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TECHNICAL REPORT

Biological Effects of Nuclear Explosions (BENE) Domain Guide

Approved for public release; distribution is unlimited.

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14. ABSTRACT

This Biological Effects of Nuclear Explosions (BENE) Domain Guide presents relevant documentation, references, and bibliographic citations for the student and researcher interested in original test documentation in the BENE phenomenology area.

This document reflects the effort of some two decades of work to organize and review the atmospheric test documentation and Nuclear Test Personnel Review (NTPR) data managed by the Defense Threat Reduction Agency (DTRA). This effort was led by Dr. David Auton (†), who died before this Guide's completion. This effort is dedicated to his memory. Dr. Glen Reeves of Applied Research Associates added information and edited and updated the initial document.

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CONVERSION TABLE

Conversion factors for U.S. customary to metric (SI units of measurement)

MULTIPLY TO GET	BY BY	TO GET DIVIDE
angstrom	1.000 000 x E-10	meters (m)
atmosphere	1.012 25 x E +2	kilo pascal (kPa)
bar	1.000 000 x E + 2	kilo pascal (kPa)
barn	1.000 x E – 28	meter^2 (m^2)
British thermal unit (thermochemical)	1.054 350 x E + 3	joule (J)
calorie (thermochemical)	4.184 000	joule (J)
cal (thermochemical)/cm^2	4.184 000 x E-2	mega joule/m^2 (MJ/m^2)
curie	3.7000 000 x E + 1	giga becquerel (GBq)*
degree (angle)	1.745 329 x E – 2	radian (rad)
degree (Fahrenheit)	Tk = (t +459.69)/1.8	degree kelvin (K)
electron volt	1.602 19 x E – 19	joule (J)
erg	1.000 000 x E – 7	joule (J)
erg/sec	1.000 000 x E – 7	watt (W)
foot	3.048 000 x X-1	meter (m)
foot-pound-force	1.355 818	joule (J)
gallon (U.S. liquid)	3.785 412 x E – 3	meter^3 (m^3)
inch	2.540 000 x E -2	meter (m)
jerk	1.000 000 x E + 9	joule (J)
joule/kilogram (J/kg) (absorbed dose)	1.000 000	Gray (Gy)**
kilotons	4.183	terajoules
kip (1000 lbf)	4.448 222 x E + 3	newton (N)
kip/inch^2 (ksi)	6.894 757 x E +3	kilo pascal (kPa)
ktap	1.000 000 x E +2	newton-second/m^2 (N-s/m^2)
micron	1.000 000 x E – 6	meter (m)
mil	2.540 000 x E – 5	meter (m)
mile (international)	1.609 344 x E + 3	meter (m)
ounce	2.834 952 x E – 2	kilogram (kg)
pound-force (lbf avoirdupois)	4.448 222	newton (N)
pound-force inch	1.129 848 x E – 1	newton-meter (N*m)
pound-force/inch	1.751 268 x E + 2	newton-meter (N/m)
pound-force/foot^2	4.788 026 x E – 2	kilo pascal (kPa)
pound-force/inch^2 (psi)	6.894 757	kilo pascal (kPa)
pound-mass-foot^2 (moment of inertia)	4.214 011 x E – 2	kilogram-meter^2 (kg*m^2)
pound-mass/foot^3	1.601 846 x E + 1	kilogram/m^3 (kg/m^3)
rad (radiation absorbed dose)	1.000 000 x E – 2	Gray (Gy) **
rem (roentgen equivalent man)		Sievert (Sv) ***
roentgen	2.579 760 x E – 4	coulomb/kilogram (C/kg)
shake	1.000 000 x E – 8	second (s)
Slug	1.459 390 x E + 1	kilogram (kg)
Torr (mm Hg, 0 degrees C)	1 333 22 x E – 1	kilo pascal (kPa)

* *The Becquerel (Bq) is the SI unit of radioactivity: 1 Bq = 1 event/s.*
** *The Gray (Gy) is the SI unit of absorbed radiation.*
*** *The Sievert (SV) is the SI unit of dose equivalent.*

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FOREWORD

This Biological Effects of Nuclear Explosions (BENE) Domain Guide presents relevant documentation, references, and bibliographic citations for the student and researcher interested in original test documentation in the BENE phenomenology area.

This document reflects the effort of some two decades of work to organize and review the atmospheric test documentation and Nuclear Test Personnel Review (NTPR) data managed by the Defense Threat Reduction Agency (DTRA).

This effort was led by Dr. David Auton (†), who died before this Guide's completion. While at the Defense Threat Reduction Information Analysis Center (DTRIAC) Dave compiled all the data for the Guide and wrote it as a draft DTRA Technical Report. Only editorial corrections and brief expansions of the data have been added. This document is dedicated to his memory.

1.0 HISTORY/INTRODUCTION

The following references contain relevant Biological Effects of Nuclear Explosions (BENE) test documentation. The intention of this listing is to denote documents, for bibliographic purposes, and to provide a convenient reference point for the researcher interested in original test documentation in the BENE area. The test history is rich in relevant experiments and observations, and understanding in this area was deemed of great importance.

The Defense Threat Reduction Information Analysis Center (DTRIAC) provides the reports on U.S. testing to eligible persons and agencies through the Scientific and Technical Information Archival and Retrieval System (STARS). Further information may be found at their web page, www.dtra.mil/DTRIAC.aspx (accessed 03 Oct 2012). DTRIAC has archived "A Guide to Nuclear Weapons Phenomena and Effects Literature" (Sachs, 1995), which summarizes project names, report numbers, and a brief description of each report under the weapons testing program.

1.1 HIROSHIMA/NAGASAKI

Three weeks after the nuclear weapon detonations in Japan, the U.S. Army organized a study of the atomic bomb casualties. Upon landing in Japan the U.S. team learned that the Japanese Government had already sent several scientists from multiple Japanese universities to study these effects. The decision for cooperation between the investigators from the two governments was made and close liaison maintained between Japanese scientists and physicians and the Army Surgeon's Office team. A group from the Manhattan District also arrived to determine what residual radioactivity was still present for purposes of troop protection as well as to study effects. COL (Dr.) Ashley W. Oughterson was the primary author of a six-volume set of documents entitled "Medical Effects of Atomic Bombs" (U.S. Atomic Energy Commission, 1945). This is an extensive and comprehensive review of the effects of the atomic bombs, and is an essential document for those required to study this topic. Distribution is available to any U.S. government agency and their contractors working in this area.

Topics of the six volumes are:

Volume 1: Introduction; physics; description of Hiroshima and Nagasaki cities.
Volume 2: Materials and methods of medical studies; clinical observations.
Volume 3: Hematology; studies of bone marrow biopsies.
Volume 4: Pathology observations from autopsies of radiation-injured patients.
Volume 5: Statistical analyses of questionnaires for patients in both cities.
Volume 6: Studies of population and casualties; building and protection studies.

Volume 1 also includes eyewitness accounts from residents of each city.

