposure to the initial radiation. Gamma rays present the major significant external hazard from residual radiation.

Injuries to personnel will range from those described previously for initial radiation exposures to lesser effects depending on dose rate. Beta burns can occur if fallout particles remain on the skin for periods of hours or more. Severity of the burns is a function of the particle radioactivity and the time period they adhere to the body. Radioactive particles entering the body by inhalation or through breaks in the skin may be deposited in the body where alpha particles, beta particles, or gamma rays continue to bombard adjacent tissues. Once fixed inside the human body, removal is almost impossible except through natural processes. The injurious effects of internal radioactive emitters to an individual usually become apparent after a period of years and are manifest as serious biologic and genetic changes.

4.4 Non-nuclear (H.E.) weapons effects and damage environments. A conventional H.E. detonation involves a chemical reaction which, upon the application of heat or shock, decomposes an explosive compound (chemical mixture) with extreme rapidity, followed by an immediate release of energy in the form of intense heat and much gas. The decomposition or rearrangement of the explosive compound results in the formation of more stable materials. The action of the intense heat on produced or contiguous gases results in the development of a sudden pressure effect called a “shock wave.” The temperature in the product gases is of the order of 5,500°F and the pressure reaches 750,000 lb/in^2. The chemical reaction necessary to generate an explosion can be initiated if sufficient energy is provided at some point in the explosive. This is usually done by means of a heated wire or by frictional heat from the impact of a firing pin, either of which acts directly upon a small amount of especially sensitive material (the detonator). If the detonator output is too low-powered to reliably initiate a high-order detonation in the main explosive, a booster is placed between the two. The chemical reaction of the booster, in turn, initiates the reaction in the main explosive. Once initiated, the intense heat and pressure developed (shock wave) are sufficient to propagate the chemical reaction through the main explosive. The way in which the reaction proceeds depends upon the physical and chemical properties of the explosive material, and the external physical factors such as the container or surrounding medium. However, two general types of behavior can be distinguished. The more important one from the viewpoint of destructive potential to Naval ships is the process of “detonation” in which the chemical transformation occurs so rapidly that it can keep up with the physical disturbance resulting from the reaction. A reaction occurring in this way develops a very narrow boundary between the explosive material in its initial state and the high-temperature, high-pressure reaction products, This clearly defined and rapidly advancing discontinuity is known as a “detonation wave” which travels with a velocity of several thousand meters per second. On the other hand, the chemical reaction in the main explosive may take place more slowly and be unable to keep up with the advancing physical disturbance of pressure and particle motion it causes. The final reaction condition is then reached more gradually and there is not a well-defined. boundary between the explosive material in its original state and the reaction products. This more gradual process is called “burning” although the rate at which it takes place may still be high, The two types of chemical disturbance, detonation and burning, correspond closely to the two major classifications of military explosives. One is the high explosives such as TNT which detonate with large and rapid evolution of energy, and are used for destructive purposes in the warheads of missiles, bombs, projectiles, torpedoes, depth charges, and mines. High explosives undergo detonation at

rates of from 3,300 to 28,000 feet per second, The other classification is the low explosives such as propellants which burn with a gradual building-up to the final state and are used for powering aircraft, missiles, rockets, projectiles, and so forth. Low explosives undergo auto-combustion at rates that vary from a few feet per second to approximately 1,300 feet per second. For purposes of this handbook, the chemical high explosives used in warheads to create damage environments against combatant ships are of principal interest. So-called “missile blast” and “gun blast” due to launching of own weapons introduce a kind of shipboard damage environment considerably different in terms of severity, both qualitatively and quantitatively, from the blast environment created by detonating warheads. The former results from the burning of low-explosive propellants while the latter results from the detonation of high-explosive charges specifically intended to cause gross damage to ship structure and equipments. The sequence of explosion phenomena and principal weapons (damage) effects following detonation of a chemical H.E warhead is shown on figure 29, The time it takes for the main filling of the warhead with product gases to be brought to complete detonation once the process is initiated is of the order of a tenth of a millisecond, When the detonation wave reaches the warhead casing, a shock wave propagates through the casing imparting an initial outward velocity to its metal particles. Under the influence of the very high pressure generated by the conversion of the solid explosive into gas, the warhead casing then expands in a balloon-like manner, This ballooning continues until the diameter reaches about 1.5 times its original size, with the warhead case meanwhile becoming thinner under the action of tensile stresses. The warhead case then bursts into fragments having velocities in the range of 3,000 to 10,000 feet per second. This fragmentation occurs by a process of mechanical slip or shear in the metallurgical microstructure of the metal. The size of the fragments is determined by several factors including: shape of warhead (case), strength of case metal and wall thickness, type and quantity of explosive, and so forth. At a relatively early stage after completion of detonation a shock wave is formed in the air. The shock front, at first, is the boundary of the gas globe but then draws ahead at several times the normal speed of sound, The shock front forms a sharp boundary between two regions: one of high pressure, temperature, density, and particle velocity behind the front; and the other of ambient pressure, temperature, density, and particle velocity of the surrounding medium (air or water) ahead of the front. Approximately 30 percent of the energy released by the detonation of a high-explosive warhead is used to rupture the case and impart kinetic energy to the fragments, The balance of available energy is used to create a shock front and resulting blast effects. The fragments are propelled at high velocity, and after a short distance they overtake and pass through the shock wave. The rate at which the velocity of the shock front accompanying the blast decreases is generally much greater than the decrease in fragment velocity because of air friction, Therefore, the advance of the shock front lags behind that of the fragments. The radius of fragment damage, although target dependent, thus exceeds considerably the radius of effective blast damage in an air burst; however, the overall damage due to fragments would not be as extensive. For nuclear weapons, the transition from explosion phenomena for conventional H.E. weapons to (free-field) weapons effects and thence to antiship damage environments is shown on figure 30, and is similar to that shown on figure 5. The process shown for H.E. detonations is less complicated than the nuclear case since the radiation phenomena effects do not exist with chemical high-explosives. The EMP and radioactivity environments

also do not occur. However, one factor unique to H.E. warheads is that of fragmentation which is very important in the vulnerability or survivability of ships and shipboard equipments against the "cheap kill" threat. The principal features of nuclear and non-nuclear (high-explosive) detonation processes, for example, relative pressures, temperatures, time durations, and so forth which are manifest as damage environments of different severity levels, were discussed earlier. What is significant to point out is that airblast (including blast-induced shock) and underwater shock are the two most critical antiship damage environments for both classes of weapons, For present purposes it suffices to state that besides warhead configuration, the two parameters which are of first-order importance in characterizing the airblast and underwater shock damage environments are charge weight W and distance R from the point of detonation to the target. Just as in the case of nuclear weapon yields which are referenced to tons TNT equivalent, so also the reference for chemical high-explosives is pounds TNT equivalent, The blast damage environments created by chemical high-explosive weapons can be divided into two groups depending on the location of the detonation which, in turn, depends on warhead configuration and fuzing, The fuze of a weapon warhead senses the optimum time for detonation of the explosive charge. The two groups of blast environments are: (1) explosions in unconfined (free) space, for example, external to a ship's hull or deckhouse; and (2) explosions in confined (enclosed) space, for example, internal to a ship's hull or deckhouse. Generally, H.E. warheads are either of the non-penetrating (general purpose - GP) type which are influence or contact-fuzed to detonate externally and, therefore, result in group (1) airblast; or of the penetrating (armor piercing - AP or shaped charge - SC) type which are delay-fuzed to detonate internally and, therefore, result in group (2) airblast,

4.4.1 Detonations in unconfined space (external bursts). For purposes of this handbook, antiship H.E. warheads of the non-penetrating, influence-fuzed type may be further categorized depending on the nature of the influence which causes (almost) instantaneous detonation-given that a specified threshold has been triggered. Influence-fuze warheads may result in one of three burst types : standoff, proximity, or contact burst.

4.4.1.1 Standoff burst. A standoff burst has been classified as one which occurs at a distance greater than 300 feet from a ship target, It represents a particular situation in that the warhead does not detonate of itself, but rather it is intercepted and hit by rounds from active point-defense gun systems (for example, CIWS). It is a case of (pre-emptive) high-order detonation of a missile warhead, for example, at as great a standoff as possible so that the warhead does not hit or detonate too close to the ship. One weapon effect or damage environment of potential concern would be airblast, the severity level of which will depend on the warhead charge weight and the standoff distance at which the detonation occurs. Another is the pre-emptive detonation of a shaped-charge warhead and the damage environment of concern would be the shaped-charge jet particles and casing fragments, the severity of which would depend on the standoff distance at detonation and the nature of the particles. Another possible situation presents itself in the case of standoff bursts where a missile warhead is not pre-er"ptively detonated, but the defensive weapons hit and break up portions of the missile structure, for example, main fuselage or control surfaces. A damage environment of concern would be the large pieces of missile debris (shrapnel) hurtling through the air at very

high speeds and hitting the ship. If the threat weapon is not pre-emptively destroyed or its flight trajectory deflected (by break-up or CM decoying), it may detonate either by proximity or by contact (inertia) influence. The resulting damage environments would be close-in airblast and fragmentation which could result in structural deformation and perforation of ship plating and exposed equipments.

4,4.1.2 Proximity burst. A proximity-fuzed burst has been classified as one which occurs at an approximate distance less than or equal to 300 feet from a ship target. This type of burst is triggered by an influence fuze which senses some target signature such as ship's near-field radar return, for example, or may be command detonated. Proximity bursts may also occur in tactical situations where an anti-ship cruise missile is flying off course or is being deflected by an off board ECM decoy so that rather than miss the target completely, the warhead is detonated by a back-up fuze which is triggered by some (minimum) signal return or set to detonate instantaneously upon losing target signal completely. The principal damage environments which result from proximity air bursts of H.E. warheads are airblast, including blast-induced shock; and high-velocity fragments. As in the case of nuclear airblast, the blast severity from a conventional H.E. detonation is reflected in the diffraction (reflected) pressure and drag (dynamic) pressure loadings. In all probability, the diffraction component would be of greater importance for H.E. detonations whereas the drag component would be more important for nuclear detonations. This general observation is based on the fact that the airblast effects are more localized and of higher severity in the case of H.E. detonations. The severity of the H.E. warhead fragmentation environment is reflected in the kinetic energy (mass and velocity) of the dispersing fragments and their ability to perforate structural plating, antennas, ordnance magazines, weapon casings, and so forth, The airblast and fragment damage environments can in themselves cause serious impairment or destruction of ship structure and sensitive equipments, or serious personnel injury. They can also result in weapon cook-off or massive detonations with attendant fire, blast, and even flooding. It was stated earlier that for a GP warhead the distribution of explosion energy from a conventional H.E. detonation in air is about 70 percent blast and 30 percent fragments. It is possible, however, to configure the weapon payload in a way as to optimize the warhead for either blast or fragment effects. For example, an enhanced blast warhead is one which is designed to achieve target damage primarily from blast effects by a combination of casing geometry (that is, shape, case material, case thickness) and special types of explosives (for example, fuel air explosive (FAE)) with enhanced blast output . A controlled fragmentation warhead, on the other hand, is intended to achieve target damage primarily from high-velocity fragment effects. A major consideration in the latter damage environment is fragment density and kinetic energy, A controlled fragment warhead is, therefore, specifically designed to generate a maximum number of fragments at a specified velocity. Whereas the weapon effects for an idealized blast payload are attenuated by a factor roughly equal to $1/R^3$, where R is measured from the point of detonation, the attenuation of idealized fragmentation effects varies as $1/R^2$ and 1/R depending on the payload design. Herein lies the principal advantage of a fragmentation payload - it can afford a greater miss distance and still remain effective because the attenuation is less. However, the type of warhead incorporated in an antiship weapon to maximize damage depends upon many other factors besides attenuation. The damage mechanisms for airblast and fragments are different so that the severity of damage caused by each effect per pound of explosive (or

total warhead weight) also depends on the type of target and its inherent hardness against each weapon effect. The mechanics and characterization of airblast resulting from a conventional H.E. weapon detonation are similar to those for nuclear airblast, although the respective initiation processes are different as described earlier. The controlling parameters which define airblast., and their variation with distance and time as shown on figures 12 through 16, are equally applicable to H.E. airblast. What is different, however, are the quantitative values such as for the design-threat load parameters in each case. The interaction between an airblast wave and a structure as shown on figure 23 is strictly applicable to a blast wave which is of large proportion compared to the size of the structure (of ship) so that it consequently becomes enveloped in the wave. This is the case for nuclear airblast, but not H.E. airblast where the wave is of significantly smaller dimensions. For the latter, the associated blast pressures act over relatively small surface areas , for example, one or two bulkhead panels of a ship deckhouse, so that the damage is more localized. There is no net lateral (translational) force similar to that from a nuclear blast wave which could result in a general deformation or tipping-over of the entire deckhouse. As will be seen from the quantitative data on environment severity levels for nuclear and non-nuclear airblast, the principal differences between the two are as follows, Conventional H.E. airblast being of a localized nature results in peak pressures (free-field overpressure, dynamic pressure, reflected pressure) which are correspondingly higher by as much as a factor of ten. Depending on weapon yield (charge weight) and standoff distance, the difference factor may range anywhere from three to ten. However, the respective pressure pulses are of significantly shorter duration, milliseconds for H.E. airblast compared to a second or more for nuclear airblast. The corresponding positive impulses, that is, area under the overpressure versus time curve for the positive phase duration (see figure 13), in general, are higher for nuclear airblast.

4.4.1.3 Contact burst. A contact-fuzed burst is the most common situation for an H.E. warhead since it does not require use of sophisticated fuzing mechanics which sense the optimum time for detonation by operating on some complex target characteristic, for example, radioactive or reflective signatures. Contact bursts simarily occur when the warhead impacts on some portion of the target and the detonation process is instantaneously triggered by an inertia-type fuze. When a contact-fuzed H.E. warhead detonates against a ship deckhouse, for example, a very high localized pressure loading results over a relatively small surface area of bulkhead or deck structure. In this instance, the damage mechanism is holing of the structural plating due to high through-the-thickness shear stresses owing to large velocity gradients across the loaded surface. Rupture begins at a point nearest the explosion and extends some distance. The resulting holing may not be localized, but damage could include entire bulkhead panels. The mechanism of blast-induced holing and plate rupture involves a complex process of high dynamic loading on structures where the mechanical or metallurgical properties of materials and their behavior under high strain rates come into play. The existence of imperfections (for example, notches and incipient cracks) in plating material can also influence the fracture and holing damage. As a consequence of holing, a portion of the high localized blast pressure is vented to the outside atmosphere and some of the expanding gas is admitted into interior spaces through the holed plating, In that case, the airblast environment is for a (partially) confined space, and the direct blast damage to interior bulkheads or decks and equipments is

assessed using a reduced weight of explosive. The blast-induced shock environment is similar to that for external proximity bursts, but the blast pressure loading is based on this reduced charge weight and the volume of the spaces into which the blast pressure vents. Also as a result of bulkhead or deck holing from a contact burst, the plating material taken out may break-up thereby creating fragments which enter the contiguous spaces. This, in combination with the vented diffraction pressure, creates a combined blast or fragment environment for internal structure and equipments analogous to that for external proximity bursts against outside structure and equipments. The degree of plating fragmentation depends on material properties and fragment properties, for example, kinetic energy, density, and so forth. For ductile materials the plating may "petal" rather than fragment, whereas for relatively brittle materials the plating is more susceptible to fragmentation and possible spalling.

