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Gamma Radiation

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1. Introduction

The content of this chapter includes a brief history of gamma radiation, units of radiation measurement, ecological importance, tables including the half life of gamma emitting nuclides, comparative sensitivity of living organisms to gamma radiation, biological magnification of radioactive and nuclear materials, and brief descriptions of case studies of Woodwell (1962), Stalter and Kincaid 2009), and nuclear power plant disasters (Three Mile Island, USA, 1980, Chernobyl 1986, Japan 2011).

Gamma radiation is somewhat similar to x-rays in that both pass through living materials easily. Also referred to as "photons" they travel at the speed of light. Gamma rays have sufficient energy to ionize matter and therefore can damage living cells. The damage produced in the cell or tissue is proportional to the number of ionizing paths produced in the absorbing material. Isotopes of elements that are emitters are radionuclides important in fission products from nuclear testing, nuclear power plant disasters or waste.

The injurious affect of gamma rays depends on (1) their number (2) their energy and (3) their distance from the source of radiation. Radiation intensity decreases exponentially with increasing distance. Radiation damage on vascular plant species was demonstrated by Woodwell (1962) who subjected a mature pine oak forest at Brookhaven National Laboratory to gamma radiation from a cesium 137 source (Figure 1).

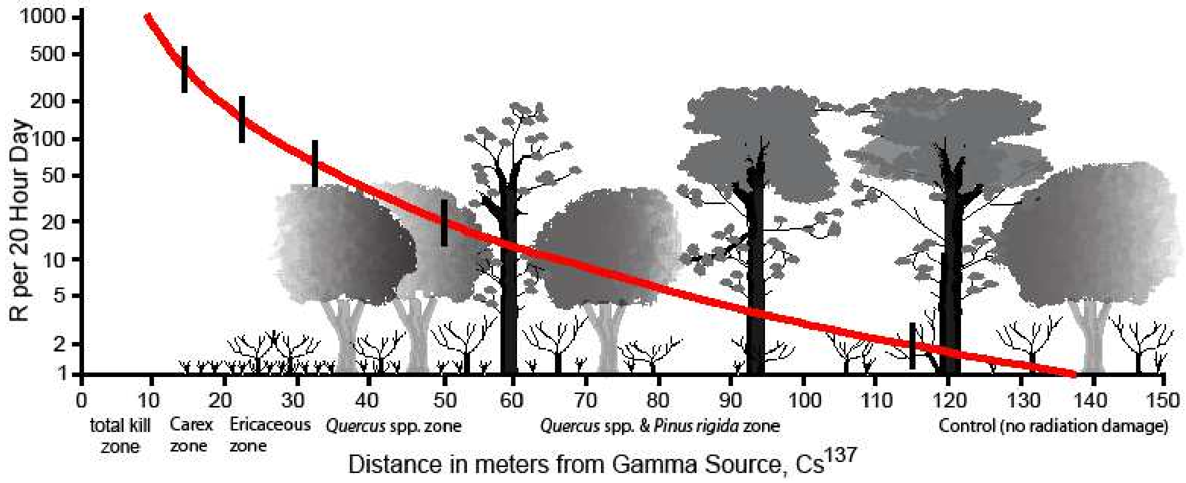

Fig. 1. Radiation dose and damage to a pine-oak forest, Brookhaven National Laboratory, 1961. Zones delineated by vertical lines (Woodwell 1962, Stalter and Kincaid 2009).

Gamma rays are external emitters that penetrate biological materials easily and produce their insidious effects without being taken internally. Alpha and beta particles are internal emitters; their damage to organisms is greatest when taken internally. Odum (1971) summarizes this concept best, "the alpha beta gamma series is one of increasing penetration but decreasing concentration of ionization and local damage." Alpha and beta radiation, unlike gamma radiation, are corpuscular in nature. While alpha particles travel but a few centimeters, and can be stopped by a layer of dead skin, they are dangerous because they produce a large amount of local ionization which can cause mutations disrupting cell processes. Beta particles are high speed electrons. While much smaller than alpha particles, they are able to travel up to a couple of centimeters in living tissue, giving up their energy over a large path. Beta particles, like alpha particles can damage tissue, and like alpha particles, can cause mutations that affect the functioning of cells.