The government of Japan published a book, "Medical Report on Atomic Bomb Effects", which was favorably reviewed by the Journal of the American Medical Association a year later (National Research Council of Japan, 1953). Unfortunately, as of September 2012 it is not available in the U.S.

1.2 PACIFIC PROVING GROUNDS

Shortly after WW II was concluded the United States established the Pacific Proving Grounds (PPG) for nuclear weapon testing. A number of sites in the Marshall Islands and a few other places in the equatorial western Pacific Ocean suitable for nuclear weapon testing composed the PPG. One of the aims of the testing program was to conduct biological and medical research to better understand the effects of nuclear weapons on biological specimens and, by extension, to man. This isolated area of ocean permitted the testing of large atmospheric devices with relatively low risk of human injury, although several inhabitants of the Marshall Islands and, on one occasion, the crew of a Japanese fishing boat were harmed by fallout.

An extensive research effort on all aspects of weapons was conducted for each test. Experiments designed to study the biological effects of nuclear explosions were conducted and reports written, most of which have been declassified.

(**N.B.** For ease of reading the nine operations at the PPG are listed together, and the tables summarizing the reports conducted under each operation are together at the end of this section.)

Operation CROSSROADS (Table 1.1) tested large numbers of mammals (goats, pigs, and rats) as well as seeds, soil (to see if tomatoes and grass could grow in irradiated soil), and the effectiveness of radiation on biological warfare agents.

Operation SANDSTONE (Table 1.2) assessed the effects of ionizing radiation on a variety of seeds, insects, and bacteria.

Operation GREENHOUSE (Table 1.3) assessed the effects of nuclear radiation on mice, pigs, and dogs; objectives included lethality ranges, pathology of injury, effects of shielding (foxholes), and comparison of effects with laboratory irradiated animals as well as dosimeters.

Operation IVY (Table 1.4) did surveys of plant and animal specimens before and after Test Mike to determine the changes in biological materials before and after this shot. (**N.B.** Test Mike was performed in November 1952 but the report noted below not written till the following year.)

Operation CASTLE (Table 1.5) was a follow-on to IVY in developing thermonuclear weapons. They did not initially plan to conduct biomedical projects; however, the first test had a yield much higher than predicted and the crew of a Japanese fishing boat was exposed to high levels of fallout. Physicians and researchers hurried to treat and also study these men, and a program for biomedical studies was implemented. The injured and exposed Marshallese, as well as American military personnel, were studied for several months after the incident.

Operation WIGWAM (Table 1.6) detonated a device deeply underwater to observe various radionuclides as they ascended the food chain.

Operation REDWING (Table 1.7) researched thermal radiation effects on the eyes of rabbits and monkeys that were constrained to face the fireball.

Operation HARDTACK (Table 1.8) was initially designed as an extensive series of tests to be conducted at the PPG. However, the second phase of the series was done at the Nevada Test Site. HARDTACK I studied chorioretinal burn damage in rabbits analyzed with respect to exposure conditions.

Operation FISHBOWL, part of Operation DOMINIC I (Table 1.9), also studied production of chorioretinal burns in rabbits. Unfortunately, during the Bluegill Triple Prime test, two military personnel accidentally received retinal damage; the damage was permanent in one man.

Table 1.1 Operation CROSSROADS, 1946

Report Author	Report Title	Number	Objective
Bureau of Medicine and Surgery (BUMED) Research Group, 1950a	Target Stations and Biological Materials Exposed During Tests Able and Baker	XRD-163	Identifies locations of each biological sample
BUMED, 1950b	Airblast Effects of an Atomic Bomb Explosion	XRD-164	Rat model used; autopsies studied trauma and thermal (not radiation) effects
BUMED, 1950c	Gross Autopsy Findings and a Statistical Study of the Mortality in the Animals Exposed at Bikini	XRD-165	Autopsy findings on all animal models (goats, pigs, rats)
BUMED, 1950d	Germination of Vegetable Seeds Exposed at Bikini During the Atomic Bomb Test Able	XRD-170	Assess effects of radiation exposure on plant germination and growth (several vegetables and cotton studied)
BUMED, 1950e	Residual Effects of Atomic Radiation in Soil on Seed Germination	XRD-171	Studied ability of plants to grow in irradiated soil
BUMED, 1950f	Effect of the Bikini Atomic Bomb Test Able on Soil Microorganisms	XRD-172	Compare quantities of microorganisms in irradiated and non-irradiated soils
BUMED, 1950g	Analysis of Tissues for Induced Radioactivity	XRD-175	Induced radioactivity measured in bones of rats, pigs, and goats
BUMED, 1950h	Vycor Glass Gamma Ray Dosimeters	XRD-176	Readings from dosimeters designed to measure dose on animals exposed to high levels of radiation
BUMED, 1950i	Aberrations Found in the Progenies of Plants Grown from Irradiated Cotton	XRD-177, -178	Analysis of second-generation seeds from cotton in XRD-170
Armed Forces Special Weapons Project (AFSWP), 1947	Test Site Survey	XRD-212	Post-operation measurement of residual radiation in soils, plants, sea life

Table 1.2 Operation SANDSTONE, 1948

Report Author	Report Title	Number	Objective
Berkhouse et al., 1983	Biological and Animal Container Studies	SS-33 (also DNA Report 6033F)	Assess effects of radiation on seeds, insects, and bacteria; design cages for animal exposure in future events

Table 1.3 Operation GREENHOUSE, 1951

Report Author	Report Title	Number	Objective
LeRoy and Langham, 1951	Evaluation of Program 2 (Biomedical Tests)	WT-21	Summary of Greenhouse biomedical experiments
Carter et al., 1951	Annex 2.2, Control Studies of Operation Greenhouse Test Animals	WT-6, -18	Exposures of mice, pigs, dogs to laboratory radiation simulating weapon environment
Anderson et al., 1951	Annex 2.4, Experimental Data Obtained in the Field	WT-43	Comparative analysis of mice with Annex 2.2 results; testing of materials to simulate human, mice, and pig tissues; evaluation of plants as gamma dosimeters
Cronkite et al., 1951	Annex 2.5, Mortality Rate as a Function of Distance	WT-22	Survival of exposed mice, pigs, dogs as function of distance from Ground Zero
Tullis et al., 1951	Annex 2.6, Pathology of Radiation Injury	WT-16	Detailed clinical and autopsy observations of dogs and pigs exposed to nuclear environment
Pearse et al., 1951	Annex 2.7, Thermal Radiation Injury	WT-9	Nature of skin burns in dogs and pigs
Talbot and Maupin, 1951	Annex 2.9, Blast Injuries in Foxholes	WT-8	Measurements of blast, thermal, and radiation environments; autopsies of exposed dogs
LeRoy, 1951	Annex 2.10, Miscellaneous Studies of Dosimeters	WT-13	Evaluation of Glomerella fungus and corn as well as physical materials for dosimetry suitability