4.4.2 Detonations in confined space (internal bursts). Some of the more lethal antiship weapons are equipped with armor piercing (AP/SAP), delay-fuzed warheads which first penetrate a ship's structural envelope and then detonate a large H.E. charge within its confines. The three principal weapons effects or damage environments are: (1) shock (blast) wave; (2) confined-explosion gas overpressure; and (3) high-velocity fragments. For the shock wave, the critical loading is the high pressure discontinuity at the shock front, The damage environment which results from the shock wave is holing or rupture of bulkhead and deck plating close to the point of detonation, similar to that which occurs for external near-contact bursts. This holing results from high shear strains through the plating thickness owing to high velocity gradients across a plate surface due to the localized pressure loading. Rupture begins at a point of a stiffened plate structure nearest the explosion and extends to its boundaries so that nearly the entire plate is removed. This type of holing damage is controlled by: weight of explosive, standoff distance, plate thickness, and material properties. The analytical techniques for assessing holing damage and deriving environment severity levels are the same as those for external near-contact bursts, and are based on empirical formulas derived from experimental test data. Besides holing damage to internal structure, the high pressure discontinuity at the shock front also imparts sudden accelerations and high velocities which can result in shock damage to sensitive electronics and machinery components located inside a ship's hull or superstructure. The mechanism for the airblast-induced shock motions is similar to that for external proximity-burst H.E. weapons-. The shock motions are again due to the direct pressure loading rather than a consequence of foundation motion, and is predominantly in the horizontal direction with any vertical component resulting from mechanical coupling. The high-velocity fragment environment for internal-burst weapons is the same as for external proximity bursts. The controlling parameters are the mass and velocity (kinetic energy) of the fragments, and their density in predestined dispersion patterns. The data base and techniques for assessing fragment damage to ship plating and equipments, and for deriving environment severity levels, are the same as for external proximity-burst H.E. weapons. The confined-explosion gas overpressure environment is somewhat different from the case of the free-field overpressure environment resulting from external proximity bursts.

4.4.2.1 Confined-explosion gas overpressure, For internal-burst H.E. weapons, the resulting airblast effects are significantly different from those in free air (unconfined space) for two principal reasons. One is that the energy release for an internal burst gives rise to a shock (blast) front and, hence, overpressure which is initially confined within the space where the warhead originally detonates because of no immediate venting. Thus the term "confined airblast". The overpressure is not only a function of the charge weight and type of explosive, but also the volume of the space in which the warhead detonates. As a result of damage (rupture) to bulkheads, decks, and overheads surrounding the burst space, the gas overpressure is vented to adjacent spaces and becomes relieved since the confinement volume is now larger. The resulting pressure level is governed by this new volume. The extent to which the damage spreads, therefore, depends on the severity of the initial burst, the volume of the burst space, the volume of adjacent spaces, and the design strength of interior structure to resist the pressure environments . The other reason for the difference between confined and unconfined blast damage environments has to do with the detonation process itself. The amount of oxygen available in the burst space to ensure complete burning of the explosive prior to detonation is an important consideration. More complete burning of the explosive results in higher induced gas pressures. The volume of the burst space, the weight of explosive charge, and the chemical composition of the explosive, all of which determine the amount of oxygen available for the detonation process, are factors controlling the overpressure and the specific impulse loadings imparted to internal structure and vital equipments, The controlling parameter which incorporates all these factors is the ratio of charge weight W (in pounds) to volume V (in cubic feet) of the burst space, for example, W/V. A short discussion of the confined-explosion gas overpressure process is given below to highlight some of the basic principles involved. After passage and decay of the shock wave from an internal burst, confinement of the explosion gases leads to a pressure loading $\bar{p}_m((t)$ which has a duration that is long compared to the response time (eigen-period) of typical stiffened structures. This type of pressure loading is referred to as "quasi-static" as compared to the dynamic nature of the blast-induced incident overpressure, and resulting reflected pressure, for unconfined airblast from proximity-fuzed external bursts. For example, from tests of TNT explosions in closed chambers it was found that typical time durations for the mean pressure $\bar{p}_m(t)$ are on the order of several seconds whereas the positive phase duration for the airblast overpressure in free space is on the order of milliseconds. A sample trace of the pressure-time history recorded at a point on the wall of a (partially) closed chamber when an explosive charge is detonated in the center of the chamber, is shown on figure 31. The several pressure peaks observed are caused by repeated reflections of the blast wave off the chamber walls; however, because of their short duration, the impulse they impart is small so that their damage effect on internal structure and equipment would be negligible. In completely closed compartments , heat loss to the surrounding walls is the only mechanism for reducing the confined gas overpressure in time, but this phenomenon is neglected because of the very long durations involved. For practical ship deckhouses there will be vent areas through which the confined gases can escape such as hatch openings, stair-wells, and so forth and even the hole of the piercing warhead or projectile into the burst space and any fragment penetrations. The confined gas overpressure would, of course, change due to failure of the structural walls and decks enclosing the

burst space, thereby venting the overpressure to adjacent compartments. This effects an increased confinement volume for the expanding gases of the initial-explosion. The change in the "quasi-static" pressure level of the confined gas mixture with time due to this venting and expansion process needs to be determined in order to realistically assess the extent of structural damage to interior compartments . The vent areas through which the explosion gas expands and the volume increases are controlled by failure criteria governing damage to compartment walls and decks. If the "quasi-static" overpressure in the burst compartment reaches a high enough level so as to collapse the surrounding bulkheads and decks, the pressure is vented into adjacent compartments. This venting takes place very rapidly during the initial phase so that the expanding gases are considered to follow the aerothermodynamic laws of sonic flow. When the gas flow velocities become reduced due to venting of the pressure, further expansion of the gases into the fill compartments is assumed to behave according to subsonic flow. If the gas pressure in the fill compartments is still excessive, additional bulkheads or decks may fail with further venting of the confined gas overpressure into adjacent compartments. As the venting propagates to more and more compartments and the expanded gases occupy larger volumes, the overpressure is progressively reduced. When it has decreased to the point where no further bulkheads or decks are failed, the damage propagation stops and there is no further venting of the explosion gases. The criteria for holing of interior bulkhead or deck structures for internal H.E. bursts are similar to those for external H.E, bursts since the damage mechanisms in both instances is the high pressure discontinuity at the (blast) shock front. For internal bursts, the greatest extent of damage to ship structure almost always results from the "quasi-static" pressure loading, For this loading the damage is generally plate rupture due to large elastoplastic deformations. Plate rupture tends to begin at locations of high stress concentration usually at boundaries where web-frames and stiffeners introduce structural "hard spots" and thus points of high bending stress. Furthermore, welding of grillage (stiffening) elements at these locations usually introduces notches and points of incipient cracking, as well as material property reductions due to heat-affected zones. The rupture will usually propagate along the plate boundaries effectively removing most of the bulkhead or deck structure, Analytical procedures and algorithms for determining the overpressure levels and associated parameters from confined blast, and for establishing environmental severity levels, are available.

4.4.3 Specially configured warheads. The principal above water weapons effects resulting from the detonation of conventional high-explosive (H.E.) warheads against ships are airblast, blast-induced shock, fragmentation, and penetration. Generally, H.E. warheads will produce all four effects, but to different levels depending upon the intended purpose of the weapon and its particular design features. Antiship weapon warheads can be specially configured to maximize their lethality in terms of any of the principal damage effects, This has led to the development of: (1) enhanced blast warheads; (2) controlled fragmentation warheads; (3) kinetic energy penetrators (projectiles); and (4) shaped-charge warheads. Each of these is briefly discussed.

4.4.3.1 Enhanced blast warheads. The lethality of blast-type warheads can be significantly enhanced by use of advanced high-explosives based on aluminized mixtures and composite explosives technology. Other techniques for enhancing the blast output of an H.E. payload include: use of reactive liners (or surrounds) around the main explosive charge; and use of fuel-air explosives

(FAE). In all cases, the objective is to extend the positive duration of the explosion process while at the same time increasing the peak overpressure, so that overall the positive impulse is significantly increased for a given total weight of explosive change. A comparison of the free-field overpressure versus time waveforms for the different blast processes of interest to this handbook is shown on figure 32. The classical exponential waveform for the standard monoexplosive TNT is shown on figure 32(a), while those for enhanced-blast explosives and nuclear payloads are shown on figures 32(b) and 32(c), respectively. The waveform for nuclear airblast is also of the classical type; however, the positive phase is of the order of 1 or 2 seconds whereas that for conventional H.E. airblast is of the order of milliseconds. An order of magnitude for the corresponding positive impulse in each case is indicated on the figure. The blast output of different chemical high-explosives is quantified in terms of free-air "equivalent weights" for peak overpressure, positive impulse, and so forth. The equivalent weight of a particular explosive gives the weight of the standard explosive (TNT) necessary to produce shock (blast) wave parameters of equal magnitude under the same conditions. The concept of "equivalent weight" derives from the similitude law for high explosives.

4.4.3.2 Controlled fragmentation warheads. When an explosive charge contained within the metal casing of a conventional warhead is detonated, the ruptured and usually non-uniform remnants of the metal casing form high velocity fragments. The high initial velocities imparted by the rapidly expanding explosion products and resultant high internal pressure can make these fragments a lethal and highly efficient means of destruction. The damage that fragments can cause is related to their size, shape, velocity, and spatial distribution. These controlling parameters have been extensively studied and used to design efficient fragmentation warheads that are capable of delivering literally hundreds of high velocity penetrators whose damage potential (lethality) is much greater than the primary blast and shock weapons effects produced by the detonation itself. This has led to the development of "controlled fragmentation" warheads. The penetration capability of fragments is determined by fragment velocity, mass, presented area, and diameter. Initial fragment velocity is governed by the mass of the explosive charge, the mass of the metal casing, and the energy per unit mass of the explosive that can be converted into mechanical work. Composite aluminized high-explosives, for example, Composition B, H-6, Pentolite, and HBX-1 are used to provide higher explosion energies for (significantly) increasing the initial velocity imparted to the fragments resulting from the break-up of the warhead metallic casing. For controlled fragmentation warheads, methods have been developed to control the size and shape of fragments which, in turn, determine their mass, presented area, diameter, and spatial distribution in terms of polar zones. Controlled fragmentation warheads use various techniques to configure the casing in a way such as to produce fragments with predetermined lethality characteristics, that is, size and shape. This includes: preformed fragments, notched or grooved rings, notched or grooved wire, notched casings, multiple walls, and fluted liners, Preformed fragments are simply pieces of metal fabricated to the desired size and incorporated into the liner of the warhead. The liner may be anything from a wax base that holds the fragments in a matrix to a system of two concentric liners of plastic or thin metal within which the preformed fragments are held. This technique provides the ultimate control over the fragmentation since the fragments are already formed, and it only remains for the explosive payload to accelerate them. The technique of notched or grooved

rings involves placing a series of such rings together so as to form sections of the warhead casing perpendicular to the axis of symmetry. The rings are assembled on a liner and pressed together as tightly as possible. Retainers are then fitted to hold the rings in place, The notches or grooves in the rings provide a path of least resistance and help to control fragmentation along the circumference of the rings while the width and thickness of the rings provide control in the other two dimensions. Adherence to certain fabrication details for the notched (grooved) rings usually results in fragments of from 80 to 95 percent of the design weight and to within 10 percent of the predicted initial velocity. The technique of notched or grooved wire for controlled fragmentation warheads is very similar to the notched ring concept. A long wire (or bar) is notched in a fashion similar to the rings and then wound in a helix around the warhead casing. In the technique of notched casings, the warhead casing is notched in a two-dimensional network to provide weaknesses in the casing for fragmentation control. The notches can be either machined or cast on the inside or outside of the casing. As with the notched rings technique, notched casings provide 80 to 90 percent achievement of desired fragment size. The technique of multi-walled casings will not provide any great measure of fragment control, but they will result in some uniformity. The use of close-fitting cylinder walls, each with thickness t/n (t is the thickness of a one-wall shell and n is the number of walls) ensures that all fragments will have the same thickness. The total number of fragments ejected would be approximately n times the number from a single-walled shell, but the average fragment mass would be less. In the technique of fluted liners, plastic, paper, or a thin metal liner is used to shape the high-explosive next to the casing. This causes jets to form on detonation and fragments to form when the casing is ruptured by the expanding explosion gases.

4.4.3.3 Kinetic energy penetrators . Although generally of the non-explosive type in the usual sense, a class of antiship weapons of concern to ship armor designers are the kinetic-energy penetrators. This type of weapon causes damage by first completely or partially penetrating an assigned target, and then detonating a high-explosive payload inside the ship to cause maximum damage. The exact mechanism by which the penetration is accomplished depends upon the nature of the target. The key weapon design parameter is the ratio of charge weight-to-casing weight. Against a light target, GP bomb or missile warhead with a large percentage of its total weight dedicated to explosive payload would detonate on contact if inertia-fuzed, or in close proximity to a target if influence-fuzed. The desired damage would be caused by blast and fragmentation effects. Against a hard (armored) target, a GP warhead would possess insufficient lethality to cause significant damage, In that case, an AP or SAP warhead with a greater percentage of its total weight dedicated to the casing is used to ensure target penetration prior to detonating an explosive payload. Target penetration by K.E. munitions, either partial or complete, is often accompanied by fragments which result from either the break-up of the projectile (warhead) casing, spalling of target plating surfaces, or disintegration of fragile equipment impacted by the projectile or by previously generated fragments. The vulnerability of a ship to a specific weapon threat will depend to a considerable degree upon the lethality of the weapon when it reaches the target. This lethality, in turn, depends largely upon the weapon’s terminal ballistics, In the case of K.E. penetrators, this includes primarily the kinetic energy of the warhead or projectile, and its

nature and condition. The kinetic energy at any point in a projectile's flight is proportional to the product of its mass (weight) and velocity squared. Since projectile velocity at any point depends primarily upon initial (muzzle) velocity and range from the point of firing, the kinetic energy, and thus lethality, would decrease as the range-to-target increases. In addition to weight, projectile characteristics which have a direct bearing upon lethality are its shape, material, and final condition at impact. Shape, in addition to affecting drag characteristics and thus velocity, might also affect stability and hence penetrating capability, especially at higher impact obliquities. In general, the tougher and harder the projectile material the greater its penetration capability as long as brittleness is not a factor. If the material is too brittle, the projectile may break up on impact and the lethality problem would be one of fragmentation rather than penetration.

4.4.3.4 Shaped-charge warheads. Shaped-charge warheads represent a special case of H.E. weapon detonation designed to primarily pierce thick armor plating, but differ from standard AP warheads in their principle of operation. Whereas the degree of penetration of an AP warhead is dependent upon striking velocity, the thickness of material a shaped-charge warhead can penetrate is essentially independent of striking velocity and, in fact, the warhead itself remains at the outer face of a target where it detonates on contact, producing a high-velocity jet of metal particles which pierce the structural envelope, including any armor. A shaped-charge warhead consists basically of a thick-walled explosive-filled case open in front, a thin front liner for the explosive made of inert material such as metal and usually conical or hemispherical in shape (the concave side always facing forward), a contact-fuze and detonating device, and a thin nose cone for warhead aerodynamic shaping. A typical shaped-charge warhead with a conical liner is shown on figure 33. The shaped-charge is characterized by the geometry of the front liner. When a shaped-charge warhead strikes a target, the point-detonating nose fuze fires a length of detonating cord which leads to a booster in the rear of the warhead. The booster, in turn, detonates the main charge and a detonation wave travels forward causing the metal front liner to collapse. Collapse of the liner starts at its apex. When the liner collapses it ejects a narrow sword-like jet of explosive products and metal particles from the face of the liner out the front end of the thick warhead casing at velocities ranging from about 2,000 to 25,000 feet per second. The velocity of the tip of this continuous shaped-charge solid jet is of the order of 25,000 feet per second while the trailing end has a velocity of the order of 5,000 feet per second. This produces a velocity gradient which tends to stretch the jet. The jet is then followed by a slug which consists of about 80 percent of the liner mass and having a velocity of about 2,000 feet per second. The sequence for the shaped-charge penetration process is shown on figure 34. If a shaped-charge jet strikes a target of armor plate, pressures of about 250,000 lb/in^2 are produced at the point of contact. This extreme localized pressure causes stresses far above the yield strength of the (target) material so that it flows out of the path of the jet as would a fluid. There is so much radial momentum associated with the material flow that the diameter of the hole produced is considerably larger than that of the jet. The difference between jet diameter and that of the hole depends upon the characteristics of the armor plate. However, the depth of penetration into a thick slab of mild steel will be only slightly greater than that for homogeneous (monoblock)

armor because the material flow is the same in either case. As the jet particles strike the target, they are carried radially outward along with the plating material. The jet is used up as it strikes and penetrates the target so that it becomes shorter and shorter until finally the last jet particle strikes the target and the primary penetration process stops. The actual penetration continues for a short time after cessation of jet action because the kinetic energy, imparted to the target material by the jet, must be dissipated. The additional penetration caused by this afterflow is called secondary penetration. Having penetrated a ship's structural envelope, for example, deckhouse weather bulkheads, each shaped-charge jet particle which impacts internal structure will produce secondary plate fragments capable of penetrating a plate thickness equal to own thickness. This results in an additional damage environment to whatever is located in the compartment behind each penetrated bulkhead. For example, if a shaped-charge jet produced 50 high-velocity jet particles that impact on an interior bulkhead, then as many as 200 total particles may exit from the bulkhead; approximately 50 will be jet particles and the other 150 secondary plate particles. The trajectories of the secondary particles fall within a cone having a central angle up to 130 degrees and apex at the point where the bulkhead is penetrated. Impacting heavy machinery and equipment in penetrated compartments would, of course, impede further penetration by the particles. It has been found that generally the depth (P') of main penetration by a shaped-charge jet is related to the length (L) of the jet, the density (Pm) of the target material, and the average density (P_j) of the jet, by the following expression:

$$P' = L\sqrt{\rho_j/\rho_m}$$

The strength of the plating material has no appreciable effect on the depth of primary penetration because the material is fluid in nature during jet penetration. The jet density is dependent to a large degree on the density of the particles of the shaped-charge liner which are dispersed throughout the primary jet. The standoff distance for a shaped-charge warhead is defined as the distance from the base of the shaped-charge liner to the surface of the target at the time of detonation. Standoff distance is extremely important in obtaining maximum jet penetration. An increase in standoff permits an increase in the length of the jet, but at the same time decreases its average density. It would appear that an increase in standoff increases the depth of primary penetration since depth varies directly as jet length but only as the square root of jet density. This is true up to a certain distance, beyond which irregular developed particles in the jet cause it to spread somewhat causing, in turn, a decrease in the depth of primary penetration.