2. The history of gamma radiation as applied to biological systems

Most are familiar with the discovery of x-radiation by Roentgen in 1895 and the isolation of radium by the Curies in 1898 (Goodspeed and Uber 1939). Researchers soon learned that both x-rays and radioactive substances such as radium produced similar effects on biological materials. Koernicke (1905) noted that cell division was delayed on x-ray and radium treated cells. Both Koernicke (l905) and Gager (1907) described “striking chromosomal disruptions” after cells were dosed with x-rays or exposed to radium, a gamma emitter. Gamma irradiated cells were also broken or fragmented by radiation treatment (Gager 1907, 1908). For additional historical work on radiation and plant cytogenetics the reader is directed to a review article by Goodspeed and Uber (1939). Smith (1958) compiled a paper on the use of radiation in the production of useful mutations based on papers presented in three symposia in the United States from August 1956 to January 1957. A more recent review article on ionizing radiation damage to plants was prepared by Klein and Klein (1971).

There are numerous studies applying gamma radiation to biological systems. Several investigations involving botanicals follow. Nuttall et al (1961) found that yellow sweet Spanish onions exposed to 4000 or 8000 rad prevented sprouting in 97% of their experimental group suggesting that irradiation might be a viable method of prolonging storage life for onions. This study, while intriguing, has not been generally accepted by a public concerned with the problems of radiation. A second article by Heeney and Rutherford (1964) examined the effects of gamma radiation on the storage life of fresh strawberries. A dose of 330,000 rad prevented fungal development of the redcoat strawberry variety stored at 40 degrees F for 26 days. The fugal free period was sharply reduced at lower radiation doses and/or at higher temperatures. Pritchard et al (1962) studied the effect of gamma radiation on the utilization of wheat straw by rumen microorganisms. They concluded that, “high levels of gamma radiation were needed to release nutrients trapped in wheat straw needed by microbes. However, the levels of gamma irradiation necessary for nutrient release were well above what was practical for commercial purposes.”

Baumhover et al (1955) investigated the use of gamma irradiation on male sterilization on the control of screw-worm flies in the southern United States while Bushland (l960) Cutcomp (l967) and Lawson (1967) discussed this practice as a general way of controlling certain insect pests. Gambino and Lindberg (1964) examined the response of the pocket mouse to ionizing radiation. McCormick and Golley (1966) presented data on irradiation of natural vegetation in the southeastern United States while Monk (1966) published a similar study on the effects of short-term gamma radiation on an old field. Witherspoon (1965, 1969) examined radiation damage to a forest surrounding an unshielded fast reactor in l965, and followed this study with a report in 1969 on radiosensitivity of forest tree species to acute fast neutron radiation. Odum and Pigeon (1970) researched the effect of irradiation and ecology of a tropical rain forest in Puerto Rico.

3. Units of measurement

Three units, the gigabecquerel (GBq), gray (GY), and roentgen (R) are used to measure radiation. The GBq measures the number of gamma rays emitted from a source of radiation and is a unit of radioactivity that is defined as 1.37×10^{-12} atomic decays each second. The weight of the material comprising a GBq varies. One gram of radium is 37 GBq while 10^{-7th} of a gram of newly formed radio-sodium is also 37 GBq since both release 3.7×10^{-10} disintegrations/second (Odum 1971). In dealing with biological systems, smaller units are generally used such as the millicurie microcurie and picocurie which are 10^{-3}, 10^{-6} and 10^{-12} respectively.

A second measurement of radiation is the GY. The absorbed dose of 1 GY means the absorption of 1 joule of radiation energy per kg of tissue. The third, the roentgen is nearly the same as the GY, and is used as a unit of measurement for exposure to gamma and x rays. Both are units of the total dose of radiation received by an organism. The dose rate is the amount of radiation received per unit time.