Table 1.4 Operation IVY, 1952

Report Author	Report Title	Number	Objective
Donaldson, 1953	Project 11.5, Radiobiological Studies at Eniwetok Before and After Mike	WT-616	Collect and ash plant and animal samples for pre- and post-test radiological counting

Table 1.5 Operation CASTLE, 1954

Report Author	Report Title	Number	Objective
Folsom et al., 1958	Project 2.7a, Radioactivity of Open-Sea Plankton Samples	WT-954	Measurement of bioconcentration of fallout products and effects of biological processes
Cronkite et al., 1954	Project 4.1, Study of Response of Human Beings Accidentally Exposed to Significant Fallout Radiation	WT-923	Detailed observations of injuries and treatments of Marshallese over first 76 exposure days.
Cohn et al., 1954	Project 4.1 Addendum, Nature and Extent of Internal Radioactive Contamination of Human Beings, Plants, and Animals Exposed to Fallout	WT-936	Effects of internal contamination by fallout materials studied
Bond et al., 1955	Project 4.1A Addendum, Medical Examination of Rongelap People Six Months After Exposure to Fallout	WT-937	Six-month medical follow-up examinations and studies
Sharp and Chapman, 1957	Project 4.1 Addendum, Exposure of Marshall Islanders and American Military Personnel to Fallout	WT-938	Inclusion of U.S. troops stationed in fallout area
Sondhaus and Bond, 1955	Project 4.1 Addendum, Physical Factors and Dosimetry in Marshall Island Radiation Exposure	WT-939	Description of dosimetry support

Table 1.6 Operation WIGWAM, 1955

Report Author	Report Title	Number	Objective
Schaefer et al., 1959	Project 2.5, Effects of Nuclear Explosion on Marine Biology	WT-1013	Assess possibility of radiation-contaminated fish entering fishing regions as well as multiple samples of other marine life

Table 1.7 Operation REDWING, 1956

Report Author	Report Title	Number	Objective
Fixott et al., 1955	Project 4.1, Chorioretinal burns	WT-1326	Medical observations and assessments of rabbits and monkeys constrained to face fireball

Table 1.8 Operation HARDTACK I, 1958

Report Author	Report Title	Number	Objective
Pickering et al., 1958a	Project 4.1, Effects on Eyes from Exposure to Very-High-Altitude Bursts	WT-1633	Study of chorioretinal burns in rabbits on the ground and behind Plexiglas aircraft canopies

Table 1.9 Operation DOMINIC I, 1962

Report Author	Report Title	Number	Objective
Berkhouse et al., 1983	Operation DOMINIC I	DNA 6040F	Report of early signs and symptoms of eye injuries and follow-up clinical measurements of visual fields and acuity

1.3 NEVADA TEST SITE

Land tests at Nevada Test Site (NTS), now called the Nevada National Security Site, were begun in 1951. As with the PPG, the area chosen was relatively isolated. Atmospheric testing of weapons, as well as studies of weapon effects on animals, ceased in 1962; however high-explosive and other above-ground testing continued beyond 1962. As with the previous section for the PPG, the tables for each of the nine NTS operations are grouped together at the end of this section.

Operation BUSTER-JANGLE (Table 1.10) did further radiation dosimetry work on human body phantoms as well as study thermal effects on rats and dogs. Flash blindness (time to eyesight recovery after exposure to a nuclear flash) was studied in humans.

Operation TUMBLER-SNAPPER (Table 1.11) investigated the effects of different neutron radiation fluences on mice, as well as a study of flash blindness that inadvertently resulted in retinal burns in two human observers. Thermal irradiation of pigs protected from other nuclear insults was also studied.

Operation UPSHOT-KNOTHOLE (Table 1.12) focused its biomedical program on the radiation hazard to mice and monkeys flying through the post-detonation clouds. The biological effects of neutrons on mice above ground and in foxholes was reviewed, as well as the ocular effects of thermal radiation from the flash and beta-gamma skin hazards to humans that would be in the contaminated area post shot.

Operation TEAPOT (Table 1.13) was intended to test nuclear devices for possible inclusion in the weapons arsenal, improve military tactics, equipment, and training, and study civil defense requirements.

Operation PLUMBBOB (Table 1.14) conducted a variety of tests using large numbers of animals to research all types of weapon insults, isolated and in combination, on several different animal models. Analysis of fallout effects on animals and vegetation in the area was also conducted. Thermal radiation effects on pigs inside shelters were studied. Monkeys were exposed to neutron and gamma radiation while protected from airblast; mortality and cause of death were studied over a two year period. A large animal model (burro) was also used, and phantom dosimetry reconstructed. Swine, dogs, rabbits, guinea pigs, and mice were used in multiple and isolated insult studies. Neutron and gamma absorption were reviewed in pigs.

Operation HARDTACK II (Table 1.15) examined effects on swine and mice from very low yield detonations. Several specimens were placed in foxholes and on military vehicles. Some were also given medical radiation countermeasures beforehand. Evaluation of vision on soldiers who were placed in viewing range but facing away from the flash was performed.

Operation SUNBEAM (Table 1.16), which was the DoD code name for DOMINIC II, measured neutron and gamma radiation inside exposed sheep as well as synthetic human tissue equivalent material.

Operation ROLLER COASTER (Table 1.17) was the name given to four tests evaluating the risk of dispersal of plutonium during storage and transportation. No fission yield occurred in these experiments. Measurements were performed in various biota.

Operation MILL RACE (Table 1.18) was actually a high explosive test designed to simulate a one kiloton nuclear weapon airblast, ground motion, and, for certain experiments, thermal radiation fluence. No ionizing radiation was released during the test.

Table 1.10 Operation BUSTER-JANGLE, 1951

Report Author	Report Title	Number	Objective
Smith et al., 1952	Project 2.7, Biological Injury from Particle Inhalation	WT-396, -372	Distribution of radioactive particles inhaled by sheep and dogs post detonation exposure
Chambers, 1952	Project 4.1, Radiation Dosimetry	WT-315	Expose human body simulation materials with embedded radiation sensors to nuclear environments
Brooks et al., 1952	Project 4.2, Thermal Effects on Animals (Dogs)	WT-362	Exposed dogs with hair shaved in patches to thermal radiation environment
Sheline et al., 1952	Project 4.2a, Thermal Effects on Animals (Rats)	WT-316	As above, using rat model
Byrnes, 1952	Project 4.3, Flash Blindness	WT-341	Measure eyesight and visual acuity recovery times from nuclear flash effects in humans

Table 1.11 Operation TUMBLER-SNAPPER, 1952

Report Author	Report Title	Number	Objective
Carter et al., 1953	Project 4.3, The Biological Effectiveness of Neutron Radiation from Nuclear Weapons	WT-528	Mortality as a function of neutron radiation fluence and time measured in mice
Chambers, 1953	Project 4.4, Gamma Dose Depth Measurement in Unit Density Material	WT-529	Attempt to develop instrumented spheres to simulate human tissue
Byrnes, 1952	Project 4.5, Flash Blindness	WT-530	Vision recovery time measured in humans (two subjects unexpectedly received retinal burns)
Kingsley et al., 1953	Project 4.6, The Time-Course of Thermal Radiation As Measured by Burns in Pigs	WT-531	Study of thermal injury in pigs protected from other nuclear effects