4.4,4 Underwater detonations. The explosion phenomena and weapons effects described earlier (see 4.3,5) in connection with underwater nuclear detonations apply equally well to the case of conventional H.E. detonations. There are, however, several distinguishing characteristics between the two. One difference has to do with the significant nuclear gamma/neutron and thermal radiation effects which do not exist for H.E. weapons, These particular effects, however, do not result in any significant damage environments as such for a ship unless the underwater nuclear attack occurred relatively close (for example, less than 1 mile) to the ship, at which range it would sustain severe

nuclear and thermal radiation damage to structure, equipment, and personnel. Another difference has to do with the nature of the shock wave itself in each case. At standoff ranges where a ship can still be subject to significant shock motions (that is, sudden accelerations and high velocities), the wave front from an underwater nuclear detonation would certainly be planar whereas that for H.E. detonations would still be spherical. In the case of an underwater nuclear detonation, a ship target would experience rigid-body translation in addition to shock effects. In the case of an underwater H.E. detonation, a ship target could also experience beam-like bending motions (whipping) of its main hull girder due to the bubble pulse effect, with the possibility of resonance occurring if the bubble period is close to the fundamental vibration period (or its harmonics) of the ship's girder. If so, then severe plastic deformations (hinging) would occur, that is, "breaking the back" of a ship. Notwithstanding the differences between underwater nuclear and conventional explosion effects alluded to above, the "surface cutoff" phenomenon is the common denominator which ensures some degree of equivalence in the shock loading and motions experienced in each case. The two key parameters which control the severity of the shock environments in either case are: charge weight (k') in pounds (tons) TNT equivalent, and standoff distance (R) between the detonation center and a point on the ship's hull. For a broad range of parameter values of practical interest, the shock severity is about the same for both. This equivalence obtains for large H.E. charges, for example, greater than 50,000 pounds TNT. The primary damage effects or environments, therefore, to which surface ships would be subjected as a result of attack by conventional H.E. underwater weapons are: shock wave, high incident overpressure, and bubble pulse. The resulting damage modes to exposed structure could be hull rupture due to the shock wave and whipping due to the bubble pulse. The damage modes to sensitive equipment would be misalignment or even breaking away from foundations or mountings due to high shock motions. Similar kind of equipment damage would result from hull whipping. A secondary damage effect or environment from the shock wave or bubble phase could be flooding due to hull rupture.

4.4,4.1 Shock factor versus peak bodily velocity. Naval ships may be subjected to a variety of underwater explosions using conventional H.E. weapons which allow for a variation in charge weight, standoff distance, and attack geometry. Some form of analytic expression is, therefore, needed to relate the underwater shock environment to the attack conditions. An empirical relation has been developed which has led to the well-known "shock factor". This index for measuring shock severity from conventional detonations has proven useful. Peak bodily velocity is a meaningful parameter for expressing the shock severity from an underwater nuclear detonation (see 4.3.5.1). Shock factor is more appropriate for underwater H.E. detonations. Some attempts have been made to draw a comparison between peak bodily velocity and shock factor using measurement data from at-sea ship shock tests. For large charges, it has been observed that an approximate correlation obtains between these two parameters. The emphasis on correlation between shock factor and peak bodily velocity is important since velocity measurements are used extensively in shock evaluations of full-scale Naval ships and shipboard equipments. Also, in many of these tests large high-explosive charges are used to simulate the blast effects of nuclear weapons.

4.4.5 Antiship torpedoes. From the point of view. of weapons effects, antiship torpedoes fall into two categories (the same general categorization and associated weapons effects apply to antiship mines, which can be planted at predetermined depths). One is the side-hitting, contact-fuzed torpedo and the other is the close-underbottom proximity-fuzed torpedo.

4.4.5.1 Side-hitting contact torpedo. This weapon is designed to run at relatively shallow depths, about 15 to 20 feet depending on the target's draft, and is fuzed to detonate on impact with the side of a ship's hull, The principal weapons effects or damage mechanisms for the inertia-fuzed contact torpedo are: hull rupture (holing) due to the extremely high, localized pressures of the incident blast wave; severe shock motions imparted to shell structure and equipment components due to the impulsive nature of the blast (shock) wave; and, secondary fragments resulting from the ruptured hull plating. Large holes would be opened in the plating accompanied by extensive distortion and rupture of the transverse frames and longitudinal stiffeners. The extent of damage will depend on the size and type of explosive payload in the torpedo warhead, in addition to the structural design of the ship's hull, Subsequent venting of the explosion gases into the interior of the hull would cause further damage and start fires inside the ship. Rupture of the hull shell could lead to severe flooding, and possible sinking of the ship if too many watertight bulkheads are damaged in an attack. Breakup of the shell plating could result in a fragment environment within the hull in the form of large pieces of metal flying around. The impulsive nature of the blast loading, that is, very high pressures of millisecond duration, would impart large shock motions to structure and equipment in the form of sudden accelerations and high velocities. The shock loading is transmitted up through the hull structure to -- the upper deck levels thereby causing shock damage to sensitive components mounted on the topside or within the ship hull enclosure. These shock motions occur principally in the vertical direction because of the nature of the underwater detonation; any horizontal motions would be the result of mechanical coupling.

4.4.5.2 Close-underbottom influence torpedo. This weapon is designed to run at depths below the keel of a target ship, generally less than about 100 feet, and is fuzed to detonate upon sensing a signature influence, for example, a ship's underwater magnetic or pressure gradient. An upward-looking sonar may be employed as part of the torpedo's fuzing mechanism to sense when it first arrives underneath the ship, and is then delay-fuzed to detonate when close to the ship's centerline. The principal weapons effects or damage mechanisms for the proximity-fuzed underbottom torpedo are the shock wave, whose intensity is measured by the keel shock factor, which imparts sudden vertical motions to the hull structure and equipment components; and the bubble pulse due to the contraction and subsequent expansion of the explosion gas globe. The latter effect can cause severe whipping of a ship's main hull girder, in the form of large free beam vibrations, if the bubble period is in resonance with the natural period of the structure. This whipping can result in gross plastic deformations (hinging) of a hull girder, with possible "breaking of a ship's back". The severity of the shock motions and whipping is also controlled by the size and type of explosive charge in the torpedo warhead, and the standoff distance from the point of detonation to the ship's hull.

4.4,6 Synergistic considerations for non-nuclear (H.E.) weapons effects. The explosion phenomena and resulting weapons effects for conventional H.E. detonations are less complex, and fewer in number, than for nuclear detonations (see figure 28) because of the absence of the radiation effects (initial and delayed, including EMP and TREE, and thermal). As shown on figure 29 and summarized on figure 30, the primary (direct) H.E. weapons effects or damage environments of concern to ship structure and shipboard equipments are: fragments, shock, airblast, and blast-induced shock. To this must be added the damage effects of penetration and high-velocity jet particles which result from shaped-charge warheads whose action is initiated by the detonation of a chemical high-explosive. Examination of the sequence of explosion phenomena and free-field weapons effects as shown on figure 29 reveals two cases of significant coupling between individual effects that can result in more severe damage environments for Naval ships. For above water H.E. weapon detonations, the warhead fragments which occur first may degrade the structure integrity of ship hull or super-structure plating and exposed equipments by perforation prior to the arrival of the airblast from the same burst. It is conceivable, however, that depending on the size of the fragments (or debris) which perforate bulkhead or deck plating the airblast overpressure could be vented into interior spaces thereby reducing the degree of further damage to exterior structure. If such is the case, the vented airblast would more readily create a blast-induced shock environment for internal equipments although the confined gas pressure in contiguous compartments might be less severe because of venting to the outside (ambient) atmosphere. For underwater H.E. weapon detonations, a coupling between the damage effects due to the shock wave and the bubble pulses may occur which could prove more severe than either effect individually. As shown on figure 24, the sequence of the underwater explosion phenomena or weapons effects applicable to both nuclear and non-nuclear (H.E.) detonations - the difference between the two is reflected in the characteristics and relative severity levels for the shock wave and the bubble pulse effects. The shock front from an underwater nuclear detonation effectively acts over the entire underbottom of a ship imparting an upward rigid-body translational motion to the entire ship rather than a more localized loading as would occur in the case of an H.E. weapon detonation. Similarly for the bubble pulsation effects and damage environments created. The expanding or contracting gas bubbles from an H.E. detonation introduce a localized impulse loading on a ship's main girder and, being of the right frequency and at a critical loading point, could lead to resonance ("whipping") of the hull. Shock damage to the hull structure effectively reduces the bending rigidity of a ship's main girder and also alters its natural vibration frequencies. The consequence of this would be a weakened girder so that the whipping damage induced by the bubble pulse resonance would add to the shock damage of the hull. There would also occur a synergism between the shock damage to hull or deck-mounted equipments and the subsequent damage effects resulting from the (longitudinal) beam-like whipping of the entire ship.

4.5 Non-nuclear (non-explosive) weapons effects and damage environments. Besides the standard antiship weapons employing detonation-type warheads to inflict damage by direct effects such as shock, airblast, fragmentation, and so forth, other weapons exist in the inventory of potential Naval adversaries (or are projected) that utilize different damage mechanisms. Within this

category the most numerous are chemical, biological or radiological (CBR) weapon delivered agents. The salient features of this non-destruct type weapon is described below.

4.5.1 CBR effects. CBR warfare at sea remains a distinct possibility although little practical experience exists in the use of such agents against ships and shipboard personnel. Much of what is known about employment of CBR agents at sea is based on theoretical studies and limited experiments. Furthermore, in view of the availability of tactical nuclear weapons and effective conventional H.E. antiship weapons that are not constrained by international agreements limiting or prohibiting their use, the utilization of CBR agents cannot be ruled out. CBR warheads are of strategic importance since they are capable of destroying life without causing obvious structural damage to a ship and its equipments. A chemical warhead is designed to expel poisonous substances as the payload and thus cause personnel casualties by contamination and ingestion. A small explosive charge placed in a chemical (or other CBR) warhead can be used to initially disperse the agent. The chemical agents are usually delivered in the form of poison gases; however, liquids may also be employed. Except in high concentration, gases are normally invisible and without a definite odor. Some gases attack the respiratory system causing irritation of the lungs and throat while others can produce serious skin burns, paralysis, or cause death by affecting heart action. Personnel casualties can range from instant death to delayed sickness. Equipment and procedures are available for detecting and identifying chemical agents, A biological warhead utilizes living micro-organisms (bacteria) as the payload which may be selected to produce antipersonnel effects ranging from brief but crippling disease to widespread illness and death, Biological agents can be released as aerosols; that is, cloud-like formations of solid or liquid particles, in which the agent is held suspended. There are no simple rapid methods available for detecting biological agents. Positive detection and identification of a pathogen is accomplished by collecting samples, growing an organism culture under laboratory conditions , and then subjecting the culture to specific biochemical and biological tests. A nuclear warhead could be especially designed to produce an abnormally large amount of radioactive material. Use of such warheads against ships is considered unlikely in view of the availability of tactical nuclear weapons which could achieve high levels of radioactive contamination and other damaging effects with lesser difficulty.

4.6 Primary and secondary shipboard damage environments. As indicated at the outset, the following terminology has been adopted for this handbook. Weapons effects are said to be produced by the weapon itself detonating in the free-field; that is, in the absence of any target in the vicinity of the detonation. For example, a nuclear weapon detonated near the ocean surface would always produce thermal radiation, airblast, and initial and residual radiations as the primary weapons (damage) effects. For high altitude detonations , the electromagnetic pulse caused by atmospheric ionization would also prove to be a primary nuclear weapon effect. An underwater nuclear detonation would produce shock, base surge, water waves, bubble pulses and, depending on weapon yield and depth of burst, vented airblast as the primary weapons effects. The primary (damage) effects produced by a conventional H.E. weapon detonation are airblast, fragmentation, and underwater shock. If a

ship target is in close proximity to a weapon detonation, the interactions between weapons effects and ship are manifest as damage environments. These may be categorized as primary or secondary damage environments depending on the conditions and sequence of occurrence. The primary nuclear damage environments and the associated load parameters which characterize their severity are airblast pressure, shock velocity (blast-induced and underwater), thermal flux, EMP electric field, TREE dose rate, and nuclear radiations dose. Secondary nuclear damage environments include explosions, fire, flooding, debris and capsizing. However, these are not as easily characterized as the primary environments. The primary high-explosive damage environments and characteristic parameters are airblast pressure, impulse shock velocity (blast-induced and underwater), fragment kinetic energy, shaped-charge jet particle kinetic energy, penetration depth (for AP and SC warheads), perforation (hole) size, and so forth. Secondary H.E. damage environments include explosions, fire, flooding debris, spalling (secondary fragments). Fire may also be considered a primary shipboard damage environment in the case for detonating warhead which contains napalm or other incendiary-type materials for the damage payload.

4.7 Coupled shipboard damage environments. There are coupled (combined) shipboard damage environments which result from the natural synergism between individual weapons (damage) effects for each of nuclear and high-explosive detonations . These synergistic damage environments may be considered one notch above the primary environments themselves since the combined (damage) effects are usually more severe than either of the component effects; for example, nuclear airblast coupled with thermal radiation. One “combined” damage environment which transcends all others is that which may be triggered by airblast; for example, which could lead to secondary (fuel) explosions or fire which could lead to weapon cook-off which could lead to more blast damage effects. As has been demonstrated by numerous wartime experiences and at-sea ship accidents, the consequence of such a chain of events could prove devastating. However, this kind of coupling is not in the context of naturally-occurring synergisms. For purposes of this handbook it is also assumed that a nuclear attack against ships will not occur at the same time as a conventional H.E. attack so that the respective damage environments are considered to occur separately. Sequential interactions from separate nuclear and H.E. weapon attacks are not considered to influence the degree of design protection or hardness level needed to limit shipboard damage. For nuclear attack, it is further assumed that the damage environments are produced from a single explosion so that no consideration shall be given to the damaging effects of more than one weapon. For conventional H.E. weapon attack, on the other hand, more than one missile, bomb, projectile, torpedo, or other type of antiship ordnance may be used in a single attack. However, the weapon aim points will be sufficiently separated so that interactions between the damaging effects of separate hits can be neglected. For example, two proximity-fuzed projectiles may explode near a ship in rapid succession. However, the respective blast overpressures and other weapons effects produced shall not be considered additive even if this would result in a more severe environment than for a single explosion. Two synergisms of concern involving combined nuclear weapons effects which can have an impact on ship protection design priorities are thermal radiation plus airblast, and underwater shock plus blast-induced shock. These naturally occurring combination effects can lead to structural damage or failure whereas the individual effects may not prove as critical . The thermal wave which precedes the blast wave by several seconds can

seriously degrade the strength properties of structural materials, including those of equipment components, to the point where the airblast overpressure effectively loads a weakened structure. This would be particularly true for aluminum alloys and plastic composites, for example, fiberglass. Ceramic materials or coatings could be used, where appropriate, to preclude the damaging effects of the thermal radiation. The degree of synergistic damage would depend on the weapon yield and standoff distance to target. In the second instance, a tactical situation obtains where both underwater and above water shock effects against sensitive topside equipments could occur (almost) simultaneously. This is the case for a shallow underwater nuclear burst in which the shock-wave energy is vented through the air or water interface, resulting in airblast shock in addition to underwater shock. The relative severity and damage potential of the two shock effects depend on the weapon yield and depth of the detonation. The underwater shock effects in themselves may not be critical because of the venting; however, the combination of airblast and underwater shock may prove seriously damaging. The main synergism of concern in the case of conventional H.E. weapons effects which can have an impact on ship protection design priorities involves fragmentation plus airblast. The fragment dispersion from the breakup of a missile warhead precedes the blast wave so that any perforation of structural plating by the fragments, whether bulkhead or deck plating or equipment elements, would effectively weaken them. The airblast pressure which follows would, therefore, load a weakened structure with the consequence of premature failure as compared to a non-perforated plate or piece of equipment. The degree of synergistic damage in this instance would depend on the type of warhead (for example, controlled fragmentation), size of explosive payload, and the standoff distance to target.