4. Ecological importance of radionuclides

There are different kinds of atoms of each element; these are referred to as isotopes. Some isotopes are radioactive, some not. Radioactive isotopes are unstable. These decay into other isotopes releasing radiation. Each radioactive isotope, radionuclide, have a specific rate of disintegration, its half life.

Radionuclides fall into well defined groups (Tables 1 and 2). Naturally occurring nuclides are included in Table 1 while those from fallout produced by fission or uranium and other elements are found in Table 2. Fission isotopes are produced from nuclear explosions which have for the most part been eliminated and from "controlled" reactions that produce nuclear power. While most of the aforementioned nuclides are not essential for the growth of organisms, they may be incorporated in biogeochemical cycles and become concentrated in food chains, especially strontium and cesium. Thus Woodwell (1962) used cesium as a gamma radiation emitter in his well published study of an irradiated pine oak forest at Brookhaven National Laboratory, Long Island, New York. More will be said about this research later in this paper.

5. Sensitivity of organisms to radioactivity

There is a wide range of sensitivity of organisms to radioactivity. Mammals are most sensitive while bacteria are most resistant especially as spores. Moreover there is a wide range of tolerance to radiation during the life cycle of an organism. Radiation sickness in humans can be caused by as little as 0.35 Gy while a dose of 6-8 Gy is lethal to nearly 100% of individuals (Donnelly et al 2010). A dose of 2 Gy may kill some insect embryos while a dose of 100 Gy is necessary to kill all adult individuals (Odum 1971). Dividing cells are generally more susceptible to radiation than resting cells. The toxicity of radionuclides depends on the absorption, distribution in the body, half-life, elimination half-time, type of radiation emitted, and their energy.

Element	Half-Life	Radiations Emitted	
Uranium-235(^{235}U)	7 x 10^8 yrs.	Alpha^3	Gamma^0
Radium-226 (^{226}Ra)	1620 yrs.	Alpha^3	Gamma^0
Potassium-40 (^{40}K)	1.3 x 10^9 yrs.	Beta^2	Gamma^2
Carbon-14 (See Table 3.)			

Table 1. Naturally occurring gamma emitting isotopes which contribute to background radiation (Odum 1971).

Element	Half-Life	Radiations Emitted	
The cesium group	33 yrs.	Beta^2	Gamma
Cesium-137 (^{137}Cs) and	2.6 min	Beta	Gamma^1
daughter barium-137 (^{137}Ba)	2.3 yrs.	Beta^1	Gamma^2
Cesium-134 (^{134}Cs)			
The cerium group	285 days	Beta^1	Gamma^0
Cerium-144 (^{144}Ce) and	17 min.	Beta^2	Gamma^2
daughter praseodymium-144	33 days	Beta^1	Gamma^1
(^{137}Pr)			
Cerium-141 (^{141}Ce)			
	1 yr.	Beta^2	
The ruthenium group	30 sec.	Beta^3	Gamma^2
Ruthenium-106 (^{106}Ru) and	40 days	Beta^1	Gamma^1
daughter rhodium-106 (^{106}Rh)	65 days	Beta^1	Gamma^1
Ruthenium-103 (^{103}Ru)	35 days	Beta^0	Gamma^1
Zirconium-95 (^{95}Zr) and daughter	12.8 days	Beta^1	Gamma^1
niobium-95(^{95}Nb)	40 hrs	Beta^2	Gamma^2
Barium-140 (^{140}Ba) and daughter	11.3 days	Beta^1	Gamma^1
lanthanium-140(^{140}La)	2.6 yrs.	Beta^1	Gamma
Neodymium-147 (^{147}Nd) and	61 days	Beta^2	Gamma^1
daughter promethium-147(^{147}Pm)	2.4 x 10^4 yrs.	Alpha^3	Gamma^1
Yttrium-91 (^{91}Y)	8 days	Beta^1	Gamma^1
Plutonium-239 (^{239}Pu)	7 x 10^8 yrs.	Alpha^3	Gamma^0
Iodine-131 (^{131}I)			
Uranium-235 (^{235}U)			

Table 2. Elements important in fission products entering the environment through fallout or waste disposal.

