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Shielding of Ionizing Radiation in Nuclear Power Reactor Environments (A Technical Memorandum)

Bahman Zohuri[1]*, Seyed Kamal Mousavi Balgehshiri[2] and Ali Zamani Paydar[2]

[1]Galaxy Advanced Engineering, Chief Executive Officer, Consulting Firm, Albuquerque, New Mexico, United States of America 87111

[2]Physics and Energy Engineering Department, Amirkabir University of Technology, Tehran, Iran

ABSTRACT

Since release of movie known as "China Syndrome" in early march of 1979, and was about story of a reporter who finds what appears to be a cover-up of safety hazards at a Nuclear Power Plant (NPP), and a hypothetical sequence of events following the meltdown of a nuclear reactor, in which the core melts through its containment structure and deep into the earth causing all kind of nuclear radiation. Nuclear accidents are one of the greatest debates that in several decades ago has risen around the world in past until now, we encountered with the worst nuclear accident in Three Mile Island (TMI) in 28 March of 1979, which was less than two weeks after release of the movie, which start raising the concern of radiation leak to environment from TMI-2 reactor. This start putting future of nuclear power industry driven energy producing electricity, into serious doubt and the matter become worst, when on 26 April 1986 the Chernobyl nuclear disaster occurred at the No. 4 reactor of this power plant and released huge amount of radiation into surrounding environment very dangerously that still exists today. We almost were about forgetting about these incidents by putting them in backburner of our mind, then on 11 March 2011 a huge tsunami hits cost of Fukushima, Japan, where Fukushima Daiichi nuclear power plant was residing and consequently caused its accident and it was the most severe nuclear accident in the world so far to this point that is still consider that was this event another China Syndrome? Radiations released from these accidents internally and externally to its environment is serious matter and needs serious attention by scientist, engineers and creators of these reactor and what could be done to shield them, when come to ionizing radiation, which is subject of this Technical Memorandum (TM).

***Corresponding authors**

Bahman Zohuri, Galaxy Advanced Engineering, Chief Executive Officer, Consulting Firm, Albuquerque, New Mexico, United States of America 87111. Email: bahmanz@aol.com

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Introduction

As of March 2022, Chernobyl reactors in Ukraine is back on the news since invasion of Russian troops into this country and in March of this year took over this reactor facility by force and shooting toward its infrastructure (i.e., Figure-1). Fortunately, apparently the reactor core was not shot at and so far, it seems there is no serious leak of radiation but rumor is that after Russian forces have seized control of this power plant in northern part of Ukraine, the site of the world's worst nuclear disaster, and are holding staff hostage. The site of the worst nuclear disaster ever in 1986 has been under the control of Russian troops since the early stages of the invasion. However, according to Ukrainian official, the occupant troops are leaving the facility behind with radiation sickness among them.

Figure 1: Partial Destruction of Chernobyl Power Plant

Although by international law and agreed among the international countries of legal regime around the world not to attack any nuclear reactor facilities under any circumstances, yet Russian military bombs or artillery brough Chernobyl under destructive attack and around 210 staff of the plant were taken hostage by the soldiers, and have been forced to keep working in reportedly poor conditions.

Surprisingly, in 1956, the International Red Cross (IRC) proposed an immunity from attack for installations, including "nuclear power stations," where the attack might endanger

The United Nation's (UN) nuclear agency confirmed on March 21, 2022 that for the first time, the remaining members of the one shift technical staff were relieved.

The International Atomic Energy Agency (IAEA) said: "Ukraine's regulatory authority said about half of the outgoing shift of technical staff left the site of the 1986 accident yesterday and the rest followed today, with the exception of thirteen staff members who declined to rotate".

The IAEA's Board of Governors passed a resolution that deplored the Russian invasion and urged Russia to allow Ukraine to continue to control its nuclear facilities.

The technical staff who have left are reportedly being replaced by Ukrainian colleagues based in the nearby town of Slavutych.

While the plant is now defunct, workers still need to maintain and monitor the site. This plant has lost power several times during Russian troops' occupation, and the staff at Chernobyl reportedly refused to carry out any more safety-related repairs due to sheer exhaustion Figure-2.

