Transactions of the Korean Nuclear Society Autumn Meeting
Changwon, Korea, October 20-21, 2022

Comparison of shielding concepts between onshore power plants and nuclear ships

Youg Jae Lee, Jeong Ik Lee*
Dept. Nuclear & Quantum Eng., KAIST, 291 Daehak-ro, Yuseong-Gu, Daejeon 34141, Republic of Korea
**Corresponding author: jeongiklee@kaist.ac.kr*

1. Introduction

While efforts are being made worldwide to achieve the goal of being carbon neutral, among many energy sources, nuclear power, which has the characteristics of eco-friendly and high efficiency, is gaining great interest. Nuclear powered vessels, those are more efficient than conventional fossil fuel vessels, are receiving more interest, as it is possible to sail without supply of fuel for decades even with a small amount of fuel injection.

In addition to eliminating needs of refueling for a long period of time, nuclear powered ships have the advantage of using a relatively inexpensive fuel, uranium, and being eco-friendly because they do not emit greenhouse gases.

However, as a nuclear-powered ship uses nuclear energy, it must be designed well to protect the sailors on board with a good shielding design. In addition, nuclear ships have spatial limitations compared to onshore nuclear power plants due to the characteristics of the ship, and the load limit of the nuclear reactor facility exists due to the limited loading capacity of the ship. Therefore, it is necessary to design a shielding concept in consideration of volume and mass due to these different boundary conditions.

Therefore, in this study, the shielding concept of the onshore nuclear power plant and the shielding concept of the offshore nuclear power plant are compared and analyzed to suggest a desirable shielding concept for the nuclear ships.

2. Radiation Shielding

There are alpha, beta, gamma, and neutron radiations in a nuclear reactor. For the nuclear reactor shielding, gamma and neutron radiations are the important radiations to shield due to charge neutrality.

The process of shielding against neutrons can be roughly divided into three stages. As the first step, inelastic scattering is performed to reduce the speed (energy) of neutrons. The nucleus absorbs the kinetic energy of high-speed neutrons by using elements with large atomic numbers, such as iron (Fe) and lead (Pb). Next, elastic scattering is performed to further reduce the energy of neutrons as a second step. Considering the property that neutrons lose a lot of energy when they collide with light elements, hydrogen is an element typically used to collide with light elements. Therefore, water, paraffin, concrete are typically used for neutron shielding. Slow neutron absorption is performed in the following three steps, using an element with a large trapping reaction (absorption) cross-sectional area, for example, cadmium (Cd), boron (B), xenon (Xe), hafnium (Hf), etc. In response to the decrease in neutron velocity, shielding is carried out using the neutron absorption reaction.

In addition to neutrons, shielding against gamma rays must also reduce energy and absorb particle of photons. The pair-production in high energy region, the Compton scattering in medium energy, and the photoelectric effect in low energy region are each used for reducing and absorbing energy of gamma photons. For all three reactions, the greater the number of protons in the reacting nucleus, the higher the probability of reaction is. Therefore, gamma-ray shielding is performed using a material such as lead with many protons and high density.

3. Shielding of onshore power plants

In a land-base nuclear power plant, concrete is mainly used as a shielding agent to shield these neutrons and gamma rays together. Since concrete has a high linear attenuation coefficient of gamma rays due to its high atomic weight and density, it is also effective in shielding gamma rays.

Therefore, based on the reactor core design, which is the radiation source, the shielding is carried out by building up several layers of concrete walls around the main systems. This concrete wall serves as a biological shield during normal operation and power plant accidents.

The primary barrier surrounds the reactor vessel. The primary barrier is designed to resist temperature and pressure in the event of a loss of coolant. The primary barrier also structurally supports the reactor vessel.

The secondary barrier wall is a cylindrical structure inside the containment building and protects the reactor vessel. The secondary barrier provides structural support for the platform and pipe supports/containment devices on multiple levels, as well as providing a biological barrier for the coolant flow path and equipment. Secondary shielding compliments primary shielding by attenuating gamma rays from primary shielding.

Finally, the containment building shields the radiation, which is constructed with reinforced concrete. The containment building surrounds the nuclear steam supply system. A reinforced concrete dome and a thick cylindrical wall reduces radiations from the primary and secondary shieldings.