Sparrow (1962), Sparrow and Evans (1961), Sparrow and Woodwell (1962), and Sparrow et al (1963) have demonstrated that sensitivity of ionizing radiation is directly proportional to the size of the cell nucleus or chromosome volume. The larger the chromosome volume the more sensitive the material is to radiation. There are also differences in radiation tolerance between wild and laboratory rodent populations. Gambino and Lindberg (1964) and Golley et al (1965) have reported that the lethal dose for 50% of some wild rodent populations is roughly twice that of laboratory white mice or white rats, likely due to the reduced variation in the latter.

Radioactivity has been successfully used to sterilize certain male insect pests. Sterile males are introduced to natural populations in large numbers which mate with females. A female mates only once, and once mated with a sterile male produces no young. Introducing radiated sterile male screw-worm flies in areas where they occur successfully reduced the number of screw-worm flies, a major pest in the southern United States. For those seeking more general information on this topic see Baumhover et al (1955) Bushland (1960), Cutcomp (1967), Knipling (1960,1964, 1965, 1967) and Lawson (1967).

6. Radiation effects on ecosystems

Since the early 1960's there have been numerous studies on the effect of gamma radiation on ecosystems. These studies were fueled by the arms race between the Soviet Union and the United States (Stalter and Kincaid 2009). After lengthy negotiations between the two powers the SALT (Strategic Arms Limitation Treaty) was signed in 1971 and extended in 1977. With the signing of the treaty, less funding for irradiation studies was available (Stalter and Kincaid 2009). Thus most studies cited in this paper are those conducted prior to the SALT agreement of 1971. The gamma source that has been used has been either cesium 137 or cobalt 60. These include the studies of Woodwell (1962, 1965a) at Brookhaven National Laboratory, Long Island, New York, a tropical rain forest , Puerto Rico (Odum and Pigeon 1970) and the desert of Nevada (French 1965). Additional studies have been conducted in the fields and forests of Georgia (Odum and Kuenzler 1963) (Platt 1965), and Oak Ridge, Tennessee (Witherspoon 1965, 1969). Much additional work involving a portable gamma source on plant communities has been conducted at the Savanna River Ecology Laboratory, Aiken, South Carolina (McCormick and Platt 1962, McCormick and Golly 1966, Monk 1966, McCormick 1969).

Stalter and Kincaid (2009) investigated community development following gamma radiation at a pine-oak forest, Brookhaven National Laboratory, Long Island, New York. The objective of this study was to compare vascular plant community change at five vegetation zones the site of Woodwell's (1962) gamma irradiated forest (Figure 1). The zones were: the dead zone where all vegetation was killed; a gramminoid *Carex pensylvanica* zone; an ericaceous zone; an oak dominated zone; and a control, the original oak pine forest. Radiation greater than 63,000 roentgens killed all vegetation. *Carex* dominated the zone receiving 27,000 to 63,000 roentgens, ericaceous shrubs, *Vaccinium* spp. and *Gaylussacia baccata* were dominant at the zone receiving 11,000 to 27,000 roentgens while oaks survived at the zone receiving 3600 to 11,000 roentgens. Upon completion of the Woodwell study in the 1970's, pitch pine (*Pinus rigida*) has invaded the total kill zone as bare mineral soil favors pine regeneration (Stalter and Kincaid 2009). *Carex* remained the dominant taxon in the original *Carex* zone demonstrating again that different plant species vary in their tolerance of radiation.

Herbaceous plant communities may be more resistant to radiation than mature forests because many early successional species have small nuclei (Sparrow and Evans 1961) and also because herbaceous taxa like *Carex pensylvanica* have more below ground plant material which is shielded from gamma radiation. Sparrow (1962), Sparrow and Evans (1961), and Sparrow et al (1963) present detailed information on the relationship between nuclear volumes, chromosome numbers and relative radiosensitivity.