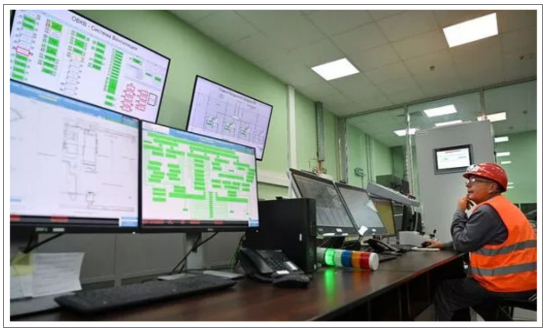

Figure 2: Staff are still needed at the Plant for Monitoring and Maintenance

This sparked fears that radioactive material could leak from the Nuclear Power Plant (NPP) as a cooling system regulating nuclear waste has to run on a backup diesel generator, thus need continuous supply of fuel without any disruption of supply chain delivering diesel fuel to these backup machineries.

Ukrenergo, Ukraine's electricity operator, warned on Facebook: "The Chornobyl NPP is an important facility that cannot be left without a reliable energy supply. The power plant has remained within a large restricted area known as the Chernobyl Exclusion Zone (i.e., Figure-3) ever since the accident at Reactor No. 4.

Figure 3: Chernobyl Exclusion Zone

This recent event in Ukraine Chernobyl reactor is considered as the worst man-made event, yet Ukraine has total of three other Nuclear Power Plants (NPPs) (i.e., Figure-4) speared all over this nation and they are in operational mode, and they should be considered and protect under safety umbrella of UN's resolution that was passed on 3rd March of this year (i.e., 2022).

As illustrated in Figure-4, Ukrainian Nuclear Power Plants' Locations and Russian Forces Occupied Areas as of March 3, 2022. Available at: https://www.intellinews.com/a-night-that-could-have-stopped-the-history-of-ukraine-zelenskiy-warns-after-russia-attacks-europe-s-largest-nuclear-power-plant-236992/ You will find more infographics at Statista.

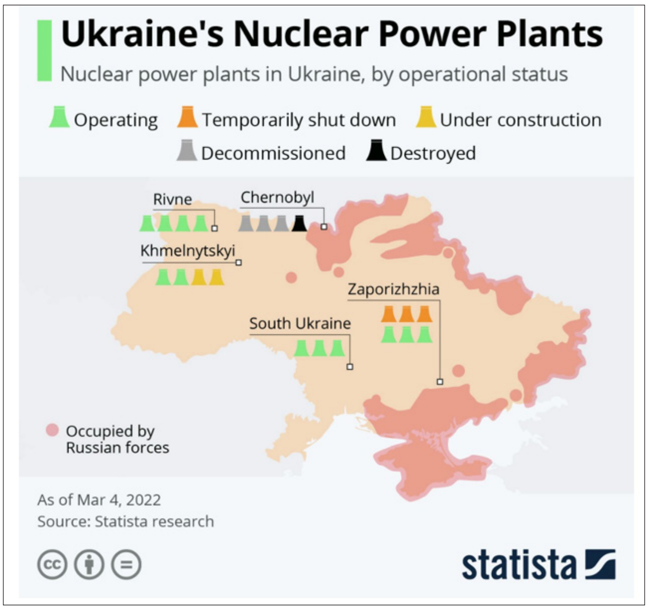

Figure 4: Ukraine's Nuclear Power Plants

As it can be observed in Figure-2 above, the other three Ukrainian reactor complexes—at Rivne, Khmelnystkyi, and South Ukraine—are still outside Russian-occupied areas.

This may change as Russian forces press their attacks, change attack vectors, or counterattacks occur; it should also be noted that all these facilities are subject to attack by aircraft or long-range ballistic missiles.

Although the issue of attacking reactor facilities has been considered for some time, the international legal regime that addresses attacks on nuclear and associated facilities—including those that have occurred in Ukraine—is not as clear cut as one might think. Still, protocols of the Geneva Conventions, the rules of International Humanitarian Law, and Russia's own military regulations do prohibit the kinds of attacks that Russia made on the Zaporizhzhia Nuclear Power Plant in recent days since their attack of Ukraine as of 24 February of 2022. Figure-5

Figure 5: Russian Attacks in Ukraine

Circumstances, such as man-made disaster to Chernobyl nuclear power (i.e., March 2022) or operator error of April of 1986, following Three Mile Island accident in March of 1979, then March 2011 Fukushima tsunami natural disaster, thus damaging Fukushima Daiichi reactors, where all together they are source of ionizing nuclear radiation is concern of safety issues of operation of these reactors.