In addition, the auxiliary building outside the containment and containing piping and appliances with potentially contaminated fluids have to be also shielded. The shielding includes concrete walls, covers, doors and movable blocks for radiation protection.

The shielding using concrete, the radiation dose is more than 5,000mSv/hr inside the primary shielding but inside the secondary shielding is lowered to less than 5,000mSv/hr. In addition, the radiation dose is lowered to within 10mSv/hr outside the secondary shielding. Finally, due to the shielding with the containment building, the radiation dose outside the containment is lowered to less than 0.003mSv/hr. In addition, the interior of the auxiliary building is lowered to less than 0.01mSv/hr except for certain pipe passages.

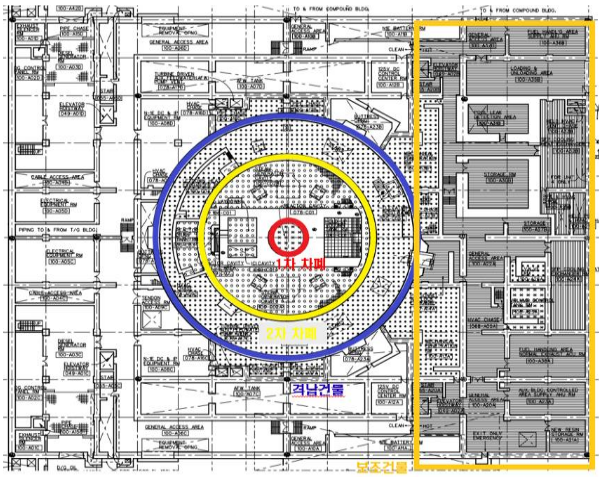

Fig. 1. Primary (red circle) and Secondary (yellow circle) Shielding of land-base nuclear power plants

4. Shielding of nuclear-powered ships

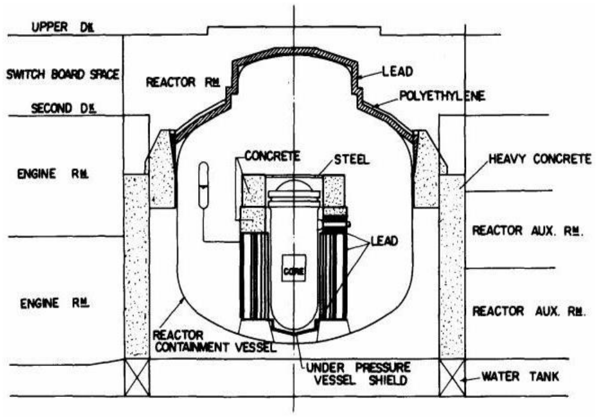

Fig. 2. Shielding for the early days of nuclear ships

Unlike land-based power plants, nuclear-powered ships have space and load limitations. Thus, using heavy thick concrete as a shielding material is not preferred. Therefore, water is mainly used for shielding.

In the early days of nuclear-powered ships, the primary shielding surrounded the reactor pressure vessel. The secondary shielding was constructed with heavy concrete and this existed outside the containment vessel. However, since the secondary shield surrounds the containment vessel, the volume of the nuclear compartment increased considerably and became excessively heavy as well. In fact, in the case of N.S. MUTSU, secondary shielding accounted for 88% of the total weight of the shielding material. An improved shielding was introduced for MRX (Marine Reactor X) to make a more compact and lightweight nuclear-powered ship.