7. Biological magnification of radioactive material

Radioactive material may become concentrated or “biologically magnified" during food chain transfer. Numerous biology and ecology text books include information on how living organisms take up nutrients pesticides and radioactive material and concentrate them. Because this concept is well known, we direct the reader to several early studies involving the concentration of radioactive material (See the work of Foster and Rostenbach, 1954; Hanson and Kornberg 1956; Davis and Foster 1958). Ophel (1963) reported a concentration of strontium 90 in perch flesh as 5x that of lake water while that in perch bone was 3000x! Additional information on radioecological concentration can be found in Auberg and Crossley (1958), Auberg and Hungate (1967) and Polikarpov (1966).

8. Radioactive fallout

Radioactive particles that fall to the earth after above ground nuclear tests and nuclear power plant accidents are called radioactive fallout. Radioactive particles mix with the dust in the atmosphere and eventually fall to earth often thousands of miles from the initial explosion.

There are two types of nuclear weapons, the fission bomb and fusion bomb or thermonuclear weapon. In thermonuclear devices, deuterium fuses to form a heavier element with the release of energy and neutrons. A fission bomb is needed to trigger the fusion reaction. The thermonuclear weapon produces more neutrons which induce radioactivity in the environment than a fission device per unit of energy released. Roughly ten percent of the energy of a nuclear weapon is in residual radiation which may become dispersed in the atmosphere (Glasstone 1957). The amount of fallout produced depends on the type of weapon, size of the weapon and also on the amount of naturally occurring material that is mixed with the radioactive material released in the explosion. Fallout patterns and intensity depend upon the direction of the wind, speed and direction of the jet stream, presence and amount of precipitation.

Atomic explosions carry radioactive material high in the atmosphere where the radioactive material becomes fused with silica dust and other material present in the vicinity of the explosion. These particles are largely insoluble. The fallout particles may adhere to vegetation where they enter food chains at the primary consumer level. Fallout from Chernobyl in 1986 was deposited in Lappland (Sweden) where caribou consumed contaminated vegetation. Shifting winds also carried Chernobyl radiation particles to northern Italy where rabbit growers fed their rabbits vegetation contaminated with radioactive fallout from Chernobyl. Ultimately the rabbits were destroyed because of the high concentration of radioactive material in their flesh.

There are differences in the kind of radionuclides that enter terrestrial and marine food chains. Soluble fission products, strontium 90 and cesium 137, are generally found in the highest amounts in land plants and animals. In marine systems fallout that forms strong complexes with organic matter such as cobalt 60, iron 59, zinc 65, and manganese 54 are most likely to be concentrated in marine organisms. In addition, those found in colloidal form such as cesium 134 and zirconium 95 are also found in high concentration in marine organisms. Cesium 134 is mostly from the fission products of a power reactor whereas cesium 137 can be formed during atomic power plant accidents or as a product of nuclear bomb explosions.

There are additional considerations/problems associated with concentrating radioactive material entering food chains as the concentration of radioactivity is also a function of nutrient richness, and the exchange and storage capacity of soils. Nutrient poor soils and thin soils such as those found on granite outcrops act as a nutrient trap providing more radionuclides to the vegetation. For example, sheep grazing on hill pastures in England accumulated 20x as much strontium 90 in their bones than sheep pastured in deep valleys where calcium content of the soil was higher and the grasses taller (Bryant et al 1957). For additional radiological work on tracers in food chains and trophic levels see Odum and Golley (1963), Odum and Kuenzler (1963), de la Cruz (1963), Ball and Hooper (1963), Foster (l958), and Foster and Davis (1956).

9. Nuclear power plant accidents

Brief descriptions of three power plant accidents in the United States the Soviet Union and Japan follow. The first nuclear power plant accident occurred at 4 am on March 28, 1979, near Harrisburg, Pennsylvania, USA, the state's capital. A malfunction in the cooling system resulted in a portion of the core to melt in the Number 2 reactor. The approximately 2 million people who lived near the plant had an average dose of 0.14 Gy (Rogovin 1980). Although some radioactive gas was released from the plant on the 29th and 30th of March there was, "not enough to cause any radiation dose above background levels in the neighborhood of the accident "(http://www.world-nuclear.org/info/info/info/inf36.html). Fortunately, there were no reported injuries or health issues emanating from the Three Mile Island accident.