Table 1.12 Operation UPSHOT-KNOTHOLE, 1953

Report Author	Report Title	Number	Objective
Langham et al., 1953	Project 4.1, The Radiation Hazards to Personnel Within an Atomic Cloud	WT-743	Drones with mice and monkeys flew through clouds
Draeger and Lee, 1955	Project 4.2, Direct Air Blast Exposure in Animals	WT-744	Dogs and rats, shielded from radiation, exposed to overpressures from blasts
Byrnes et al., 1955	Project 4.5, Ocular Effects of Thermal Radiation from Atomic Detonation—Flashblindness and Chorioretinal Burns	WT-745	Human subjects used for flashblindness studies, rabbits for chorioretinal burn assessment
Brennan, 1953	Project 4.7, Beta-Gamma Skin Hazard in the Post-Shot Contaminated Area	WT-746	Evaluation of previously unmonitored beta radiation in areas near Ground Zero
Carter et al., 1957	Project 4.8, Biological Effects of Neutrons	WT-747	Mice above ground and in foxholes studied in conditions of reduced gamma exposure (shielding)
---	Project 23-24 (series), Communal Shelter Tests	---	Various structures with emplaced biological specimens to study blast, thermal, & radiation environments
Bond et al., 1953	Project 23.1, Biological Effectiveness of Ionizing Radiation Within Shelters	WT-793	Study of ionizing radiation
Silverman and Bond, 1953	Project 23.2, Bacteriological Studies on Animals Exposed to Neutron Radiation	WT-794	Analysis of bacterial sepsis in mice exposed to supralethal doses of neutron and gamma-neutron radiation
Plough and Sheppard, 1854	Projects 23.4-23.14, 23.16, Genetic Effects of Fast Neutrons from Nuclear Detonations	WT-820	Mice, as well as various plant and fungi species were exposed, then mated, to determine relative biological effectiveness of neutrons for transmitted genetic defects
Roberts et al., 1953	Project 23.15, Effects of Overpressures in Group Shelters on Animals and Dummies	WT-798	Relationship of overpressure rise, air drag, and static overpressure levels to blast injuries in dogs
Lindberg et al., 1954	Project 27.2, Environmental and Biological Fate of Fall-Out from Nuclear Detonations in Areas Adjacent to the Nevada Proving Grounds	WT-812	Radio-ecological studies of soils, plants, and animals before, during, and after several test series to determine biological availability of radioactive materials over time

Table 1.13 Operation TEAPOT, 1955

Report Author	Report Title	Number	Objective
White et al., 1956	Project 33.1, Biological Effects of Pressure Phenomena Occurring Inside Protective Shelters Following a Nuclear Detonation	WT-1179	Observation and effects studies of animals inside shelters
Hirsch et al., 1956	Project 33.2, The Effects of Noise in Blast-Resistant Shelters	WT-1180	Noise effects on rats studied
Lindberg et al., 1959	Project 37.1, Factors Influencing the Biological Fate and Persistence of Radioactive Fallout	WT-1177	Particulate fallout matter and its location and intensities in soil, plant, and animal specimens determined
Taplin et al., 1961	Project 37.3, Evaluation of the Acute Inhalation Hazard from Radioactive Fall-Out Materials by Analysis of Results from Field Operations and Controlled Inhalation Studies in the Laboratory	WT-1172	Adverse effects on rabbits and rats placed post-detonation in fallout field studied
Palmer and Harper, 1955	Project 39.4b, Technical Photography (High Speed—Blast Biology)	WT-1197	Effects of blasts on animals and structures studied as well as autopsy specimens
Harris, 1955	Project 39.7, Physical Measurement of Neutron and Gamma Radiation Dose from High Neutron Yield Weapons and Correlation of Dose with Biological Effects*	ITR-1167	Free-field and blast-shielded chambers containing mice studied; dose compared with biological effects

* Redacted version available on World Wide Web.

Table 1.14 Operation PLUMBBOB, 1957

Report Author	Report Title	Number	Objective
McDonnel et al., 1961	Project 4.1, Effects of Nuclear Detonations on a Large Biological Specimen (Swine)	WT-1428	Twelve hundred specimens used to assess injuries from blast, thermal, and gamma and neutron radiation effects
Gulley et al., 1960	Project 4.2, Evaluation of Eye Protection Afforded by an Electromechanical Shutter	WT-1429	Evaluation of a high-speed electromechanical shutter for protection against flashblindness in human subjects
Richmond et al., 1959	Project 33.1, Blast Biology—A Study of the Primary and Tertiary Effects of Blast in Open Underground Protective Shelters	WT-1467	Dogs, pigs, rabbits, guinea pigs, and mice exposed to airblast in underground shelters with open entrances
Taborelli et al., 1959	Project 33.3, Tertiary Effects of Blast—Displacement	WT-1469	Photography of movement of dummies and spheres exposed to blast (tertiary blast effects, or displacement)
Goldizen et al., 1961	Project 33.4, Missile Studies With a Biological Target	WT-1470	Studies of dogs exposed to flying glass and rocks from airblast (secondary blast effects, or missiling)
Richmond et al., 1960	Project 33.6, The Internal Environment of Underground Structures Subjected to Nuclear Blast, II. Effects on Mice Located in Heavy Concrete Shelters	WT-1507	Sixty-day survival study
Larson et al., 1966	Project 37.1, Distribution, Characteristics, and Biotic Availability of Fallout, Operation Plumbbob	WT-1488	Near- and long-range fallout tracked throughout the biological chains in several areas over time
Taplin et al., 1957	Project 37.5, Chemical Dosimetry of Prompt and Residual Radiations from Nuclear Detonations	WT-1493	Direct-reading chemical dosimeters used to estimate prompt and residual gamma exposures and compared with results from Hiroshima and Nagasaki
Greig and Pearse, 1958	Project 39.3, Thermal Radiation Measurements	ITR-1502	Eight pigs placed inside shelters and their injuries described
Hurst and Ritchie, 1958	Project 39.5, Radiation Dosimetry for Human Exposures	WT-1504	Gamma and neutron dosimetry on several shots performed and compared against similar data

Report Author	Report Title	Number	Objective
			from Hiroshima and Nagasaki survivors
Pickering et al., 1958b	Project 39.6, Biological Effects of Nuclear Radiation on the Monkey (Macaca Mulatta)	WT-1505	Report of sixty-day observations of behavior and medical tests related to neutron and gamma radiation
Pickering et al., 1960	Project 39.6 (Supplement I), Biological Effects of Nuclear Radiation on the Monkey (Macaca Mulatta): Two-Year Evaluation	WT-1542	Observations and test results at two years
Kuhn and Kyner, 1958	Project 39.6a, Large-Animal Neutron-Gamma Irradiation Experiment	ITR-1476	Survival study of neutron and gamma irradiated burros protected from blast wave
Imirie et al., 1958	Project 39.8, Depth-Dose Studies in Phantoms with Initial Bomb Gamma and Neutron Radiation	WT-1508	Human tissue equivalent material tissue phantoms used, one simulating response to gamma, the other to neutron irradiation