Now that, we are at virtue of Research and Development (R&D) of Generation-IV (GEN-IV) International Forum (GIF) reactors or as Advance Reactor Concept (ARC) either in form of Small Modular Reactor (SMR) or advance Small Modular Reactor (aSMR), requires stiff implementation of Probabilistic Risk Assessment (PRA) from safety analysis in place, when it comes to their operational mode of these reactors [1, 2].

As advanced reactor designs become reality, technology gaps with clearly defined research direction and paths toward certain design specifications are becoming prevalent. One of required design specification due to complexity of newly SMRs and aSMRs are their instrumentation that are integrated in them. So, placing advanced sensors and associated electronics closer to a nuclear reactor core will have a sensible effect on reactor control and operation through increased signal accuracy, precision, and fidelity, resulting in safer, more efficient energy production. However, due to the extreme temperature and bombarding radiation environment that exist in nuclear applications that results development into electronics and electronic materials technologies to improve safety, monitoring, and control of the existing nuclear reactor fleet and the next generation of reactors, including micro reactors.

Instrumentation using optimally placed Radiation-Hardened (Rad-Hard) electronics would improve reactor safety and efficiency by reducing the noise that typically injected on the lengthy cabling between the sensor and electronics, thus enhance and increase demand on PRA by increasing resiliency of reactor performance and operation from perspective of having a Business Resilience System (BRS) in place, which could be considered also, as part of Beyond Design System (BDS) specification accordingly [3-7].

Post nuclear accident conditions represent a harsh environment for electronics. The full station blackout experience at Fukushima Daiichi power plant showed the necessity for emergency sensing capabilities in a radiation-enhanced environment. Hardening by architecture uses redundant commercial parts in duplicate architectures to mitigate radiation-induced effects. However, this method increases power consumption, weight, and size. The newly innovative Nuclear Energy Enabling Technologies (NEET) research and Development (R&D) project would establish a new ground role for Radiation Hardened by Design (RHBD) electronics using commercially available technology that employs Commercial Off-The-Shelf (COTS) devices and present generation Integrated-Circuit (IC) fabrication techniques to improve the Total Ionizing Dose (TID) hardness of electronics [8].

Radiation hardening by design (RHBD) makes use of chip layout techniques, device spacing, decoupling, correction circuits, etc. Radiation hardening by process (RHBP) employs known radiation-tolerant materials and processing techniques, but these materials increase the cost of electronics.

Ionizing Radiation from a damaged nuclear reactor can wreak havoc or widespread destruction on electronics integrated with complex structure reactor and Nuclear Power Reactor (NPP) and we need to show and explain how vital systems are designed to withstand worst-case scenarios.

Shielding of Ionizing Radiation

Before we step in through this section of this Technical Memorandum "TM", we need to have the understanding of the subject of "*Shielding of Ionization Radiation*" within a nuclear reactor power infrastructure.

Shielding of ionizing radiation means having some material between the source of radiation and you as an operator of reactor, or some device within reactor surrounding environment that will absorb the radiation.

Radiation shielding usually consists of barriers of lead, concrete, or water. Many materials can be used for radiation shielding, but there are many situations in radiation protection. It highly depends on the type of radiation to be shielded, its energy, and many other parameters. For example, even depleted uranium can be used as good protection from gamma radiation, but on the other hand, uranium is inappropriate shielding of neutron radiation.

With either man-made or natural-made nuclear radiation leak in Chornobyl of Ukraine, or Three Mile Island of Pennsylvania in United States of America or as recent accident of Fukushima Daiichi reactor in Fukushima Japan, we always need to watch for safety environment of any reactor Generation-III (GEN-III) in operation around the globe, or even Generation-IV (GEN-IV) that are going to be in operation in near future. All these reactors technology is based on "Fission Fuel" driven by radioactive mater such as, either Uranium or Plutonium atom.

The next generation of reactors will have greater environmental hazards, such as high operating temperatures to increase thermal efficiency. The increased temperatures limit the survivability of sensor and electronics materials. Also, these reactors take advantage of both fast neutron flux and thermal neutron flux. Each flux type has its own degradation mechanisms. For example, chronic thermal flux exposure causes transmutation through absorption of neutrons.