5. DETAILED REQUIREMENTS

Not applicable.

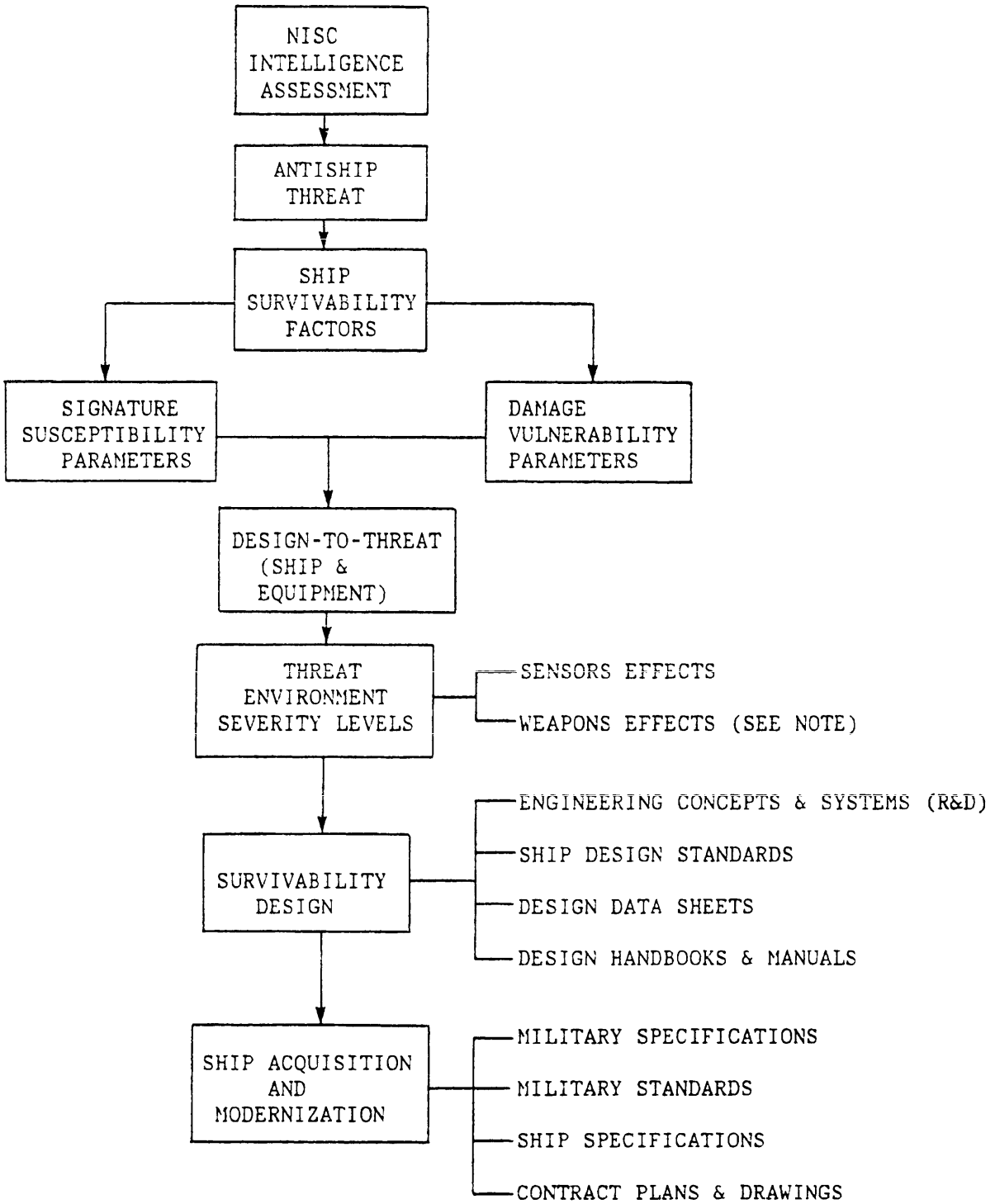
6. NOTES

6.1 Intended use. This handbook is intended for the use of ship design engineers desiring an introduction to survivability and vulnerability of ship and vital weapon systems and to passive protection design.

6.2 Subject term (key word) listing.

Above water detonations
Non-nuclear weapons
Nuclear weapons
Shipboard damage environment
Underwater detonations

Preparing activity:
Navy - SH
(Project 1990-N051)



NOTE:
Only portion of threat environment severity levels addressed by this handbook.

FIGURE 1. Relation of threat to the ship survivability design process and supporting documentation.

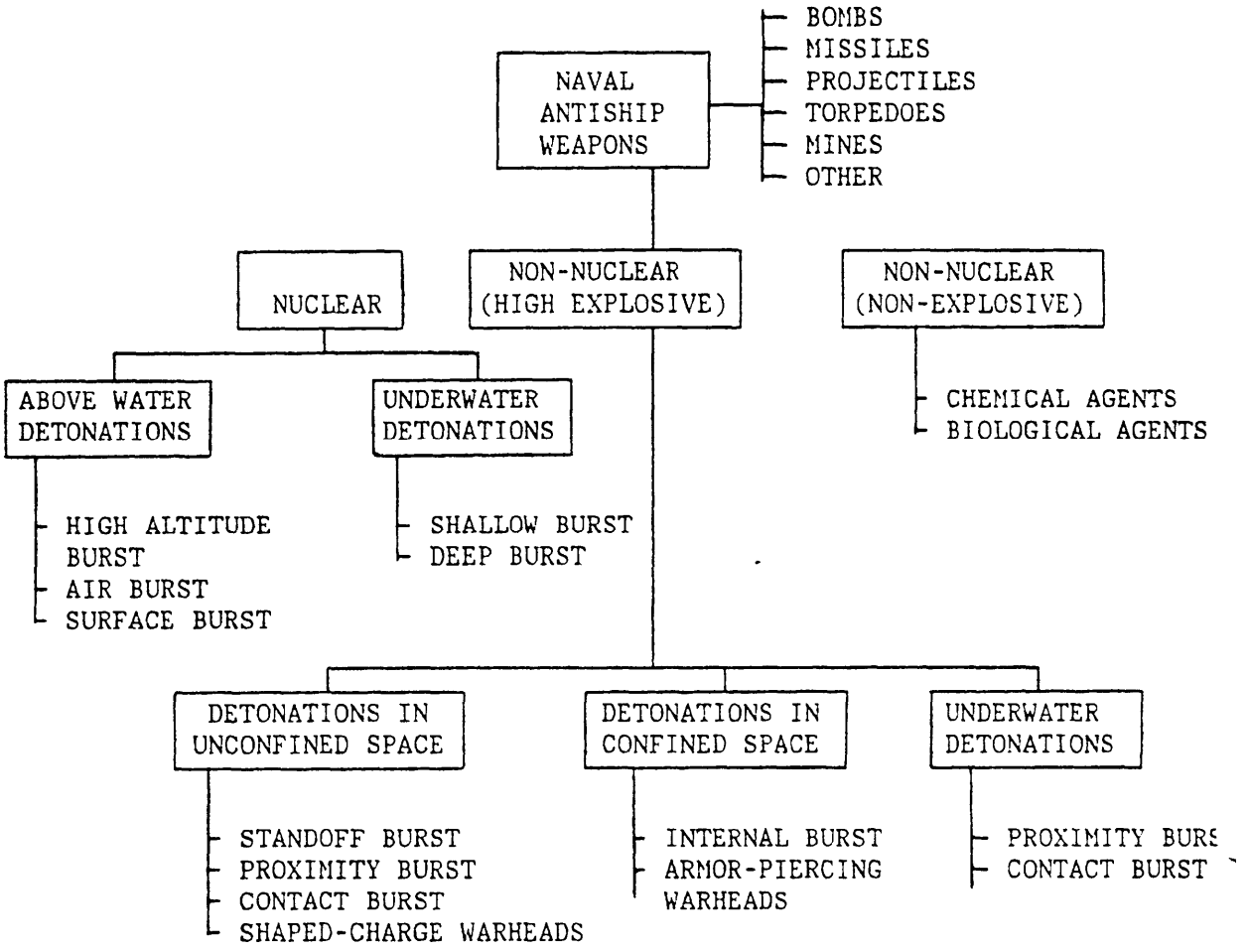


FIGURE 2. Categorization of Naval antiship weapons.

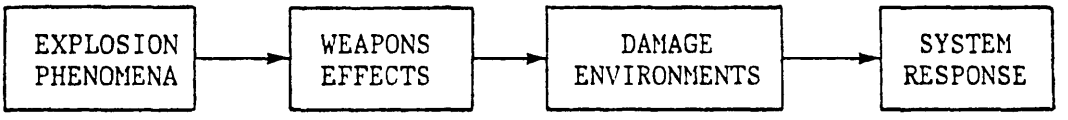


FIGURE 3. Transition process from weapon explosion phenomena to ship system response or damage.

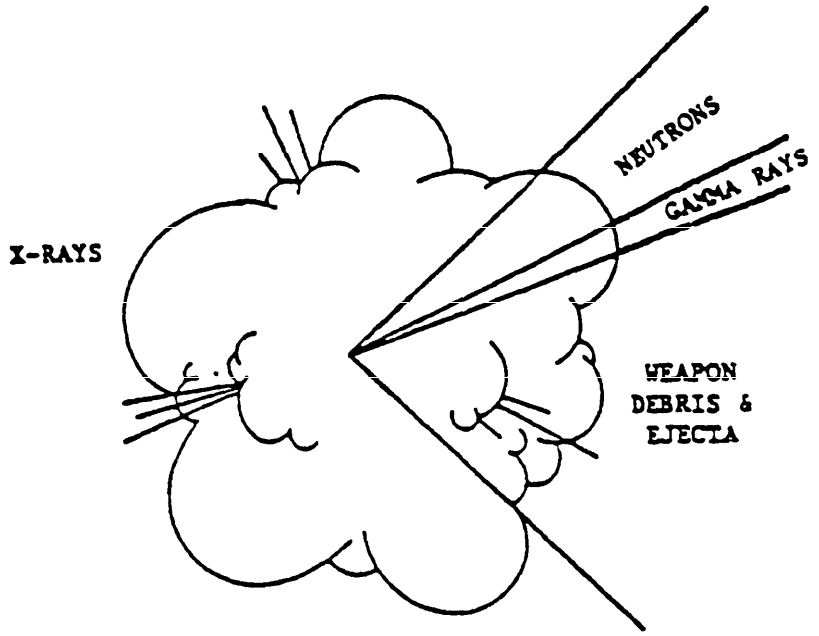


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FIGURE 4. Energy partition for nuclear explosion phenomena.

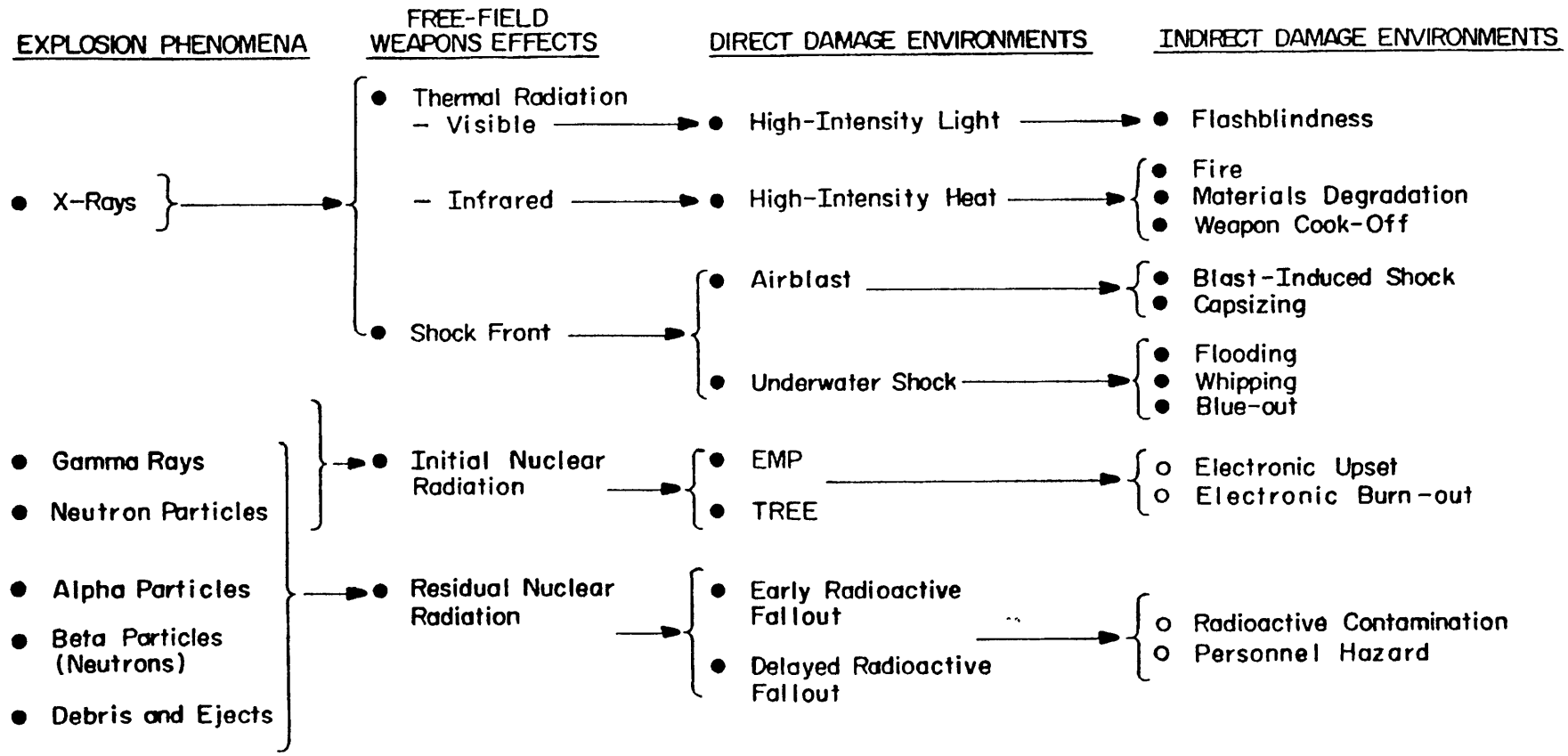

FIGURE 5. Nuclear explosion phenomena and weapons effects or damage environments.

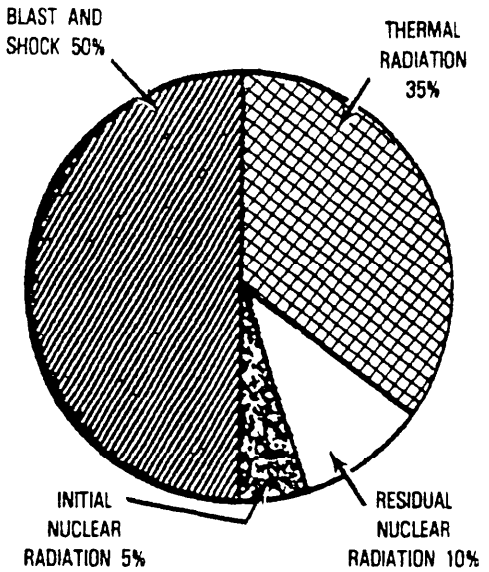

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FIGURE 6. Typical energy distribution for weapons damage effects from a nuclear air burst (40,000 feet altitude and above).