Table 1.15 Operation HARDTACK II, 1958

Report Author	Report Title	Number	Objective
Moncrief et al., 1961	Project 4.2, Effects of Very-Low-Yield Bursts on Biological Specimens (Swine and Mice)	WT-1663	Animals placed in foxholes and military vehicles and exposed to very high levels of radiation; some animals pre-medicated
Verheul et al., 1960	Project 4.3, Effects of Light from Very-Low-Yield Nuclear Detonations on Vision (Dazzle) of Combat Personnel	WT-1664	Abilities of individuals to recognize targets tested shortly post-detonation

Table 1.16 Operation SUNBEAM, 1962

Report Author	Report Title	Number	Objective
Mobley et al., 1965	Project 4.1, Tissue Dosimetry	POR-2270	Test radiation absorption of material designed to react to radiation in a human tissue-equivalent manner; sheep, synthetic material used

Table 1.17 Operation ROLLER COASTER, 1963

Report Author	Report Title	Number	Objective
Menker et al., 1966	Project 5.2/5.3a, Radiochemical Analysis of Biological and Physical Samples	POR-2515 (WT-2515)	Effects of dispersed plutonium and uranium on soft tissues, bone, and excreta from dogs, sheep, and burros exposed to debris aerosol
Major and Wessman, 1966	Project 5.2/5.3b, Radiobiological, Radiochemical, and Physiochemical Analyses	POR-2516 (WT-2516)	Data from laboratory analyses on 4,000 samples tabulated
Krey and Fried, 1965	Project 5.2/5.3d, Laboratory Analyses of Roller Coaster Samples	POR-2518 (WT-2518)	Plutonium, uranium, americium, and gamma spectrometric analyses performed on over 2,000 samples

Table 1.18 Operation MILL RACE, 1981

Report Author	Report Title	Number	Objective
Meason et al., 1982	Airblast Survivability Testing of Tactical Army Systems at Event Mill Race*	POR-7075	Testing of Biological Detection and Warning System against blast overpressure and assess crew member response to blast environment

*Report is restricted distribution.

2.0 BIOLOGICAL EFFECTS OF NUCLEAR EXPLOSIONS

2.1 INTRODUCTION

Personnel exposed to a nuclear explosion may be killed or suffer injuries of various types. Casualties are primarily caused by airblast, thermal radiation, and nuclear radiation. The frequency and severity of the effects on personnel depend on a number of factors, including the weapon yield, height of burst, atmospheric conditions, and the protection afforded by any shelter, including terrain. For instance, a nuclear explosion in or near cities and villages will produce considerable damage to structures, shelters, and facilities. This damage may extend over a considerable area, and a large number of serious injuries and fatalities can be expected for people located in this area. Casualties for those exposed in the open can also be expected but would generally be attributable to different mechanisms.

Although casualties may be produced by a single effect, such as nuclear radiation, it is likely that they will result from a combination of effects. Such combined injuries *may* be synergistic, i.e., the resulting injury may be more significant than predicted for the sum of the individual effects. For example, single injuries may have a low likelihood of lethality, but when combined, the resulting combination of injuries may produce a high likelihood of death.

2.2 FACTORS THAT INFLUENCE INJURIES

As a general rule, for bursts of a given type (e.g., air, surface, or subsurface), the range of each of the major effects (airblast, thermal radiation, and nuclear radiation) increases as yield of the weapon increases; however, the relative importance of each effect shift. Initial nuclear radiation, for example, is much more significant in comparison with air blast and thermal radiation for nuclear explosions of low yield than it is for those of high yield. As the yield of the weapon increases, the total number of casualties will increase, as will the proportion of injuries due to blast and thermal energy.

The height of burst (HOB) will have an important influence on the range to effect for airbursts. With other factors constant, there is an optimum HOB that maximizes the range to a given overpressure level. This optimum height differs for each yield and for each value of the overpressure. Similarly, there are particular heights of burst that maximize the exposure ranges for either thermal radiation or the initial nuclear radiation; however, this height is usually different from the optimal HOB for blast damage, Thus, considerable variation is possible both in the number and in the nature of injuries for any given weapon yield.

As the transition is made to a subsurface burst, at even very shallow depths of burst (DOB), injuries from initial nuclear radiation, air blast, and thermal radiation are much less than from a low airburst, or even from a surface burst of the same yield. On the other hand, the effects of ground shock and the delayed nuclear radiation hazard (fallout) would be greatly increased in the nearby region because increasing amounts of contaminated earth and debris are sucked up into the radioactive cloud. In the case of a deep (completely contained) underground burst, casualties would result only from the direct and indirect effects of ground shock.

In addition to the yield of the explosion and its HOB/DOB, local environmental circumstances can be a significant factor in the casualty potential of a nuclear weapon. For example, the shielding in ordinary houses may markedly reduce the range over which significant casualties from flash burns can occur. This is especially true for heavier structures extending below as well as above the ground; persons properly located in such buildings could be protected from blast and initial nuclear radiations as well as from thermal radiation; conversely, in certain buildings, the frequency of indirect blast injuries may be greatly increased by the presence of large numbers of missiles, such as glass from windows.

The peak overpressure and wind velocity magnitude will be altered by the size and configuration of the structure as the blast wave propagates into the structure. The magnitude of the peak overpressure in a building interior can sometimes be appreciably less than the free- field value, but there is a possibility that, as a result of blast wave reflection from walls, etc., the overpressure in the interior of a building may be increased twofold or more, depending on the geometry and location. Likewise, wind velocities inside structures may differ markedly from those existing in the free field, and blast wave jetting through openings may be significant. Nevertheless, as long as people are away from walls, windows, or lying on the floor, there is generally a lower probability of injury from direct overpressure effects inside a structure than at equivalent distances on the outside.

Similar modifications occur for both nuclear and thermal radiation inside structures. For example, buildings provide shielding against nuclear radiation. In general, the larger the building, the better the protection; this is particularly true for rooms in the interior of the building. Thermal radiation effects may be completely negated, unless the person is behind a window facing the blast. However, injuries due to burning and smoldering material may be larger than in the open.

This guide summarizes the sources of material in the Data Archival and Retrieval Enhancement (DARE) database (now called the Scientific and Technical Information Archival and Retrieval System, or STARS) describing the various effects of nuclear weapons on personnel, the injury mechanisms, and the available biomedical data (Sachs 1995). While we will mention long-term effects, we will not dwell on these issues in any detail, because the focus of the information given in this guide is on prompt nuclear effects of interest to those involved in all aspects of casualty assessment (serious injury and lethality).