Radiation can ionize atoms and disrupt a semiconductor's crystal structure and can pose a problem for electronics. For electronics that are very close to a reactor, neutrons will create physical damage to the semiconductor crystal. But most chips will fail due to the leakage that is associated with the charging of insulators. In something like a metal-oxide-semiconductor device, for example, gamma rays and X-ray radiation will knock electrons off atoms in an insulator to create electron-hole pairs. The resulting trapped positive charges will shift the operating characteristics. Devices are designed to turn on and off at a well-defined point of operation, and if that operating voltage shifts, this can create difficulties.

The effects of radiation in electronic systems can be divided into three main categories: displacement damage, Total Ionizing Dose (TID) effects, and dose-rate effects. Displacement damage is a phenomenon where an atom is displaced by collision in its lattice structure. TID degradation refers mostly to charge trapping, electric and magnetic field generation, and also chemical effects.

Dose-rate effects commonly refers to transient disruptions that changes the state of the device and occurs when a sufficient energic single particle collides to a material and cause non-damaging Single Event Upsets (SEUs) or damaging events such as Single Event Latchups (SELs). TID and Displacement damage can be both considered cumulative, long-term effects, while dose-rate effects may be having a short term or temporary in many situations.

To shield and radiation hardened any electronic device in an operating nuclear reactor are no different than space radiation environment, when it comes to ionizing radiation and their shielding against it.

Overall, there are four main areas of concern for shielding as below:

- Shield geometry and shielding analysis technique,
- Shield material composition,
- Component composition (e.g., package, passivation, metallization and semiconductor materials of a complex microcircuit), and
- Dose units.

As we stated before, "*radiation shielding means having some material between the source of radiation and you (or some device) that will absorb the radiation*". The amount of shielding required, the type of material of shielding strongly depends on several factors. We are not talking about any optimization.

In fact, in some cases, inappropriate shielding may even worsen the radiation situation instead of protecting people from the ionizing radiation. Basic factors, which have to be considered during the proposal of radiation shielding, are:

- Type of the ionizing radiation to be shielded.
- The energy spectrum of the ionizing radiation.
- Length of exposure.
- Distance from the source of the ionizing radiation.
- Requirements on the attenuation of the ionizing radiation – ALARA or ALARP principles.
- Design degree of freedom.
- Other physical requirements (e.g., transparence in case of leaded glass screens).

Note that: The ALARA (As Low as Reasonably Achievable) and ALARP (As Low as Reasonably Practicable) principles are based on reducing exposure to ionizing radiation by employing all reasonable methods. Here are three facts about ALARA and ALARP: Proper training is crucial.

1. **Proper training is crucial**. It may be tempting to have employees' multi-task, performing several different functions including obtaining radiographic images. But a person who is not trained in the ALARA or ALARP principles may unwittingly cause harm to patients or himself by taking longer-than-necessary exposures or capturing more images than are needed.
2. **Maintain the proper distance from a source** of radiation. Whenever possible, while administering imaging tests, adhere to best practices and stay the proper distance away from ionizing radiation to be protected from exposure. In some instances — such as veterinary X-rays for an animal — it is practically impossible to stay far away. In those situations, use as much shielding as necessary for protection.
3. **Shielding applies to both environment and individuals**. When designing imaging rooms, make sure the lead walls are the proper thickness. It's ineffective for employees to be stepping behind a protective wall if that wall is not really protecting them. Additionally, all physicians, nurses and technicians who work with ionizing radiation should be using lead aprons, thyroid collars and lead gloves.

Figure-6 is a presentation of "Interaction of Radiation with Matter" and is the key knowledge that constitute of modern physics. With this knowledge, which is based on experiments, the modern physics provide key information for our understanding of nature. Most modern nuclear or particle experiments use various sophisticated devices (detectors such as Gamma-Thermometer for measuring neutron flux with reactor core that can be installed in fuel bundles) for measuring and detecting sub-atomic particles. To be detected, a particle must leave some trace of its presence in a detector. Particles mostly deposit energy along their path. Knowledge of this interaction, how different particles deposit energy in the matter, and how much energy particles deposit is fundamental for understanding the problem.

Note that as Figure-6 indicates, the higher the dose the less likely you will be able to find a commercial integrated circuit to handle it. Radiation-hardened electronics are typically anywhere from two to four generations behind commercial electronics in terms of their performance. It takes extra time to do the additional engineering.

Each type of particle interacts differently, therefore we must describe the interaction of particles (radiation as a flow of these particles) separately. For example, charged particles with high energies can directly ionize atoms.