A more serious nuclear accident occurred at the Chernobyl power plant located 80 miles north of the city of Chernobyl in the Ukraine, one of the original Soviet Republics. A "routine" shut down and test that began on the 25th of April, 1986, led to this disaster. At one in the morning, 26 April, the reactor's power source dropped and when the backup safety system failed, the reactor, Reactor Four, exploded. Shortly after the initial explosion at Chernobyl, the Swedish government reported high levels of radiation at their Forsmark nuclear power plant at Stockholm. When additional European nuclear power plants also experienced higher than normal levels of radiation, they contacted the USSR for an explanation. Although initially denying the nuclear disaster, on the 28th of April the USSR acknowledged that one of their reactors had been compromised.

Group A. Naturally occurring isotopes which contribute to background radiation.

NUCLIDE	HALF-LIFE	RADIATIONS EMITTED	
Uranium-235 (^{235}U)	7 x 10^8 yrs.	Alpha[3]	Gamma[0]
Radium-226 (^{226}Ra)	1620 yrs.	Alpha[3]	Gamma[0]
Potassium-40 (^{40}K)	1.3 x 10^9 yrs.	Beta[2]	Gamma[2]
Carbon-14 (^{14}C)	5568 yrs.	Beta[0]	

[0] Very low energy, less than 0.2 Mev; [1] relatively low energy, 0.2-1 Mev; [2] high energy, 1-3 Mev; [3] very high energy, over 3 Mev.

Group B. Gamma emitting nuclides of elements which are essential constituents of organisms. Modified from Odum (1971).

NUCLIDE	HALF-LIFE		RADIATIONS EMITTED	
Cobalt-60 (^{60}Co)	5.27	yrs.	Beta[1]	Gamma[2]
Copper-64 (^{64}Cu)	12.8	hrs.	Beta[1]	Gamma[2]
Iodine-131 (^{131}I)	8	days	Beta[1]	Gamma
Iron-59 (^{59}Fe)	45	days	Beta[1]	Gamma[2]
Manganese-54 (^{54}Mn)	300	days	Beta[2]	Gamma[2]
Potassium-42 (^{42}K)	12.4	hrs.	Beta[3]	Gamma[2]
Sosium-22 (^{22}Na)	2.6	yrs.	Beta[1]	Gamma[2]
Sodium-24 (^{24}Na)	15.1	hrs.	Beta[2]	Gamma[2]
Zinc-65 (^{65}Zn)	250	days	Beta[1]	Gamma[2]

Also barium-140 (^{140}Ba), bromine-82 (^{82}Br), molybdenum-99 (^{99}Mo) and other trace elements.

Group C. Nuclides important in fission products entering the environment through fallout or waste disposal.

NUCLIDE	HALF-LIFE		RADIATIONS EMITTED	
The strontium group				
Strontium-90 (^{90}Sr) and	28	yrs.	Beta[1]	
daughter yttrium-90 (^{90}Y)	2.5	days	Beta[2]	
Strontium-89 (^{89}Sr)	53	days	Beta[2]	
The cesium group				
Cesium-137 (^{137}Cs) and	33	yrs.	Beta[2]	Gamma
daughter barium-137 (^{137}Ba)	2.6	min.	Beta	Gamma[1]
Cesium-134 (^{134}Cs)	2.3	yrs.	Beta[1]	Gamma[2]
The cerium group				
Cerium-144 (^{144}Ce) and	285	days	Beta[1]	Gamma[0]
daughter praseodymium-144 (^{144}Pr)	17	min.	Beta[2]	Gamma[2]
Cerium-141 (^{141}Ce)	33	days	Beta[1]	Gamma[1]
The ruthenium group				
Ruthenium-106 (^{106}Ru) and	1	yr.	Beta[0]	
daughter rhodium-106 (^{106}Rh)	30	sec.	Beta[3]	Gamma[2]
Ruthenium-103 (^{103}Ru)	40	days	Beta[1]	Gamma[1]
Zirconium-95 (^{95}Zr) and daughter	65	days	Beta[1]	Gamma[1]
niobium-95 (^{95}Nb)	35	days	Beta[0]	Gamma[1]
Barium-140 (^{140}Ba) and daughter	12.8	days	Beta[1]	Gamma[1]