3.0 AIRBLAST EFFECTS

3.1 INTRODUCTION

Airblast injuries may be of three main types: direct (or primary) injuries from exposure of the body to the overpressure of the blast wave; indirect injuries resulting from the impact of penetrating and nonpenetrating missiles on the body (secondary blast effects); and the consequences of displacement of the body as a whole (tertiary blast effects). Other blast injuries, such as burns from the gases and injuries from the debris carried into shelters by airblast can also occur.

The general interactions of airblast with the human body are somewhat similar to those with a structure. Because of the relatively small size of the body, the diffraction process is over quickly as the body is rapidly engulfed and subjected to severe compression. Compression continues with decreasing intensity for the duration of the positive phase of the blast wave. During this time, the blast winds exert a drag force that combines with the overpressure force. A description of the nuclear air blast environment can be found in Chapter 2 of the DNA technical manual, *Effects Manual One* (EM-I)**,** *Capabilities of Nuclear Weapons.*

Indirect blast injuries are caused by (1) the impact of missiles, either penetrating (such as glass fragments) or nonpenetrating (such as structural debris), and (2) the physical displacement of the body as a whole (translation). These injuries are considered secondary and tertiary injuries respectively. A fourth type of injury, quaternary, covers every other form of explosion-related trauma such as crush injuries, traumatic brain injury, and aggravation of pre-existing medical conditions or trauma related to dust, smoke, and toxic fumes from the blast.

Personnel exposed at distances from an explosion at which significant blast injuries can occur will likely suffer multiple injuries or a mix of the injury types mentioned above. In addition to the blast wave parameters, the type of injuries depends on the sheltering conditions (in the open, residential structures, basements, bunkers, etc.).

3.2 MECHANISMS OF INJURY

For primary injury (direct overpressure) the ear is an indicator organ for the presence of damage to other tissues. The threshold for eardrum rupture is around 5 psi (34.5 kilopascals), which is below the 20 psi (138 kilopascals) or higher threshold for lethal overpressure injury to the lungs. If tympanic membrane rupture is present, medical personnel must be alert for delayed expression of pulmonary damage such as rupture to the alveoli. Air embolism (which is created in a manner similar to that of decompression injury in divers by the sudden release of pressure, thus allowing nitrogen bubbles to form in the blood), may also be present. Air emboli can damage almost any tissue in the body by blocking blood circulation; the tissues that can cause lethality or severe injury with air emboli include the brain, spinal cord, gastrointestinal tract, and several others. Another injury mechanism is spallation, which occurs at the juxtaposition of tissues of different density. As the blast wave passes through, increased energy is transmitted from the denser tissue to the less dense tissue, resulting in creation of fragments and dispersal of tissue. Rapid

compression of air in air containing organs (lungs, gastrointestinal tract), then sudden re-expansion as the blast wave passes through, can rupture these tissues.

Secondary injury results when debris, either penetrating or blunt, strikes the body as it is blown by the blast wind. The wounding potential of blast-generated debris depends on a number of factors, including the impact velocity, the angle at which impact occurs, and the size, shape, density, mass, and hardness of the blast-energized objects. The portion of the body involved in the missile impact and the events that may occur during and after the time of impact are also important. Injuries that result can range from simple contusions and lacerations to more serious penetrations, fractures, and critical damage to vital organs.

Tertiary injury involves displacement of the body as the individual is thrown about by the blast wind (sometimes called translational injury). The hazards from whole-body displacement depend mainly on the time and distance over which acceleration and deceleration of the body occur. Injury is more likely to occur during the latter phase when the body strikes a solid object, such as a wall or the ground, rather than while "in flight". The velocity of the body at the time of impact is the significant factor. This, in turn, is determined by certain parameters of the blast wave and the initial position (standing or prone) and orientation of the body with respect to the direction of motion of the blast wave. The severity of the injury depends on the magnitude of the impact velocity, the properties of the impact surface, and the particular portion of the body that has received the decelerative impact. Individuals in a closed structure can experience this injury if there is an opening in the room that allows airblast venting. The risk of displacement is greater if the individual is standing rather than prone or supine. Reflection of the blast wave off of a nearby structure can increase its force, and thus the likelihood of displacement.

Quaternary injury, as described above, covers all other forms of explosion-related injury. Building collapse obviously is an important risk factor from a nuclear explosion. Crush injuries are common after earthquakes as individuals are trapped under structural or vehicular debris. Management of these injuries is complicated by the fact that when the extraneous material is removed and circulation restored, toxic materials released by the damaged tissue into the circulation may cause problems such as cardiac arrhythmias and kidney damage.

4.0 THERMAL EFFECTS

4.1 INTRODUCTION

A burn is an injury caused by an increase in skin temperature resulting from direct absorption of thermal radiation, or from the transmission of heat through clothing. The severity of the burn depends on the amount and duration of the temperature increase. Skin burns are generally classified by the depth of tissue damage and by the total body surface area (TBSA) involved, expressed as a percentage.

In addition to skin burns, other harmful thermal effects may be produced, including retinal burns and flash blindness. Although these effects are not life threatening, they can have an important impact on military operations unless adequate protective devices are used. Clothing and other protective devices can provide significant protection from the thermal pulse, but if the radiant exposure is sufficient to ignite the clothing, severe burns may result that can be as serious as with the case of bare skin.

Thermal radiation can cause burn casualties (1) directly by absorption of the radiation energy by the skin, (2) indirectly by heating or ignition of clothing, and (3) as a result of fires started by the thermal pulse, the air blast, or ground shock. The air blast and ground shock may initiate fires by a number of different mechanisms, including electrical shorts, disrupted gas lines, overturned vehicles, and damaged vessels containing volatile fuels.

The frequency of burn injuries from a nuclear explosion will be fairly high for personnel in the open and in fire areas. Most of these injuries are flash bums caused by direct exposure to the thermal radiation pulse, although individuals trapped by spreading fires may suffer flame burns. In addition, hot gases and dust entering the structures even though they are shielded adequately from direct or scattered thermal radiation may burn persons in buildings or tunnels close to ground zero.

Eye injuries can also be considered a form of thermal injury. Persons who happen to be looking directly at the weapon at time of detonation can experience burns to the retina, resulting in a permanent blind spot at the point where the eye focuses the incoming light from the fireball. Flash blindness, or dazzle, is a common experience for most people which they experience when leaving a darkened theater into the outside light, for example. This effect is much more pronounced with the flash of light from a weapon. Studies at the PPG and NTS cited above demonstrated, however, that this effect generally resolves spontaneously after a few minutes without permanent visual damage.

4.2 BURN SEVERITY

Burns are often classified as first, second, or third degree. A first degree burn is like sunburn involving only the top layer of skin (epidermis). A second degree burn penetrates through the epidermis into the dermis. These are often subdivided into superficial partial thickness burns and deep partial thickness burns. The time till healing is significantly delayed in the latter. Third

degree burns penetrate through both the epidermis and the dermis. Skin replacement by grafting is necessary for all but the smallest burns. Burns that go through the skin and involve the underlying fascia, muscle, or bones are considered fourth degree burns. A severe burn, in terms of both depth and TBSA involved, places the casualty at risk for fluid loss and dehydration, infection, and hemorrhage, as well as long-term scarring and risk of contracture and dysfunction of the limb. The eschar (thick, scab-like crust that forms over many burns) can also restrict circulation, particularly if it surrounds the limb. Multiple operations are often required to temporarily or permanently graft skin onto the burned area and to remove the eschar. Burns are very painful as well, although paradoxically deep burns aren't as painful, as the nerve endings, which are in the dermis proper, have been destroyed by the heat.