On the other hand, electrically neutral particles interact indirectly and transfer some or all of their energies to the matter. This is the key feature of the categorization of radiation sources. They are usually categorized into two general types as follows:

- **Charged particles** (directly ionizing)
  - o **Beta particles**. Beta particles are fast electrons or positrons emitted in nuclear beta decay, as well as energetic electrons produced by any other process.
  - o **Heavy charged particles**. Heavy charged particles are all energetic ions with one atomic mass unit or greater mass, such as protons, alpha particles (helium nuclei), or fission fragments.
- **Neutral particles** (indirectly ionizing)
  - o **Photon radiation** (electromagnetic radiation). Photons are particles/waves (Wave-Particle Duality) without rest mass or electrical charge. Also, visible light is electromagnetic radiation, but with much lower energies. The electromagnetic radiation of interest includes X-rays emitted in the rearrangement of electron shells of atoms and gamma rays emitted from the nucleus.
  - o **Neutrons**. Neutrons can be emitted by nuclear fission or by the decay of some radioactive atoms. Neutrons have zero electrical charges and cannot directly cause ionization.
  - o **Neutrinos**. Neutrinos are electrically neutral, weakly interacting elementary particles, which have very low cross sections for any interaction with matter and, therefore, low probabilities for colliding in the matter.

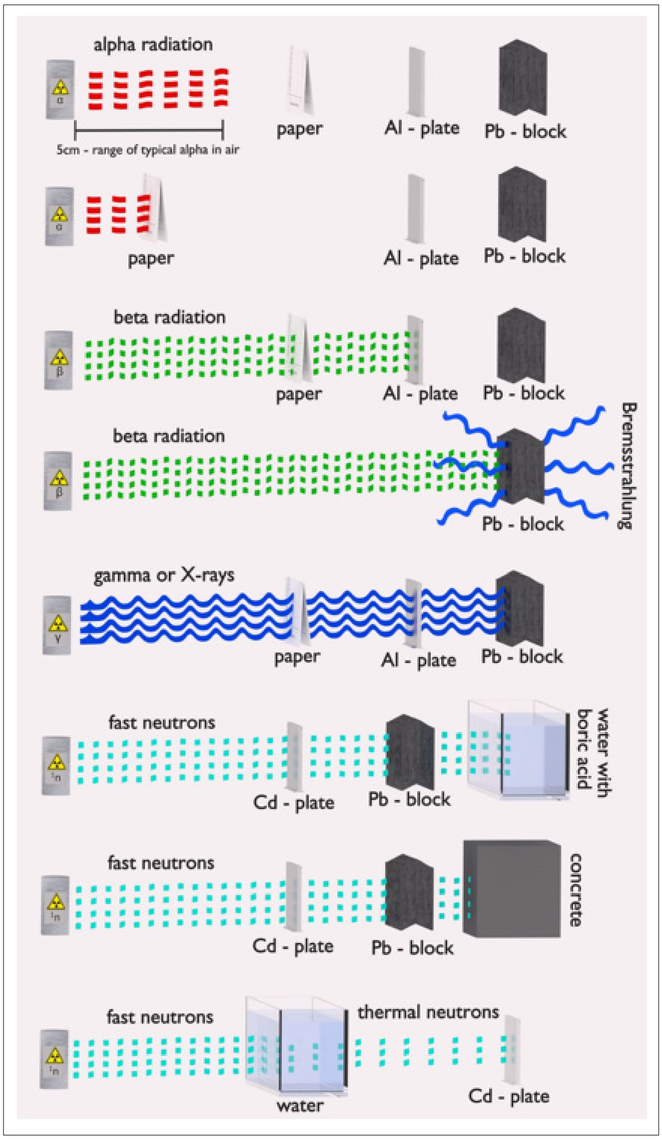

Figure 6: Shielding of Ionizing Radiation Infrastructures

The design of all nuclear reactors and other nuclear systems depends fundamentally on how radiation interacts with matter. This knowledge is very important for the understanding of:

- **Neutron Moderation**. How neutrons slow down to thermal energies.
- **Power Distribution**. Where is the energy generated?
- **Reactor Power Measurement**. How can we measure the reactor power, and how can we control the chain reaction?
- **Radiation Shielding**. How can we shield all the various types of radiation produced in the reactor core?

Each of these particles and their interaction with matter can be described with more details that is beyond the scope of this Technical Memorandum, and we leave it up to reader of this article to do their own research within domain of "*Modern Physics*" field [4, 9].