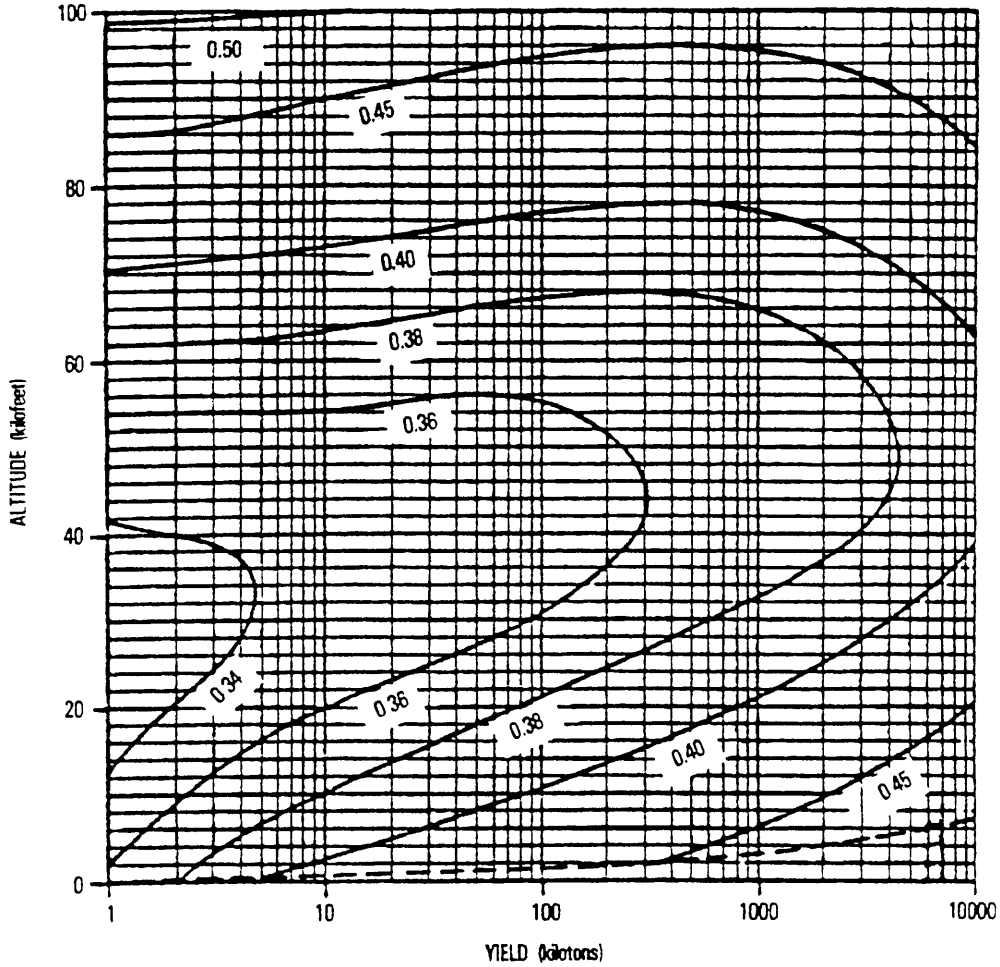

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FIGURE 7. Thermal energy partition as a function of nuclear weapon yield and burst altitude.

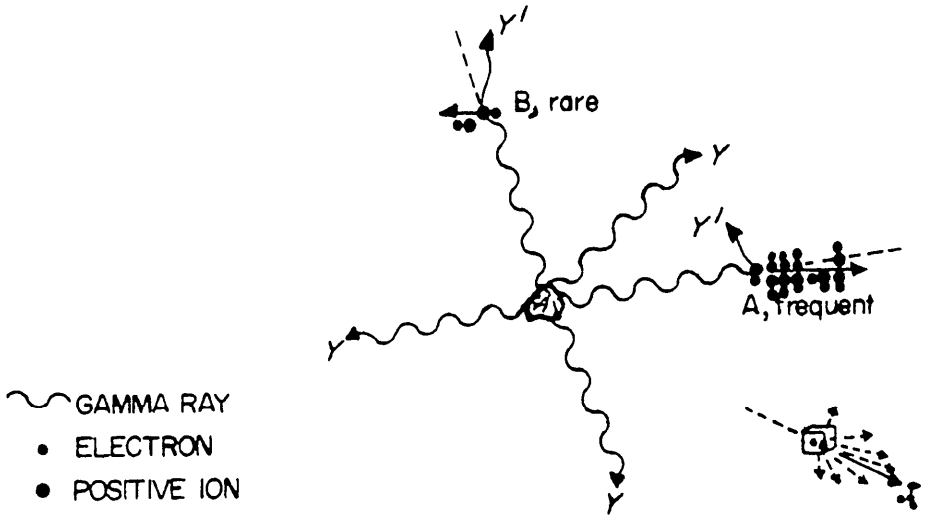

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FIGURE 8. The Compton process.

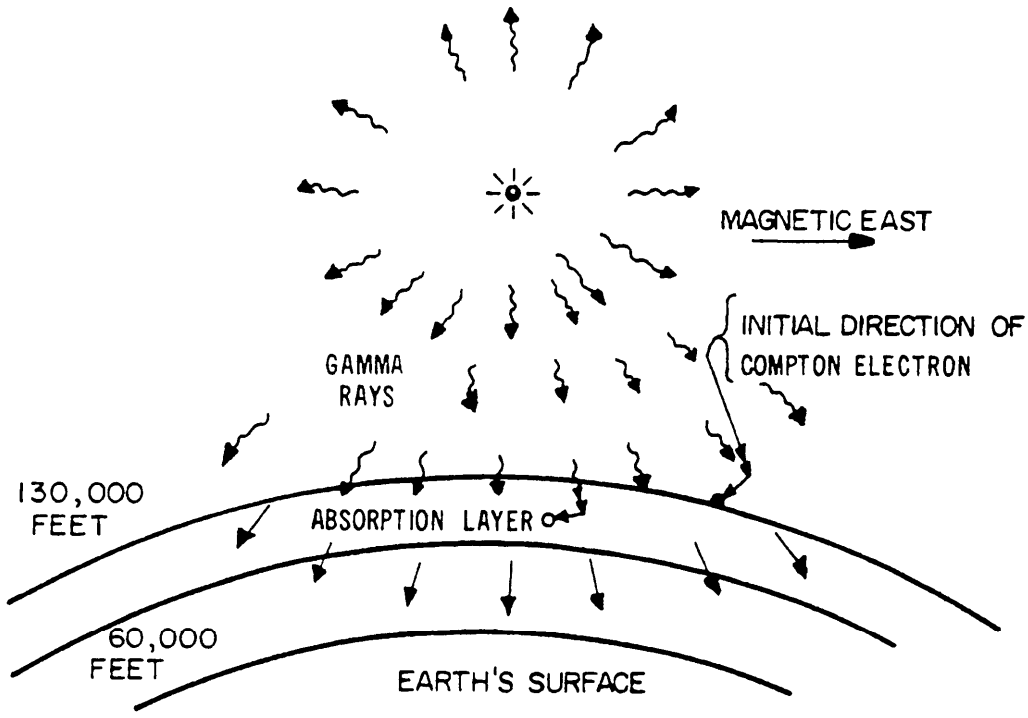

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FIGURE 9. Gamma radiation from exe-atmospheric nuclear detonation.

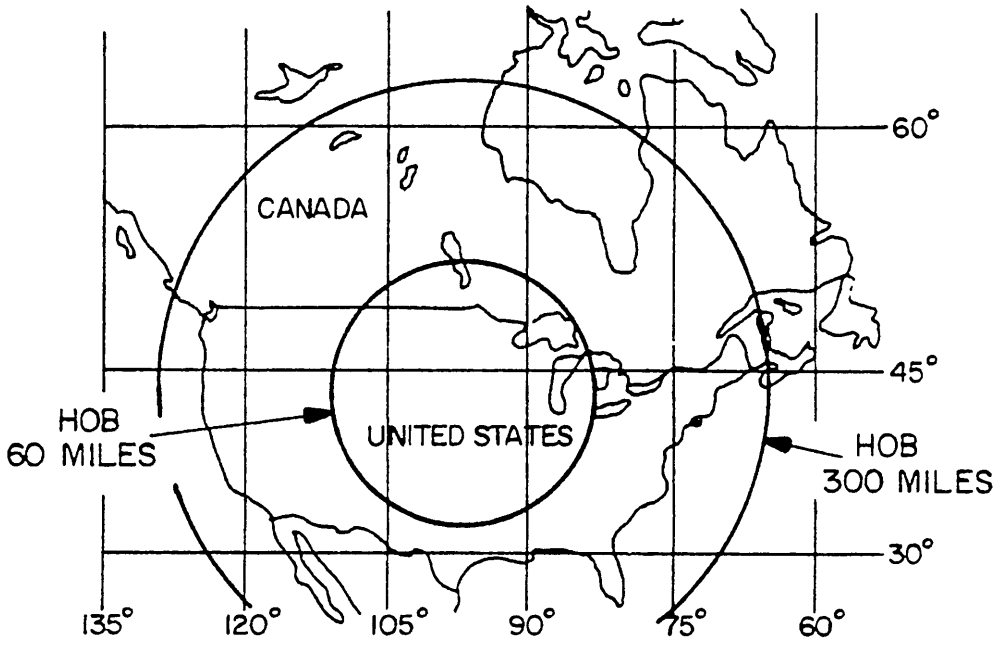

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FIGURE 10. EMP earth coverage from high-altitude nuclear detonation,

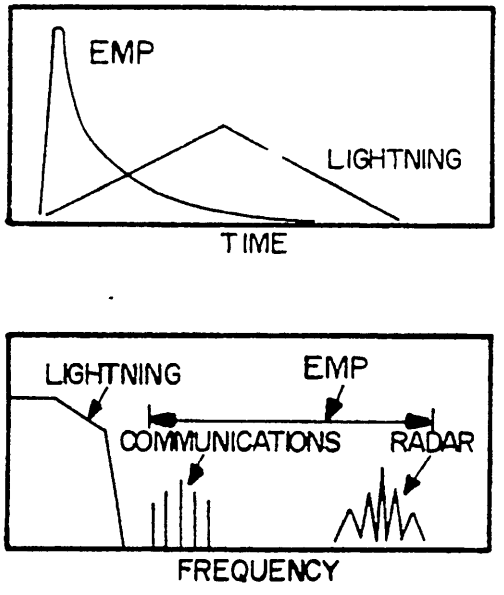

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FIGURE 11. EMP waveform and spectrum comparisons with other electromagnetic processes.

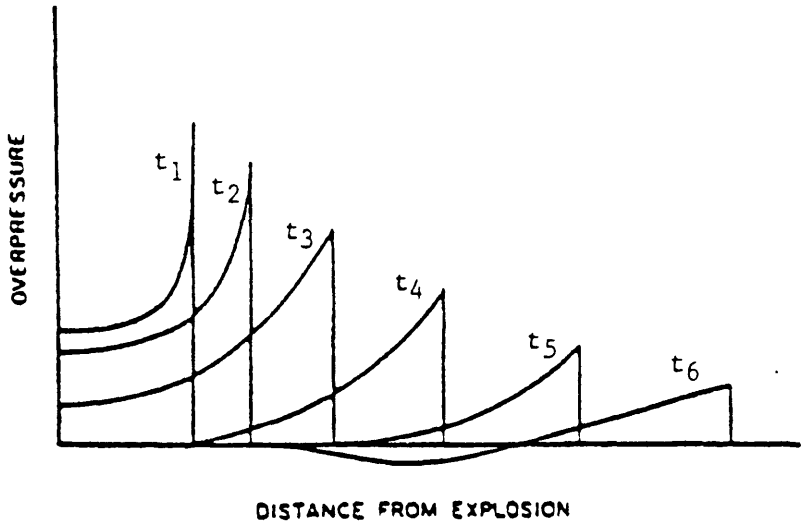

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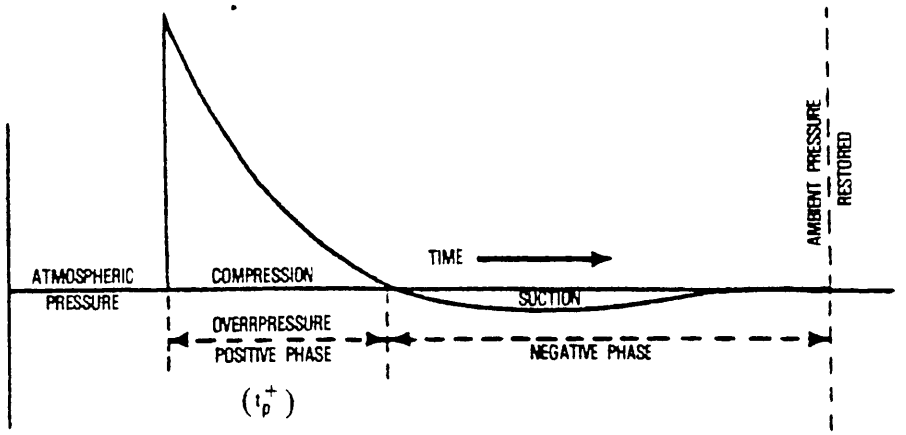
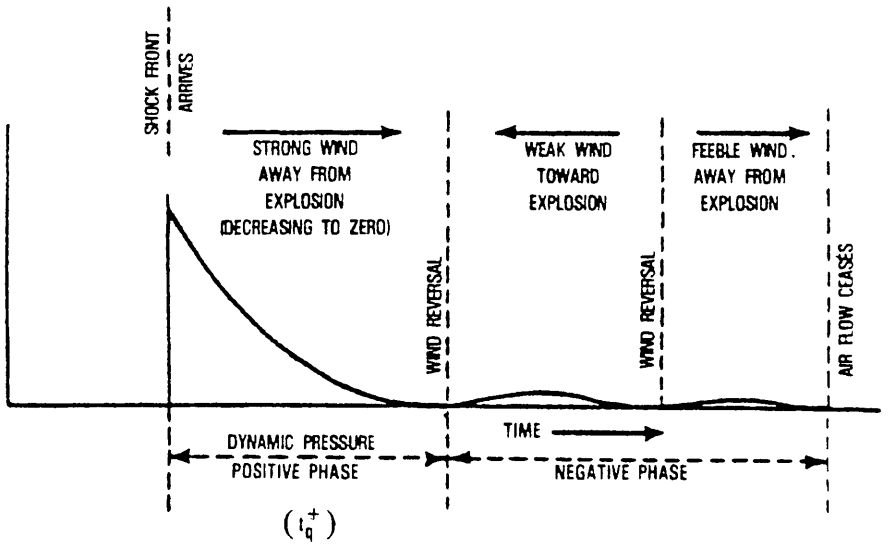
FIGURE 12. Variation of free-field overpressure with distance at successive times for an ideal shock wave in air.



$$p_o(t) = p_{om}(1 - t/t_p^+)\ e^{-t/t_p^+}$$

(a) Free-Field Incident Overpressure



$$q_o(t) = q_m(1 - t/t_q^+)^2\ e^{-2t/t_q^+}$$

(b) Dynamic (Wind) Pressure

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FIGURE 13. Time variations of airblast incident overpressure and dynamic pressure.

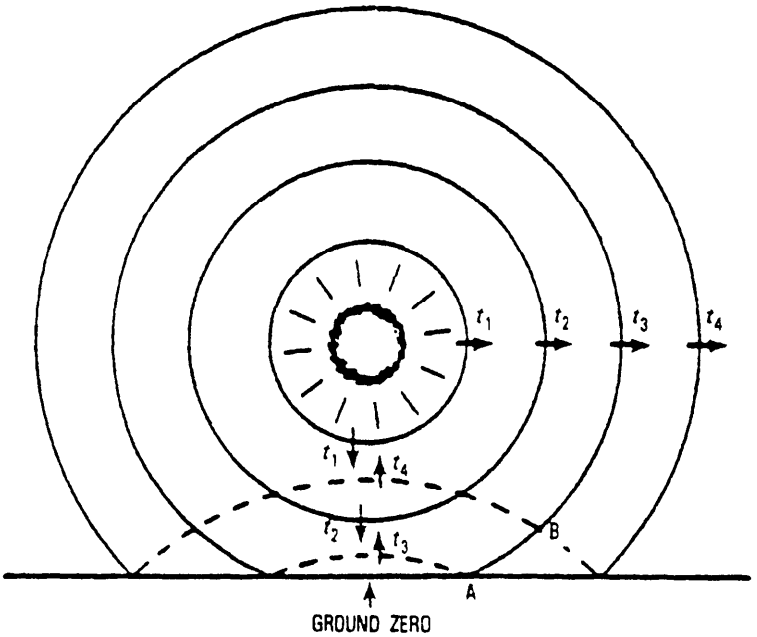

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FIGURE 14. Reflection of blast wave at earth's surface.