5.0 RADIATION EFFECTS

5.1 INTRODUCTION

The nuclear radiation produced by a nuclear explosion and the subsequent residual radiation from fallout (gamma rays, neutrons, beta particles, and alpha particles) can produce a number of different types of harmful effects to the human body. These include serious acute effects that may degrade combat performance and cause lethality, and latent effects, such as cancer. The types, incidence, duration, and severity of radiation effects depend on a number of factors, including the type of radiation, the magnitude of the absorbed dose, the rate at which the dose is delivered, the part of the body irradiated, and the dose distribution (total body or some part thereof). The three sources of nuclear radiation of primary interest to military operations and casualty assessment are the initial nuclear radiations from the nuclear explosion (fission gamma rays, air-secondary gamma rays, and neutrons), early fallout from surface and near-surface bursts, and neutron-induced ground activation. Other sources, such as late fallout, may present long-term health hazards.

5.2 EARLY EFFECTS OF RADIATION

The acute radiation syndrome (also called acute radiation sickness; both abbreviate to ARS) results from external exposure to radiation doses greater than approximately 100 rad (1 Gy) delivered to the whole body over a short time period. Doses below 100 rad are considered subclinical. ARS occurs in three (or four) phases: prodromal (initial symptoms such as nausea, vomiting, fatigue, weakness, anorexia); a latent phase (symptoms abate temporarily); manifest illness (patient becomes clinically ill with risk of death from bleeding, infection, shock if very high doses); and a fourth phase of recovery if the patient recovers.

There are three classic subsyndromes of ARS: hematopoietic, gastrointestinal (GI), and cardiovascular/central nervous system (CV/CNS). The hematopoietic subsyndrome occurs with doses from 100 – 600 rad (1 – 6 Gy), the GI subsyndrome from 600 – 3000 rad (6 –30 Gy), and the CV/CNS subsyndrome at doses above 3000 rad (30 Gy). These terms were derived from the tissue injury that caused death. Animals with hematopoietic syndrome died a few weeks post exposure from infection and bleeding. Those with GI syndrome died of diarrhea, electrolyte imbalance, and fluid loss. Those with very high doses died of shock in several hours or at most a couple of days. For the past several years, however, most clinicians have realized that ARS is an all systems disease, with damage occurring in most organs at most doses; the clinical picture is a time- and dose-dependent expression of damage from multi-organ failure or multi-organ dysfunction syndrome (MODS). With modern treatment methods several accident victims have been able to survive the hematopoietic and GI syndrome only to die of pulmonary or renal injury. Doses to these patients have generally been in the 1000 – 2000 rad (10 – 20 Gy) range.

Acute radiation mortality from hematopoietic failure resulting in hemorrhage and infection is the endpoint most studied as a function of radiation dose rate and animal species. Mice have been studied most extensively but the limited data available for hematopoietic lethality from large farm animals and primates indicate important species differences.

Chernobyl-type exposure situations represent extremely complex arrays of doses and dose rates from external and internal sources that result in early radiation injuries. Tissues with different radiation sensitivities and repair capabilities may be involved. This may result in different temporal relationships for expression of damage and healing in different body areas affected by radiation. Deep tissue injury can result when penetrating gamma rays are emitted from a contaminant. Skin, connective tissue, blood vessels, bone and muscle could all sustain significant radiation damage. In some situations surgery may be indicated. It is important that surgical procedures be undertaken within the first 24-48 hours post injury; else radiation damage to the fibroblasts and other reparative tissues will prevent wound healing. Infections could be lethal especially if bone marrow damage is also present. Rather than a discrete single "syndrome", perhaps the most realistic situation associated with a reactor "event", nuclear terrorism, or a denial scenario involving radioisotopes will be non-uniform exposure with various doses and dose rates producing very large variations in early radiation damage that could be lethal.

5.3 CHRONIC/PROTRACTED IRRADIATION

Fallout from nuclear weapons, intentional dispersal of radioactive chemicals for purposes of area denial, or terrorism are examples of sources of chronic or protracted irradiation to which personnel may be exposed. The exposure may be from external sources such as some isotope widely dispersed in or on the soil, or some point source such as a radiography unit. The exposure may also be internal from isotopes taken into the body in food, water, or air. Because most but not all cells are endowed with the capacity to repair radiation injury within minutes or hours, irradiation at low dose rates is less injurious than when the exposure is acute; i.e. instantaneous or delivered over an hour or two. In addition, when irradiation is sustained over days or weeks either in a continuous mode or as fractions separated in time, the injury is typically less than with an acute exposure. This is referred to as a chronic or protracted exposure and may last for the entire lifetime in the case of background radiation. In addition to cellular repair, proliferation of cells may occur so that tissue and organ function is preserved. The generalization is that as dose rate decreases and exposure time increases, the radiation dose necessary to produce a given effect increases. This reduced effectiveness of radiation at low dose or dose rates is expressed by a dose and dose rate effectiveness factor (DDREF); multiplying the dose required to produce a given effect at high dose and dose rate by the DDREF gives the dose required to produce the same effect given at low dose rates. Typical DDREF values range from 1-3. Likewise, the biological effect is reduced when radiation is administered in two or more fractions at high dose rate. With this form of dose protraction the diminished effect is attributable to cellular repair of radiation injury and to cellular proliferation between radiation fractions.

The effects of dose rate or protraction are less well understood for the other classical syndromes associated with early radiation effects such as the intestinal and the central nervous system syndromes. Likewise, comprehensive studies are lacking concerning what could be called the cutaneous and pulmonary syndromes that may result from high levels of radioactive contamination of the skin and the pulmonary tracts, respectively.

Rodent studies in support of radiation therapy applications have involved the tolerance of skin and lung to partial-body exposures that include all or part of the organ in question in the radiation field. How these results with external radiation relate to situations involving injuries following skin or lung contamination with radioactive fission products or other radioisotopes remains to be determined.

5.4 LATE EFFECTS

As early as the 1940's experiments on dose rate and dose fractionation regimens were sometimes extended over long periods of time up to and including the entire life span of rodents. Later, large-scale rodent studies involved external radiations such as x-rays, gamma rays or fission spectrum neutrons. Other studies involved internal deposition of fission products or other radioisotopes in various rodents and canines.