Nuclear Power Plants (NPPs) Radiation Shielding

Generally, in the nuclear industry, radiation shielding has many purposes. In nuclear power plants, the main purpose is to reduce the radiation exposure to persons and staff in the vicinity of radiation sources. In NPPs, the main source of radiation is conclusively the nuclear reactor and its reactor core. Nuclear reactors are, in general, powerful sources of an entire spectrum of types of ionizing radiation. Shielding used for this purpose is called biological shielding.

But this is not the only purpose of radiation shielding. Shields are also used in some reactors to reduce the intensity of gamma rays or neutrons incident on the reactor vessel. This radiation shielding protects the reactor vessel and its internals (e.g., the core support barrel) from excessive heating due to gamma-ray absorption fast neutron moderation. Such shields are usually referred to as thermal shields. For more granular information and extra education, we can refer to field and knowledge of "*Neutron Reflector*" as well [10].

A little strange radiation shielding is usually used to protect the material of reactor pressure vessels (especially in Pressurized Water Reactor (PWR) power plants). Structural materials of pressure vessels and reactor internals are damaged, especially by fast neutrons. Fast neutrons create structural defects, which in result lead to embrittlement of material of pressure vessel. To minimize the neutron flux at the vessel wall, also core loading strategy can be modified. In the "out-in" fuel loading strategy, fresh fuel assemblies are placed at the periphery of the core. This configuration causes high neutron fluence at the vessel wall. Therefore, many nuclear power plants have adopted the "in-out" fuel loading strategy (with Low Leakage Loading Patterns (L3P) [11].

In contrast to the "out-in" strategy, low leakage cores have fresh fuel assemblies in the second row, not at the periphery of the core. The periphery contains fuel with higher fuel burnup and lowers relative power, and a very sophisticated radiation shield.

In nuclear power plants, the central problem is to shield against gamma rays and neutrons because the ranges of charged particles such as beta particles and alpha particles in the matter are very short. On the other hand, we must deal with shielding all types of radiation because each nuclear reactor is a significant source of all types of ionizing radiation.

Conclusion

Radiation protection is the science and practice of protecting people and the environment from the harmful effects of ionizing radiation. In case of shielding of radiation in Nuclear Power Plants (NPPs) and their day-to-day safe operation is science that is required an innovative Research and Development (R&D), by designers of new generation of nuclear reactors that we know and have identified them as GEN-IV by know. It is also part of functionality and performance of Probabilistic Risk Assessment (PRA) Team, they are the one who need to look at the "*Radiation Shielding*" of Nuclear Reactor as part of design criteria as well.