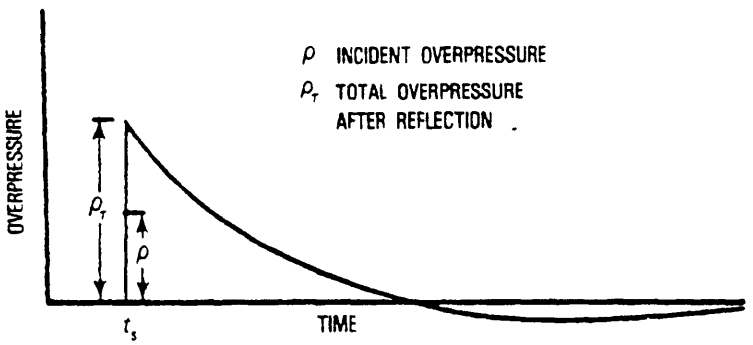

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FIGURE 15. Time variation of overpressure at point on earth's surface (regular reflection region).

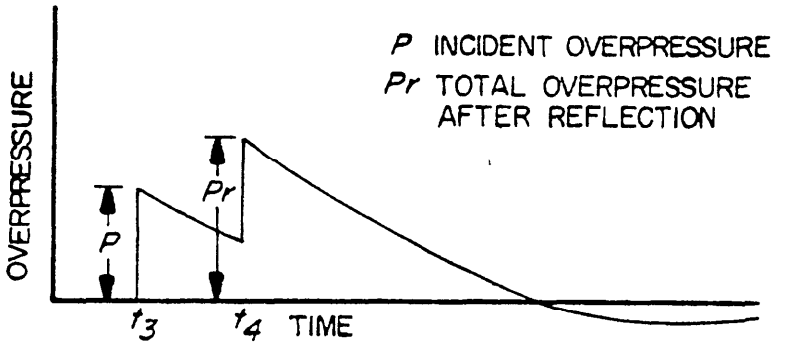

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FIGURE 16. Time variation of overpressure at point above earth's surface (regular reflection region).

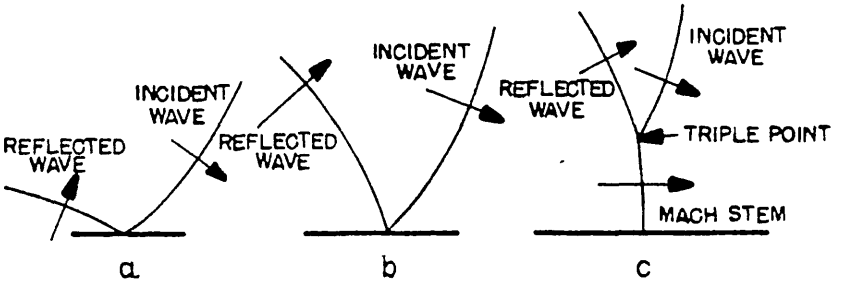

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FIGURE 17. Merging of incident and reflected blast waves; formation of Mach Y configuration.

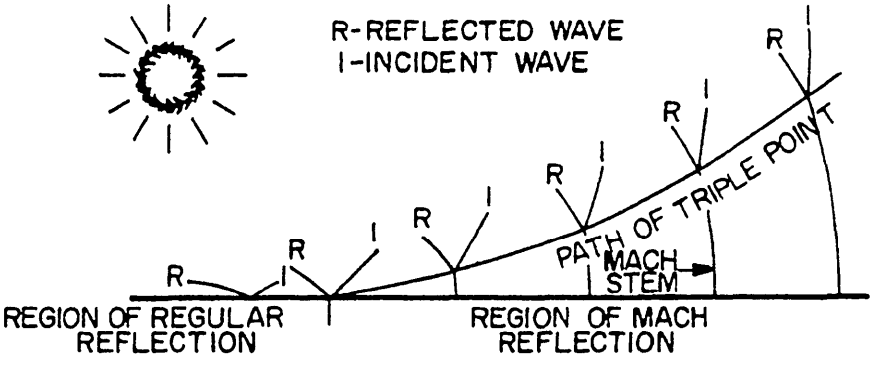

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FIGURE 18. Outward movement of blast wave near earth's surface (Mach reflection region).

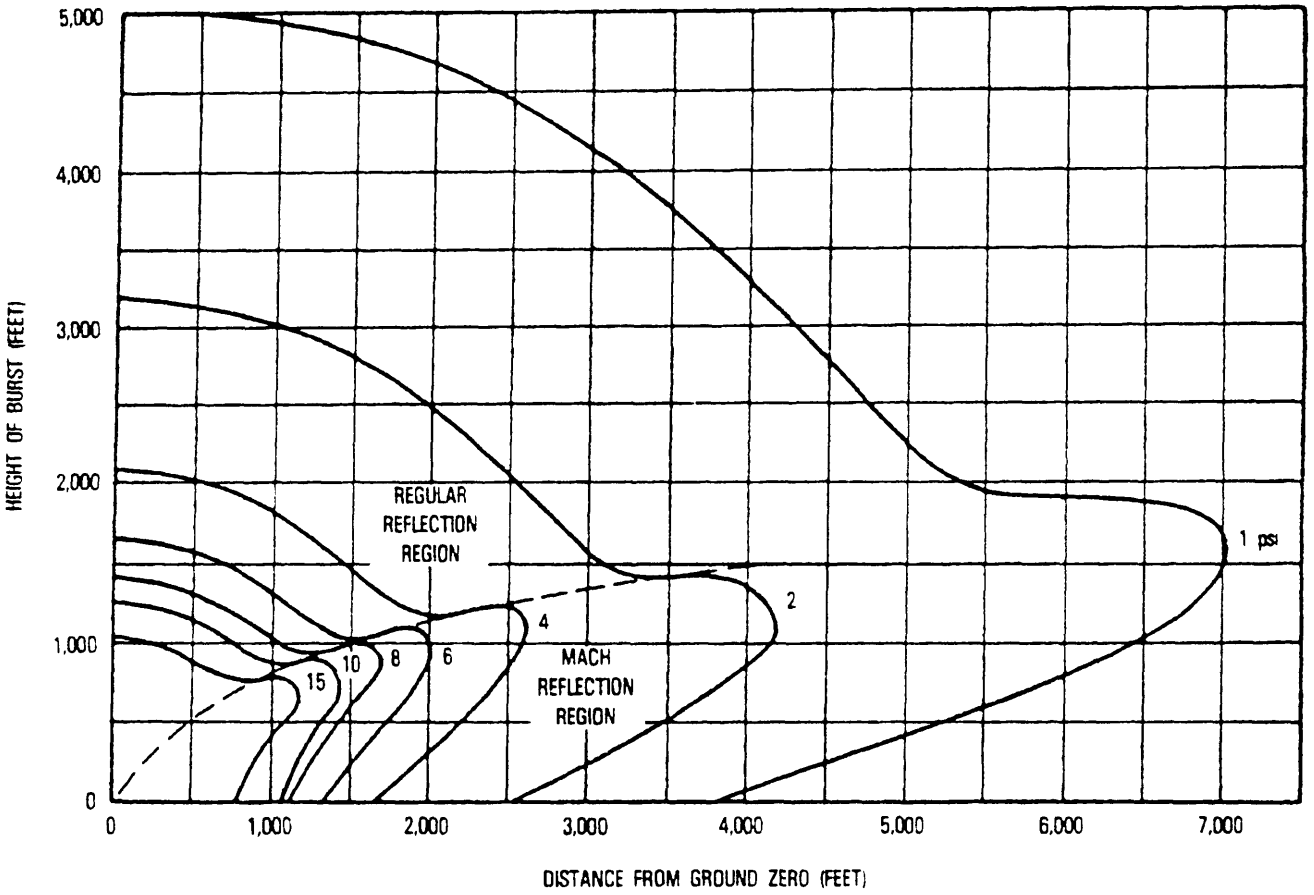

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FIGURE 19. Peak free-field overpressure on the ground for l-kiloton nuclear air burst (low pressure regime).

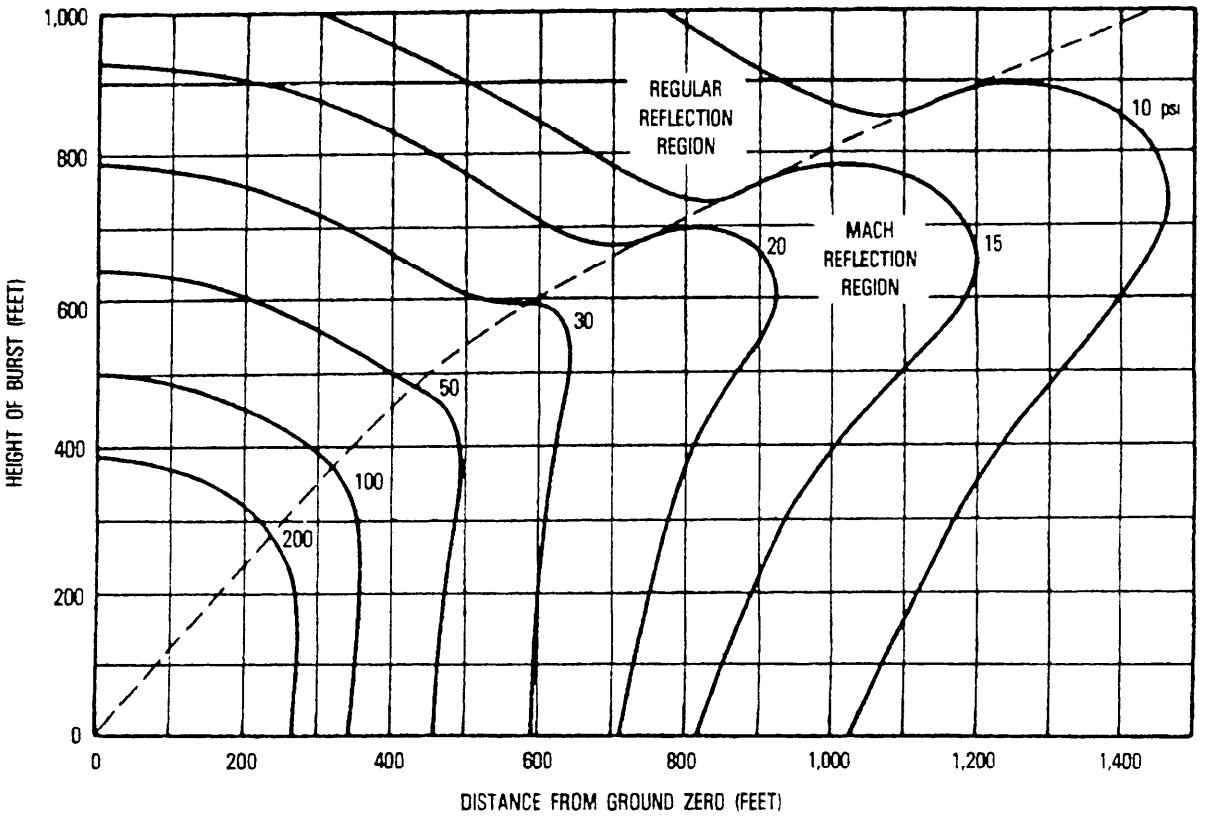

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FIGURE 20. Peak free-field overpressure on the ground for l-kiloton nuclear air burst (intermediate pressure regime).

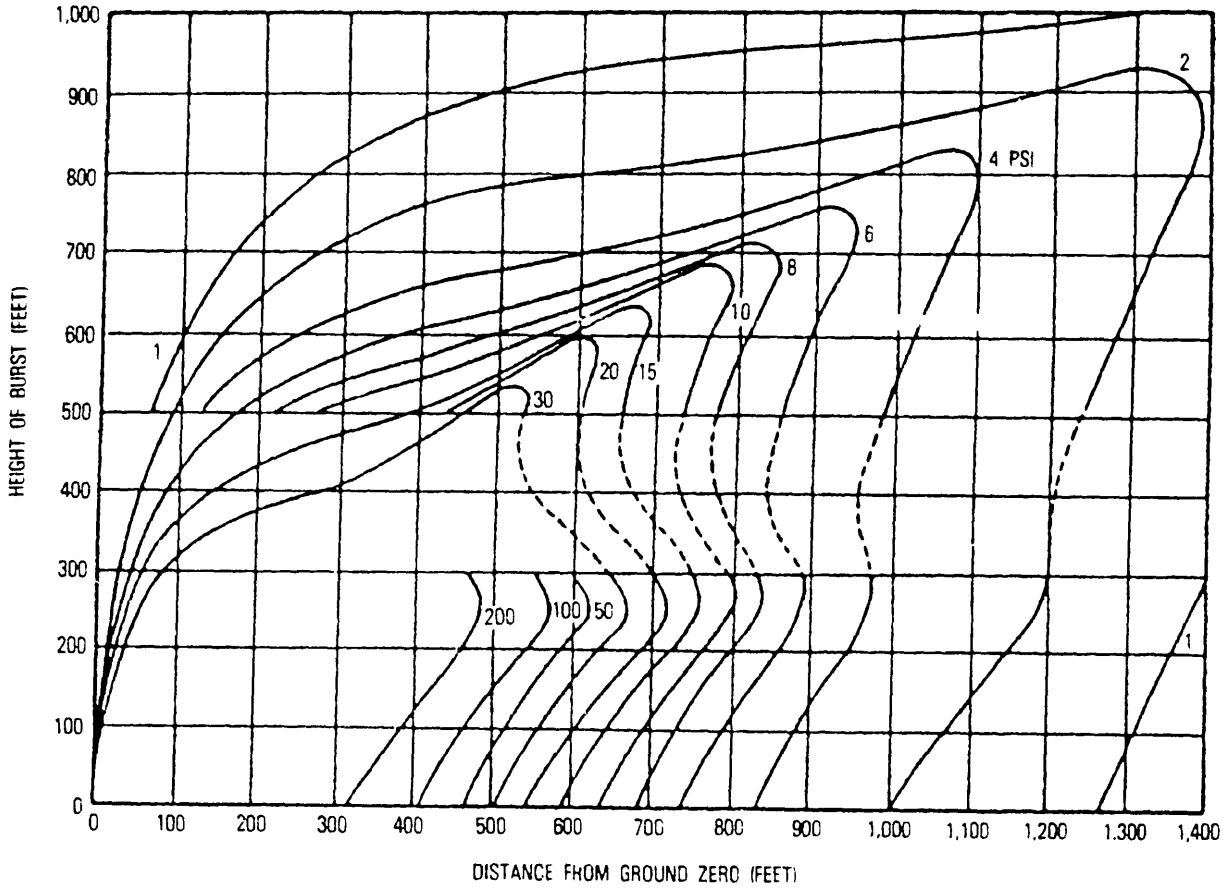

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FIGURE 21. Horizontal component of peak dynamic pressure for l-kiloton nuclear air burst.