Because tumors and other physiological changes were often seen in aged animals and irradiation appeared to accelerate changes and tumor expression [and perhaps frequency], radiation-induced aging was thought to occur. Between the 1950s and the early 1980s lifespan studies on irradiated animals were conducted to provide information on radiation carcinogenesis and many other cellular and tissue injuries. It was felt that qualitative generalization from animal experiments, when viewed with the available human data would assist with the assignment of cancer risk estimates for humans. High costs and the long times needed to collect and analyze results were among the factors that resulted in termination of most lifespan studied on animals. Also cancer risk information from humans was forthcoming from medical studies that involved radiation and from the populations exposed to nuclear weapons in Japan. During the 1990s follow up studies have been initiated on persons in the former Soviet Union who were occupationally or accidentally exposed to radioisotopes or external sources. The expectation is that cancer risk estimates will be improved based on new date from persons who received long-term exposures. The hope is that these new data for long-term exposures at low dose rates, when analyzed in comparison with cancer data for a single dose from Japan will facilitate estimation of the DDREF or sparing effect of low dose rates for cancer induction in humans.

Further studies of human populations exposed to radiation will be crucial. Human populations include Japanese exposed to nuclear weapons, persons in the former Soviet Union (FSU) exposed to chronic external or internal exposures from accidental contamination of water supplies and food or through work in the nuclear weapons industry, and unfortunate persons accidentally exposed to radiation anywhere in the world. Means to reduce radiation injury that produce deleterious early and late health effects include pharmacological agents that may be administered before or after single or fractionated doses and the use of vitamins and other dietary supplements or drugs that may be administered during continuous irradiation at low dose rates.

5.5 INTERNAL DOSE

Radioactive materials can be ingested, inhaled, or otherwise incorporated into the body through broken skin. Few new data on internal emitters have become available since the 1980s and the National Council on Radiation Protection and Measurements (NCRP) has organized volunteer committees that have produced comprehensive reviews/reports and analyzes of the available data from humans and experimental animals. In the 1990s the use of depleted uranium munitions raised questions in DOD and NATO concerning the potential environmental impacts of weapons debris as well as any health effects if the material gains entrance to the body via food, water, inhalation, or after some injury.

5.6 MULTIPLE EXPOSURES/EFFECTIVE RESIDUAL DOSE

Extensive scientific literature exists for experimental animals given multiple exposures. The concern in the late 1940s was that military personnel might be re-irradiated at high or low dose rates following an initial exposure to a weapon detonation and/or fallout. It was thought that the cumulative effect of several exposures over time would be different from the effect of the total dose given as a single exposure.

One experimental approach was to assess the "recovery potential" of various species following a high sub-lethal radiation dose by re-irradiating large populations at high dose rates and at various intervals between exposures to determine the 50% lethal dose [LD_{50}] after the initial irradiation. This was referred to as the split-dose technique. For a hypothetical example, a species characterized by an LD_{50} of 600 rad would be given a first dose of 400 rad or two-thirds of the known LD_{50}. After 20 days the population would be tested again to determine the LD_{50}. If the LD_{50} in the re-irradiated population was 600 rad, the inference was that there had been "recovery" from all of the initial radiation injury. The effective residual dose 20 days after radiation was therefore zero. Conversely, if the LD_{50} in the re-irradiated population was only 200 rad, the inference was that all the initial injury remained, there was no "recovery", and the effective residual dose was 400 rad.

During the 1950s and 1960s the U. S. Naval Radiological Defense Laboratory (USNRDL) conducted an interspecies comparison program to determine the LD_{50} and recovery rates for rodents and large farm animals. Variations in split dose methodology included the use of high dose rates for both the initial and second doses, and the use of various low dose rates for either the initial or second dose. An important extension of these studies was conducted during the early 1970s by Jones and Krebs at the Stanford Research Institute following the demise of USNRDL in 1969. The conceptual basis for this split-dose technique was attributed to Dr. Henry A. Blair at the University of Rochester, and the method was used for more than 20 years to provide a database in support of modeling efforts for military operations and civil defense planning.

In general, results showed that small rodents recover rapidly and the residual dose decreases by more rad/day than for large farm animals. Large farm animals and the Rhesus monkey recover more slowly, may not initiate recovery for several days, or may experience a transient acquired

radio resistance where the LD_{50} in the re-irradiated animals is significantly above that for a normal animal. Some data for sheep indicate that an initial dose at a high dose rate impairs the animal's ability to repair later radiation injury experienced in a low dose rate radiation field. Because of the importance of this phenomenon for modeling, it is important to repeat these experiments, determine if it occurs, and if so in what species. It is thought that an irradiated population never recovers fully, and that there is heterogeneity within the population in terms of radiation sensitivity. Work by scientists in the former Soviet Union supports this latter theory; see Kovalev, 2008.

6.0 CONCLUSION

Many, but by no means all, of the biological projects at PPG and NTS focused on a single mechanism of injury to better eliminate confounding factors in studying that particular effect and how various parameters influenced it. It should be noted that only a third of the casualties in Japan had only blast trauma, or thermal injury, or ARS. Two-thirds had combined injury. Combined injury is synergistic; that is, the effects of the different insults are not merely additive (trauma upon trauma) but work to aggravate the severity. Radiation depresses the fibroblasts and other connective tissue elements responsible for repairing fractures or re-epithelializing burned areas, for example. Several of the studies at NTS in particular did intentionally look at combined injuries to note how the three main effects (blast, thermal, radiation) combined.

The days of research into the direct biological effects of atmospheric testing are fortunately gone. Further work needs to be done based on these findings however. The reader is encouraged to carefully study the literature amassed around the testing experience, note the gaps in our current understanding of nuclear weapon injuries, and see what laboratory studies need to be done to improve our knowledge. New paradigms for understanding radiation effects have recently been developed, and the data need to be reviewed in this light.

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APPENDIX A. ACRONYMS

ARS – Acute Radiation Sickness (or Acute Radiation Syndrome)

BENE – Biological Effects of Nuclear Explosions

BUMED – Bureau of Medicine and Surgery (U.S. Navy)

CV/CNS – Cardiovascular/central nervous system

DARE – Data Archival and Retrieval Enhancement

DDREF – Dose and Dose Rate Effectiveness Factor

DNA – Defense Nuclear Agency

DOB – Depth of Burst (below ground or marine surface)

DoD – Department of Defense (U.S.)

DTRA – Defense Threat Reduction Agency (formerly Defense Nuclear Agency)

DTRIAC – Defense Threat Reduction Information Analysis Center

EM-1 – Effects Manual One, Capabilities of Nuclear Weapons

FSU – Former Soviet Union

GI – Gastrointestinal

HOB – Height of Burst (above ground or marine surface)

LD_{50} – Median Lethal Dose (lethal to 50% of the population)

MODS – Multiple Organ Dysfunction Syndrome

NATO – North Atlantic Treaty Organization

NCRP – National Council on Radiation Protection and Measurements

NTPR – Nuclear Test Personnel Review program

NTS – Nevada Test Site

PPG – Pacific Proving Ground

STARS – Scientific and Technical Information Archival and Retrieval System

TBSA – Total Body Surface Area

USNRDL – U.S. Naval Defense Research Laboratory

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