lanthanum-140 (^{140}La)	40	hrs.	Beta[2]	Gamma[2]
Neodymium-147 (^{147}Nd) and	11.3	days	Beta[1]	Gamma[1]
daughter promethium-147 (^{147}Pm)	2.6	yrs.	Beta[1]	Gamma
Yttrium-91 (^{91}Y)	61	days	Beta[2]	Gamma
Plutonium-239 (^{239}Pu)	2.4×10^4	yrs.	Alpha[3]	Gamma[1]
Iodine-131 (see Group B)				
Uranium (see Group A)				

Table 3. Radionuclides of Ecological Importance

Scientists estimate that the radiation from the Chernobyl accident was 100x that of the two atom bombs dropped on Hiroshima and Nagasaki. It is estimated that the total atomospheric release was 5200 PBq (petabecquerel, 10^{15} Bq). The immediate death toll was 31 individuals though many more may die from the long term effects of radiation. The Soviets battled blazes at the Chernobyl power plant for two weeks. Those battling the fires were heroes in this author's eyes because they knew they were exposing themselves to dangerous levels of radiation. Ultimately the Soviet authorities encased the Chernobyl reactor in concrete. A second more stable sarcophagus is currently being constructed over the original; its scheduled completion date is 2013.

There may have been additional unreported nuclear power plant accidents in the Soviet Union. Radioactive monitoring stations in Europe have picked up higher levels of radiation at various times which may have been the result of other Soviet nuclear power plant accidents.

The third and most recent nuclear power plant crisis occurred at the Fukushima Daiichi power plant in Japan. The cause of this disaster was a severe earthquake and tsunami on the 11th of March, 2011. The earth quake, which registered approximately 9 on the Richter Scale, was the event that set this tragedy in motion. The earthquake and resulting tsunami damaged the power plant compromising the cooling systems to the reactors causing the fuel rods to overheat. This disaster was rated greater than that at Three Mile Island. As of June 2011, the Fukushima disaster has released approximately one tenth the total amount of radiation as was released at Chernobyl. Unfortunately, the damaged Japanese reactor continues to spew forth radiation so the ultimate amount of radiation released from the plant cannot be determined with certainty.

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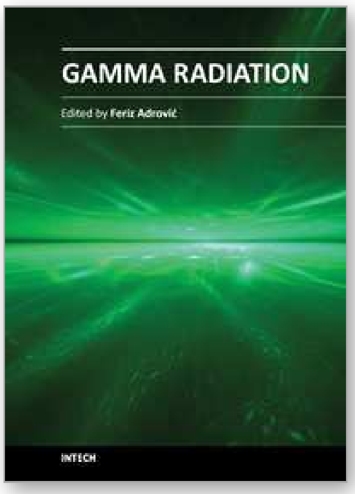

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This book brings new research insights on the properties and behavior of gamma radiation, studies from a wide range of options of gamma radiation applications in Nuclear Physics, industrial processes, Environmental Science, Radiation Biology, Radiation Chemistry, Agriculture and Forestry, sterilization, food industry, as well as the review of both advantages and problems that are present in these applications. The book is primarily intended for scientific workers who have contacts with gamma radiation, such as staff working in nuclear power plants, manufacturing industries and civil engineers, medical equipment manufacturers, oncologists, radiation therapists, dental professionals, universities and the military, as well as those who intend to enter the world of applications and problems of gamma radiation. Because of the global importance of gamma radiation, the content of this book will be interesting for the wider audience as well.

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