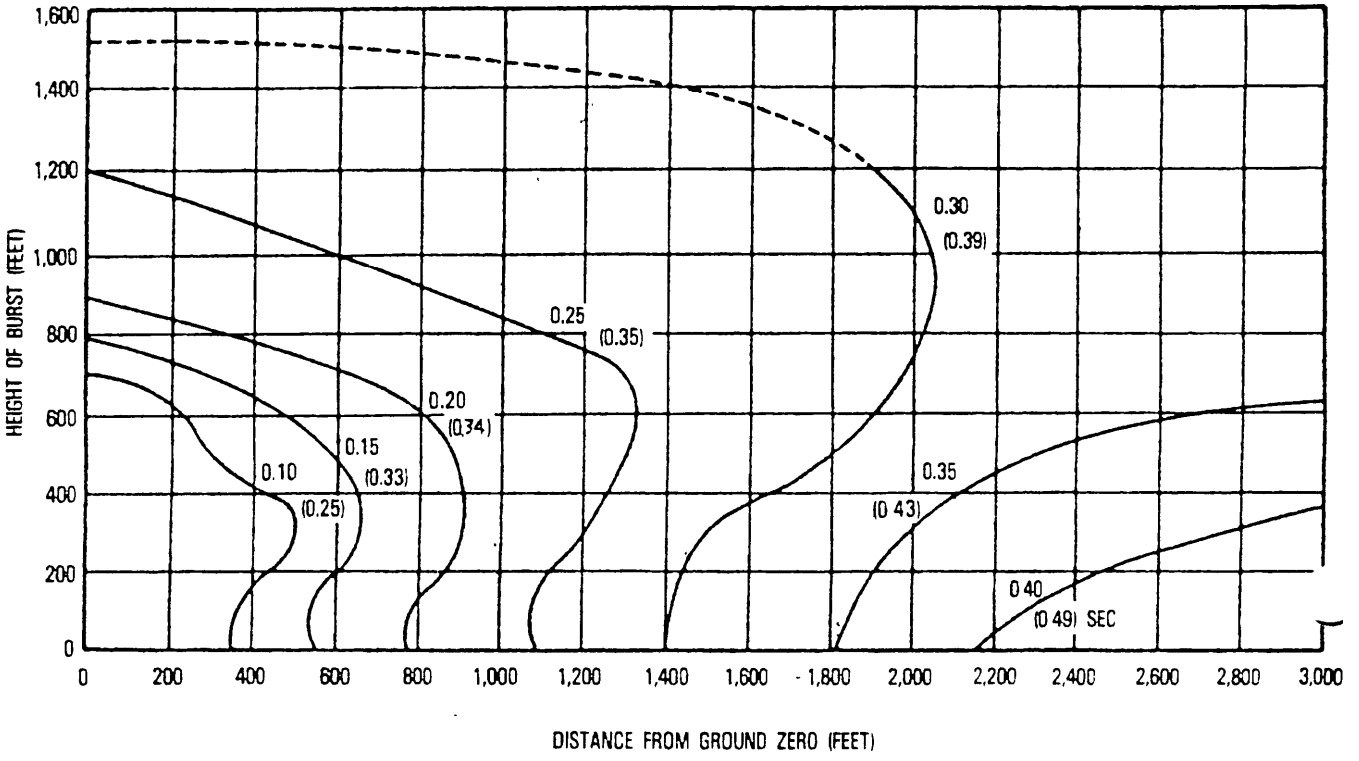

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FIGURE 22. Positive phase duration for incident overpressure and dynamic wind pressure for l-kiloton nuclear air burst,

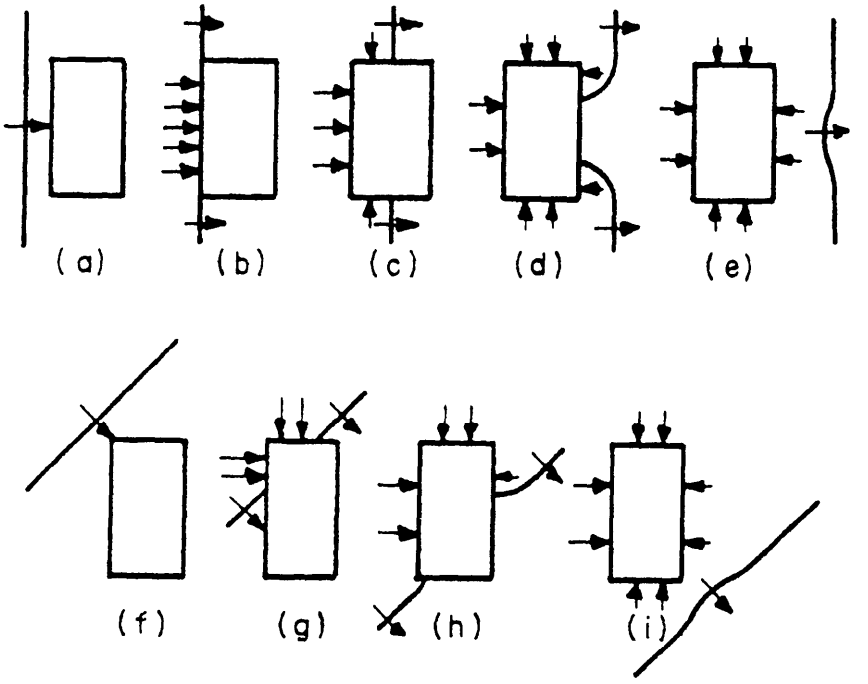

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FIGURE 23. Diffraction of blast wave by box-like structure with no openings (plan view).

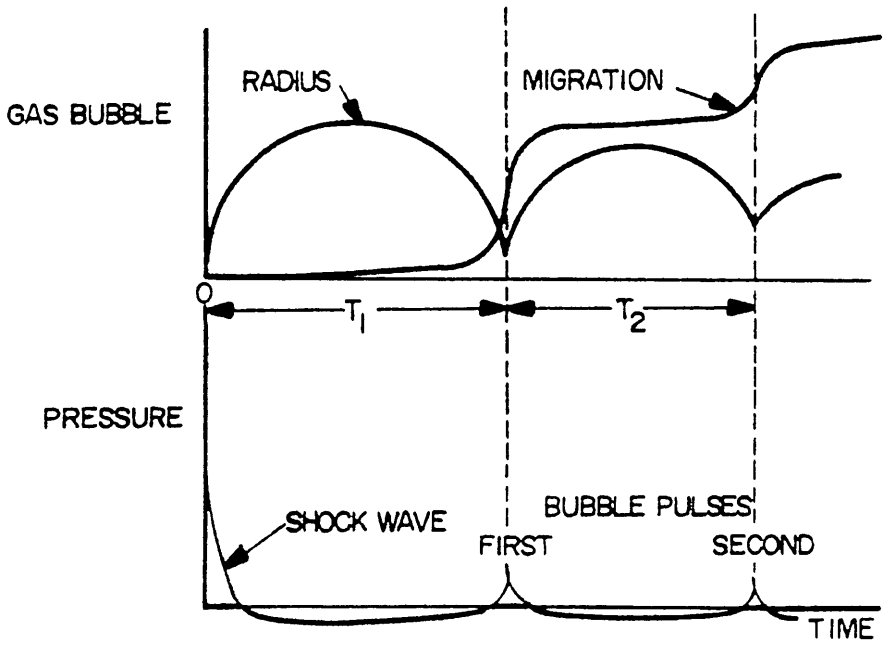

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FIGURE 24. History of underwater explosion events.

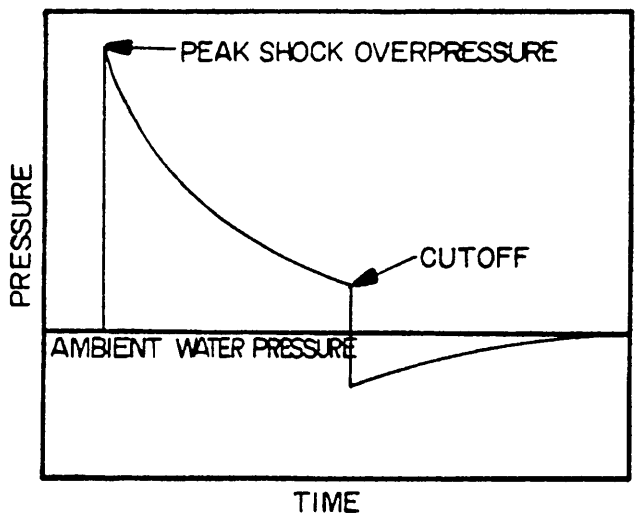

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FIGURE 25. Idealized time variation of overpressure for underwater explosion near air-water interface.

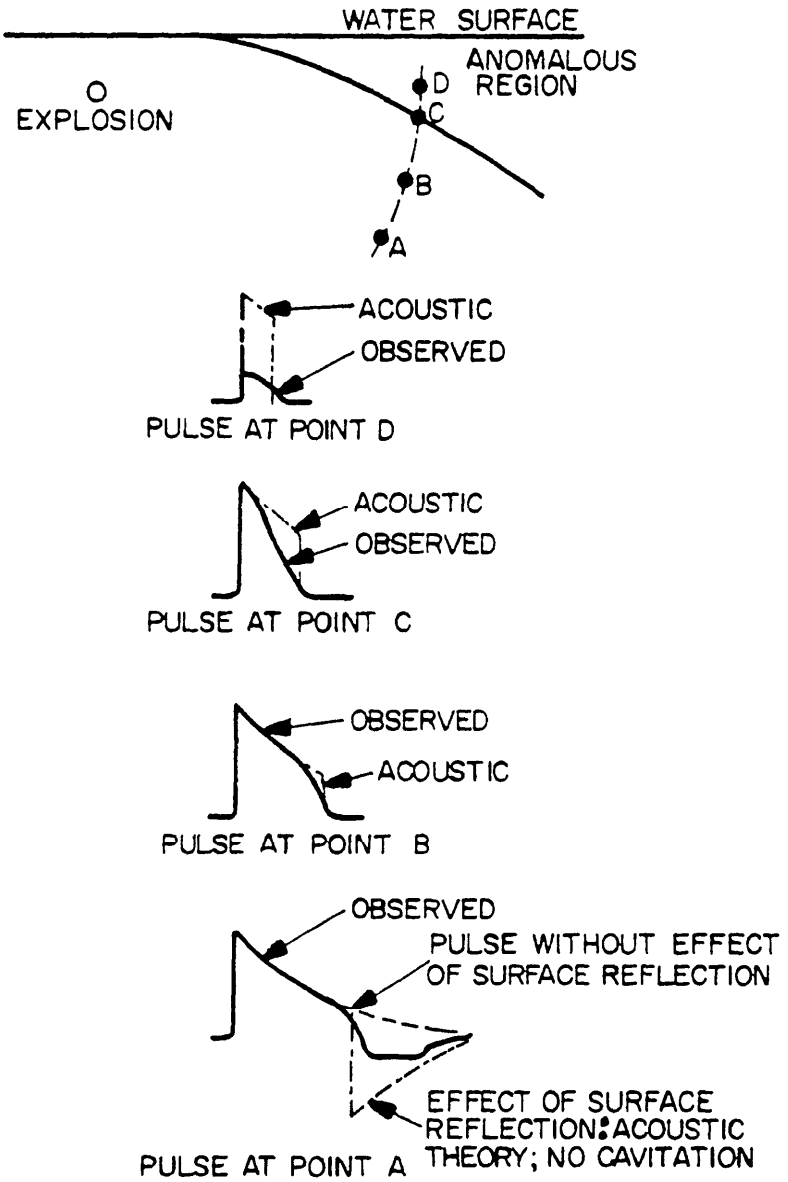

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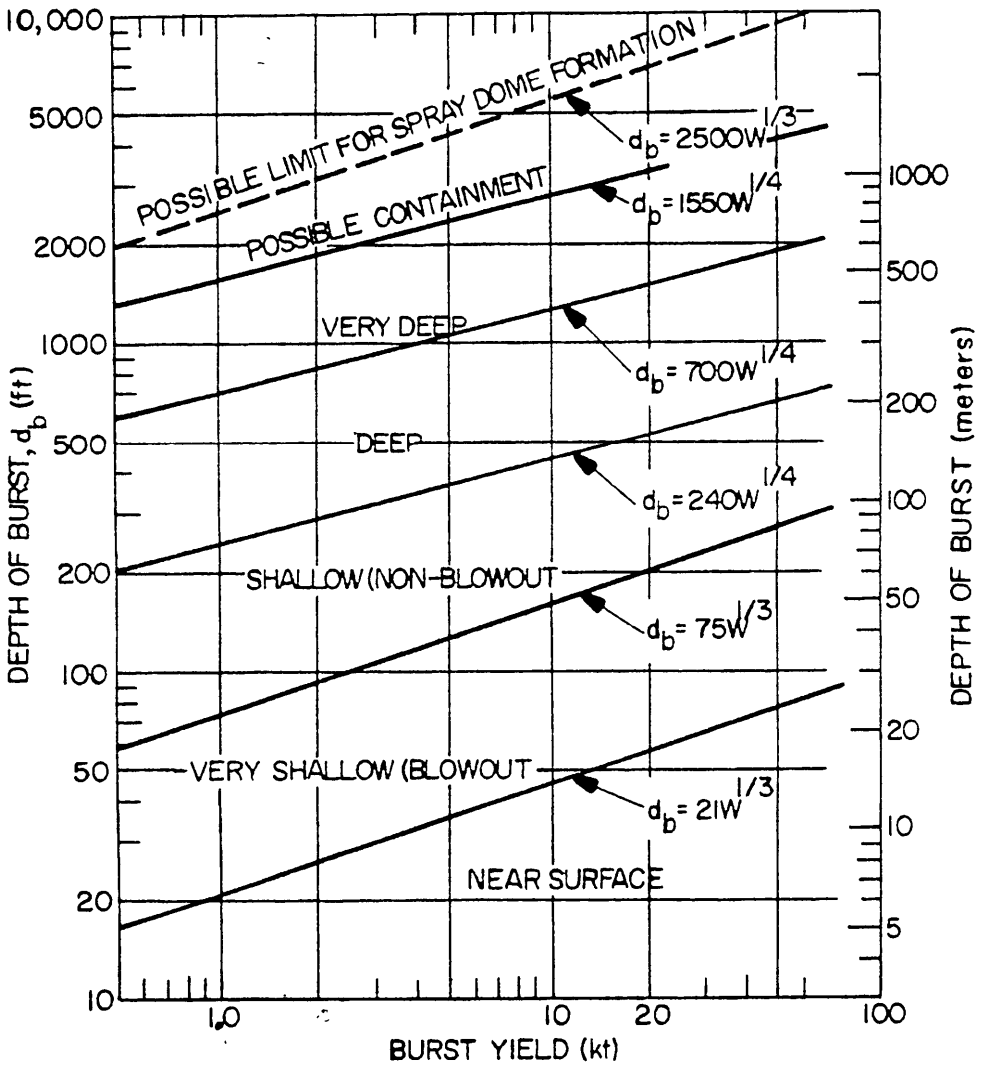
FIGURE 26. Typical underwater pressure pulses affected by surface reflection.



SH 132317422

FIGURE 27. Classification of underwater nuclear bursts.

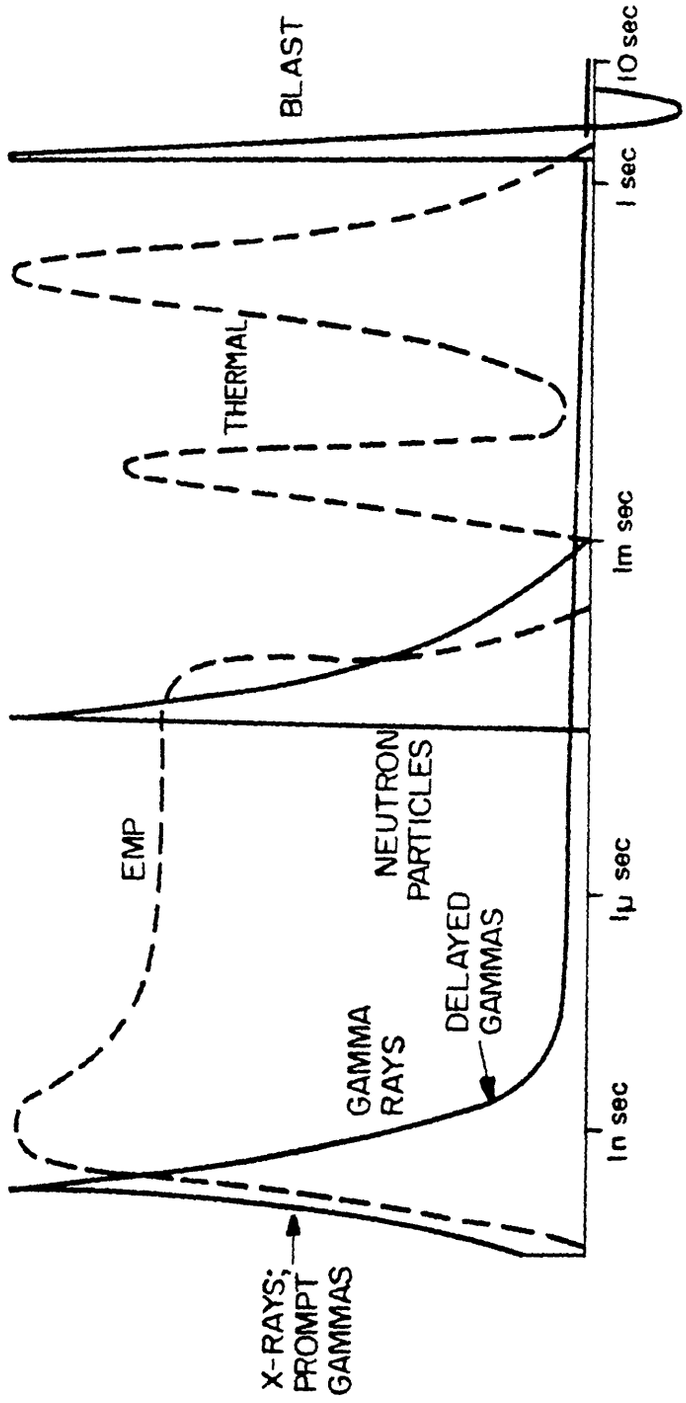


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FIGURE 28. Sequence of principal nuclear explosion phenomena and resultant weapons effects.