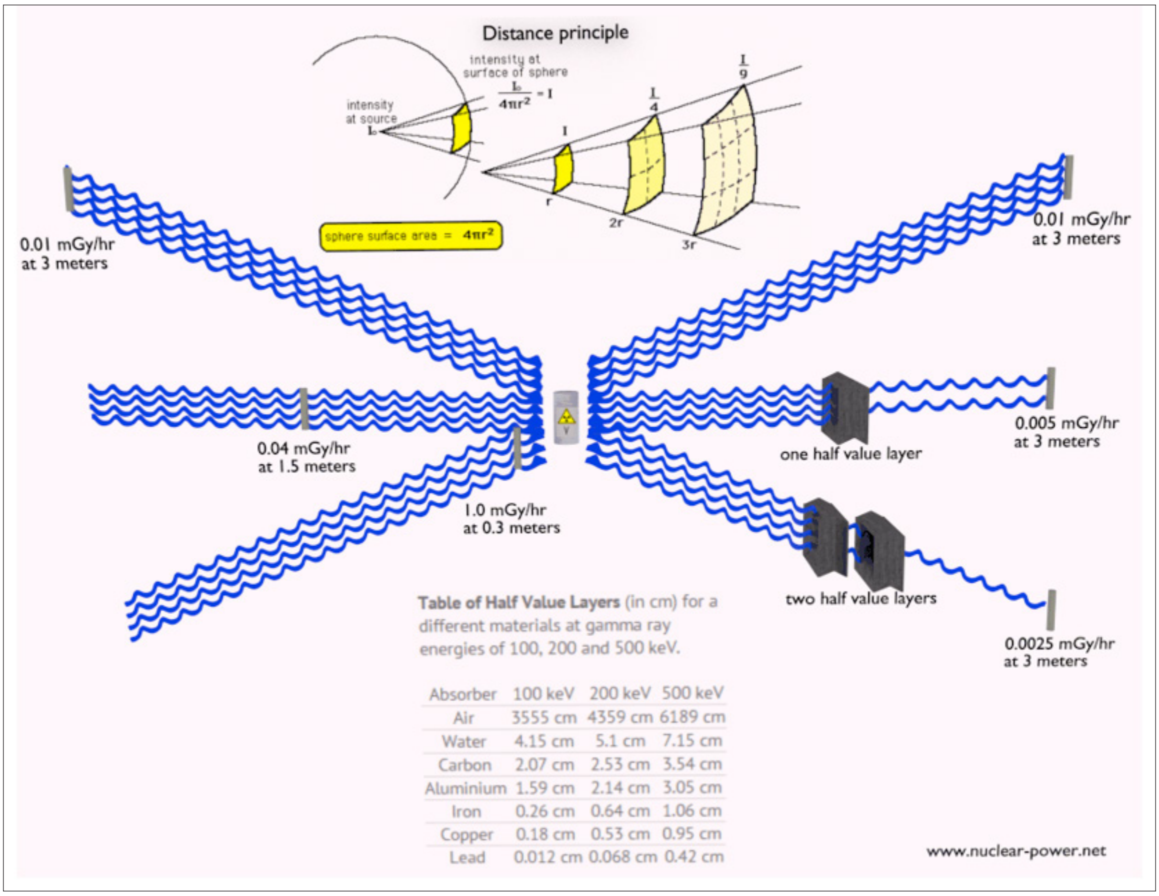

Figure 7: Illustration of Distance Principle

It is a serious topic not only in nuclear power plants, but also in industry or in medical centers. In radiation protection there are three ways how to protect people from identified radiation sources:

- **Limiting Time**. The amount of radiation exposure depends directly (linearly) on the time people spend near the source of radiation. The dose can be reduced by limiting exposure time.
- **Distance**. The amount of radiation exposure depends on the distance from the source of radiation. Similarly, to a heat from a fire, if you are too close, the intensity of heat radiation is high and you can get burned. If you are at the right distance, you can withstand there without any problems and moreover it is comfortable. If you are too far from heat source, the insufficiency of heat can also hurt you. This analogy, in a certain sense, can be applied to radiation also from radiation sources. See Figure 7
- **Shielding**. Finally, if the source is too intensive and time or distance do not provide sufficient radiation protection, the shielding must be used. Radiation shielding usually consist of barriers of lead, concrete or water. There are many materials, which can be used for radiation shielding, but there are many situations in radiation protection. It highly depends on the type of radiation to be shielded, its energy and many other parameters. For example, even depleted Uranium can be used as a good protection from gamma radiation, but on the other hand uranium is absolutely inappropriate shielding of neutron radiation
- **Radiation Halving Thickness**. Every material has a "*halving thickness*" and this is the thickness required to reduce the radiation intensity by half. 50%. Therefore, if halving thickness of a material is 1 inch, then a 1-inch-thick sheet will cut the radiation to 50%. Two inches will cut the radiation to 25%, 3 inches to 12.5%, and so forth. This fact determines the radiation Protection Factor (PF) that we need to take under design consideration. A typical house will reduce the power of the radiation to one fifteenth of that outside – this is called a protective factor of 15. Shelters constructed of the right materials can give a much greater protective factor than this. According to FEMA TR-87, Standards for Fallout Shelters, "The minimum level of protection for public fallout shelters is PF 40".

As also part of our conclusion here, we may ask this question that "*Can a reactor's electronics survive a meltdown*", thus we would not have another myth of China syndrome movie in our hand.

Certainly, in the 1960s [when the first Fukushima reactors were built], people were very aware of the risks due to radiation and there were choices of electronics that could be made that would increase the resistance to radiation by a lot.

Very basic control circuits can be made to withstand exceedingly high levels of radiation, but they're very simple in terms of function. They're not the kinds of electronics that you could use to run the entire plant. They would just be used to maintain the capability of being able at some point to turn cooling systems on or perform critical switching and control functions.

The higher the dose the less likely you will be able to find a commercial integrated circuit to handle it. Radiation-hardened electronics are typically anywhere from two to four generations behind commercial electronics in terms of their performance. It takes extra time to do the additional engineering.

At the bottom line, we may ask ourselves that, "*was it possible that electronics in the damaged Fukushima reactors could be used to boot the cooling system back up*?"

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