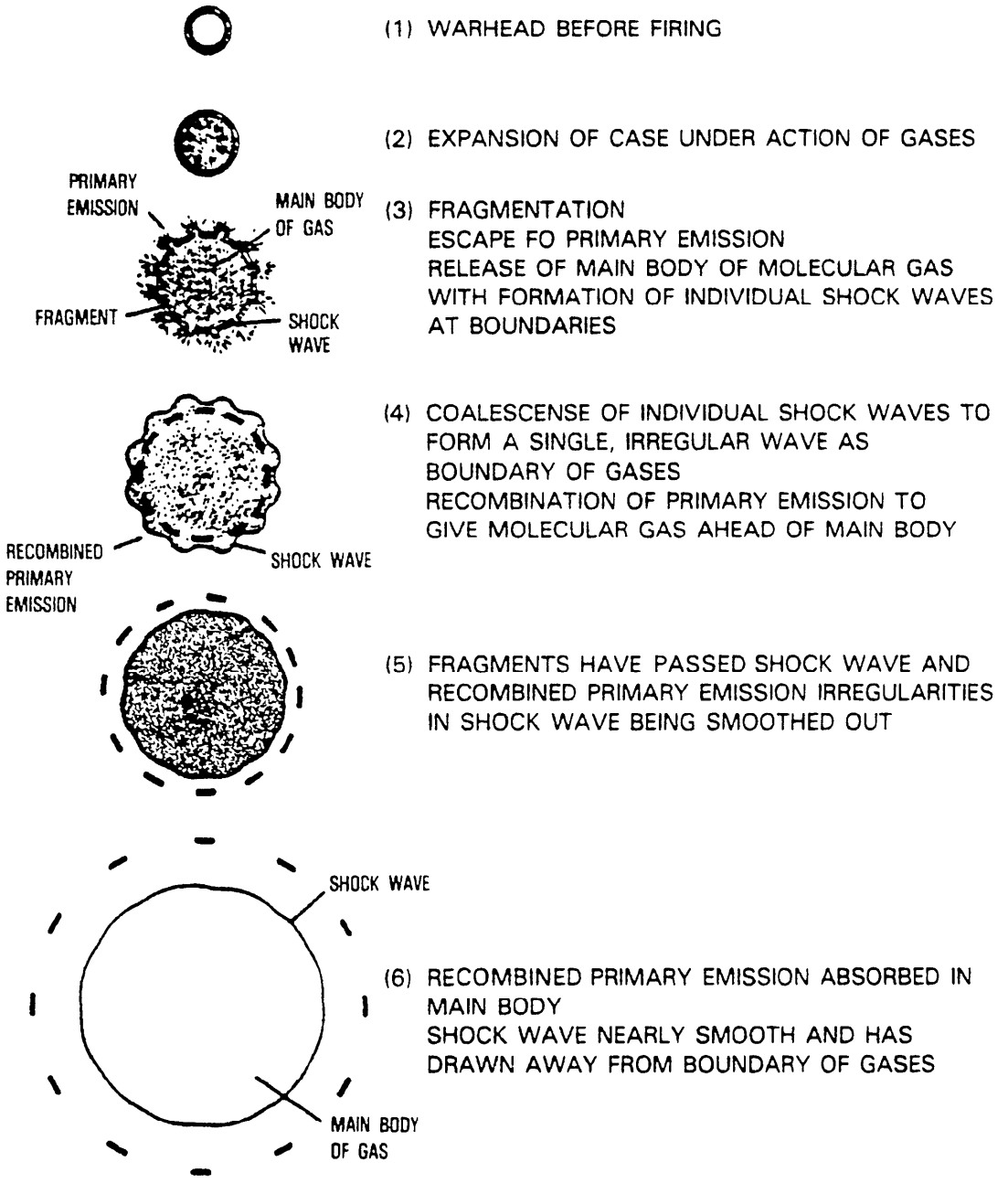

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FIGURE 29. Sequence of principal conventional H.E. explosion phenomena and resultant weapons effects.

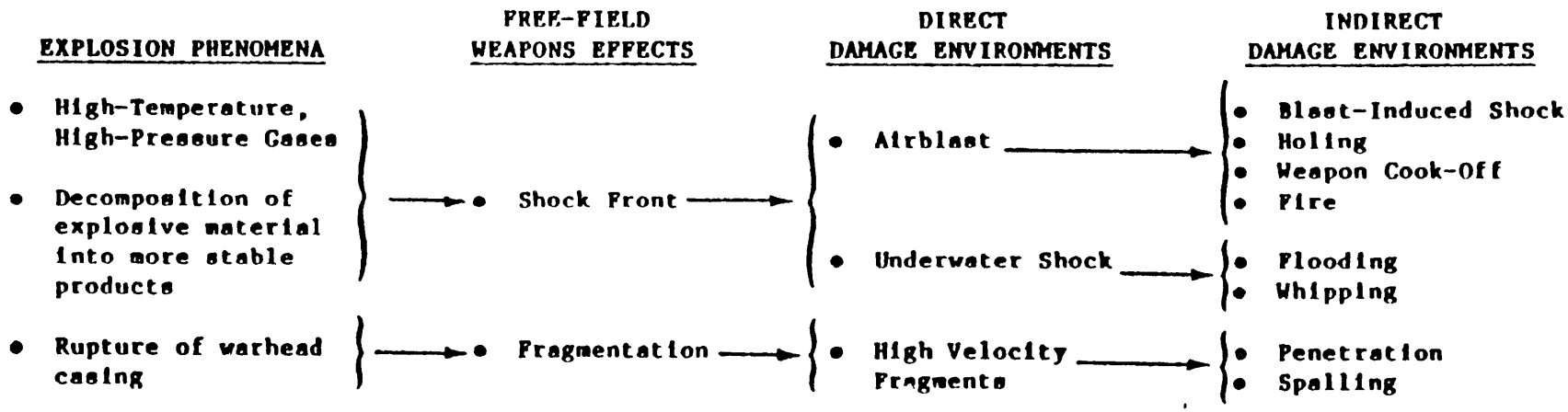

FIGURE 30. Conventional H.E. explosion phenomena and weapons effects or damage environments.

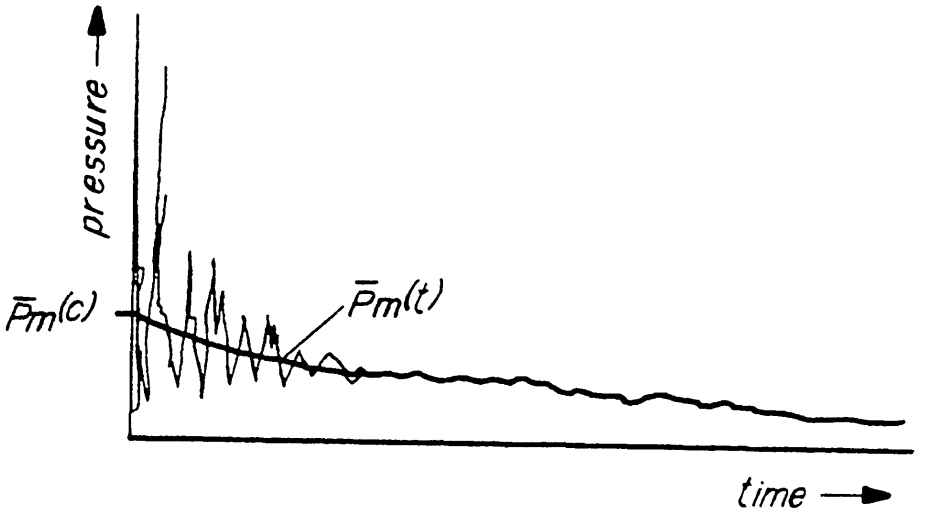

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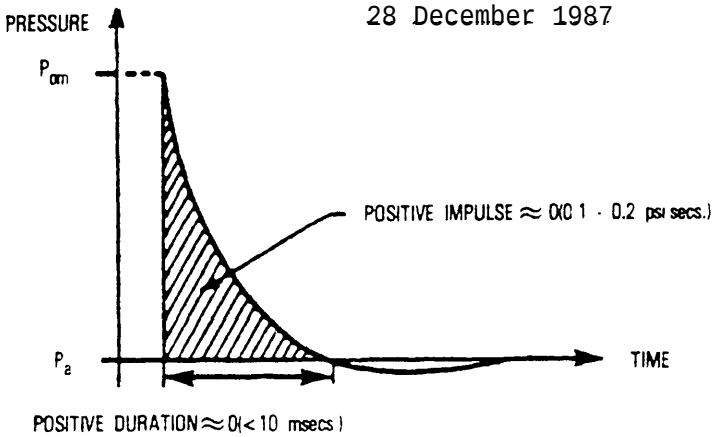
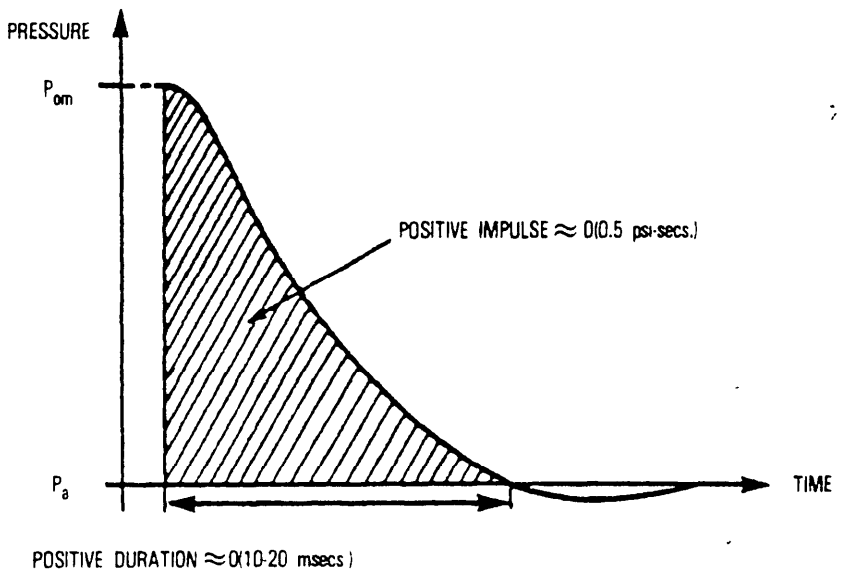
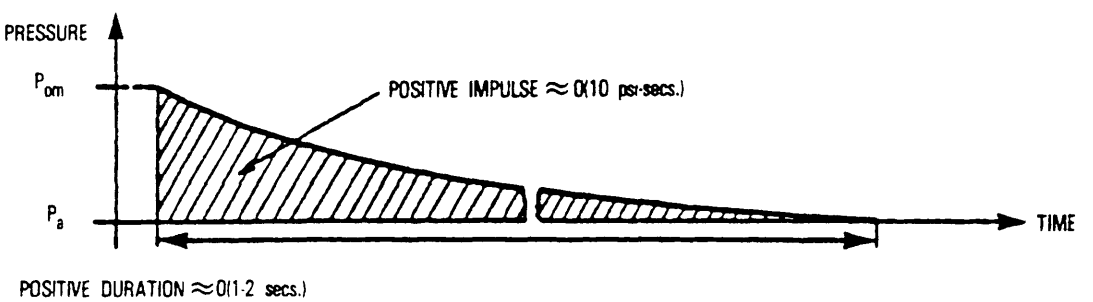
FIGURE 31. Pressure-time history at point on wall of closed chamber for internal H.E. burst (confined airblast).



(a) STANDARD TNT AIRBLAST



(b) ENHANCED AIRBLAST



(c) NUCLEAR AIRBLAST

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FIGURE 32. Comparison of free-field overpressure versus time waveforms for different airblast processes.

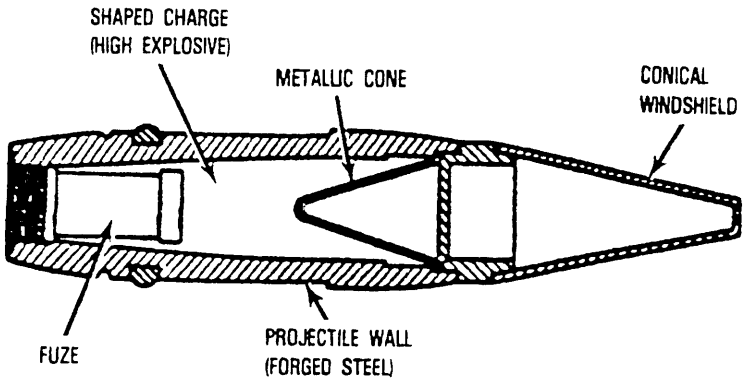

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FIGURE 33. Schematic diagram of typical shaped charge (heat) projectile.

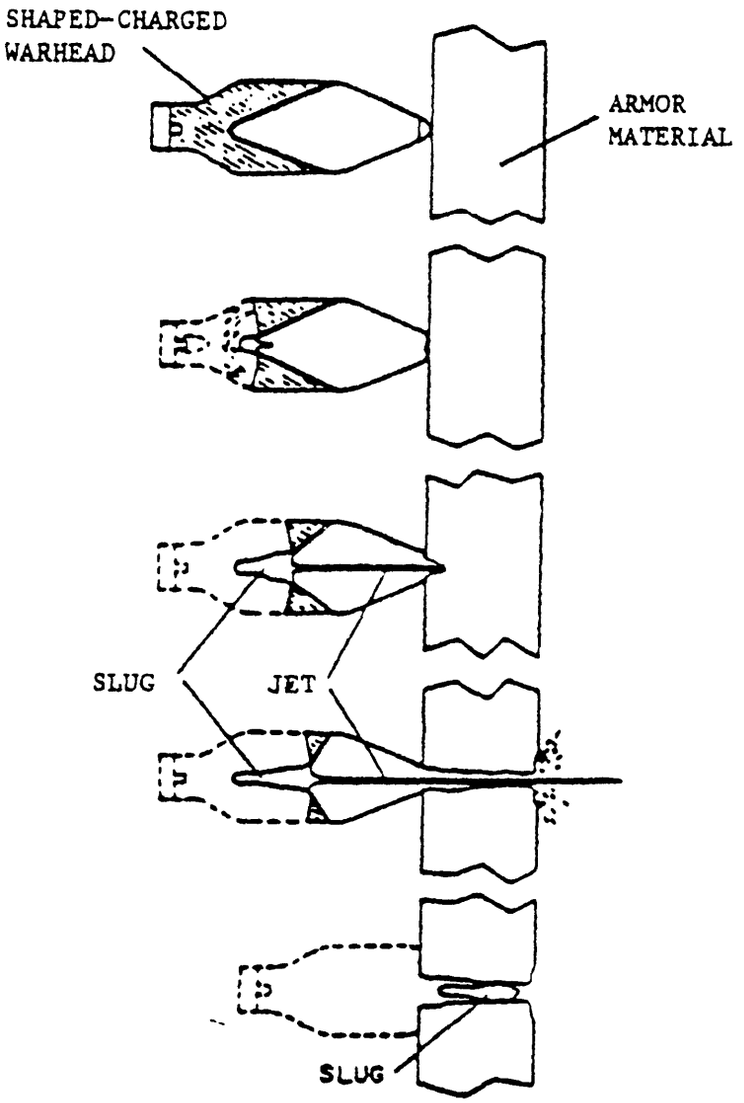

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FIGURE 34. Sequence of shaped-charge penetration events.

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