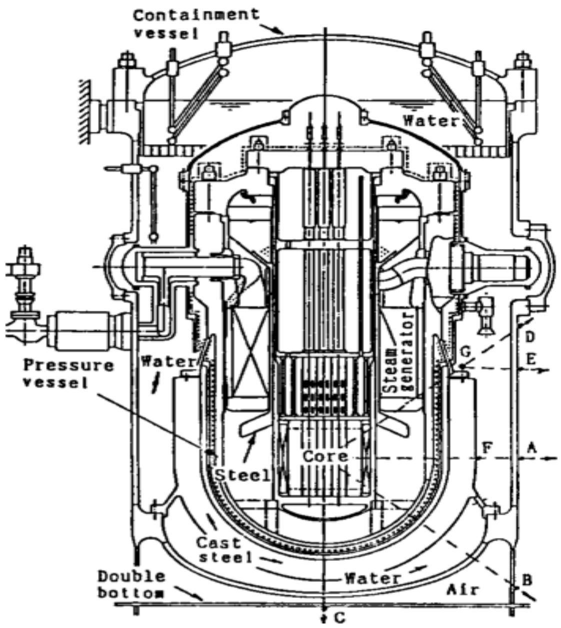

Fig. 3. Conceptual view of MRX

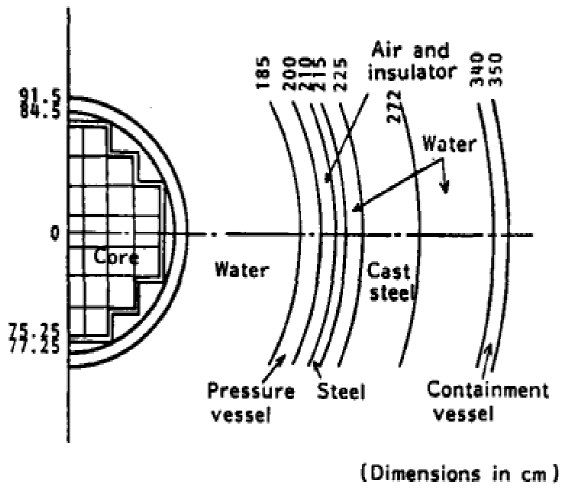

Fig. 4. Schematic section in horizontal plane of MRX's core center position

As shown in Figures 3 and 4, the shielding of the MRX nuclear reactor was mainly using water, and the shielding agent was placed in the order of water→ pressure vessel→Air and insulator→steel→water→Cast steel→water→containment vessel.

Water is effective in attenuating neutron radiation, and it is useful for reducing the radiation streaming effect, which is an effect that radiation is concentrated at penetrations. Water is relatively lighter than concrete or lead, so it has the advantage of reducing the weight of the reactor compartment, so it was used as a shielding agent.

However, when the reactor shuts down for maintenance or repair, the water level is lowered and an additional shielding agent is required. Thus, steel and cast steel were installed between the water walls.

The thickness of the water wall and other shielding materials was determined by the power of the reactor. The primary water wall was 93.5 cm, the secondary water wall was 10 cm, and the tertiary water wall was 68 cm for 100 MWt reactor core. Compared to the nuclear reactors of SAVANNAH, OTTO HAHN, and MUTSU, which had a secondary barrier on the outside of the containment vessel using iron and lead, the load of MRX could be lowered by 50~70%.

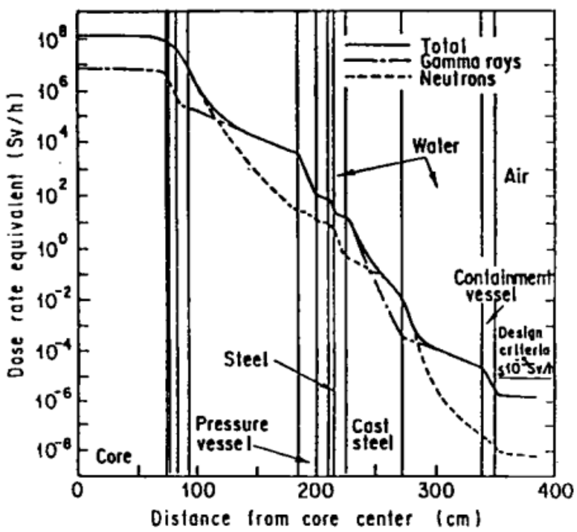

Fig. 5. ANISN calculation along radial directions of MRX

In addition, the radiation dose outside the continent vessel was reduced to 0.001mSv with the MRX shielding, which produced an excellent shielding. This value was 1/50 of the radiation dose in N.S. MUTSU.

5. Improved shielding method

When designing the nuclear reactor shield for ships considering the characteristics of the ship, the shielding method using water made an important contribution to reducing the weight of the shield, unlike the existing onshore nuclear reactor shielding configuration. However, considering the properties of the shielding body for shielding, water is effective in shielding neutrons, but it does not bring the best effect for overall shielding. In other words, although water was used to reduce the weight of the shield, the size (i.e. volume) of the shield would have been increased in order to secure the same shielding performance by using water, which has relatively low efficiency compared to other materials. This can be confirmed through the relaxation lengths (λ) indicating the shielding ability of the material.

Table. 1. Mixture shielding material of relaxation lengths

Material	Density [g/cm^3]	λ gamma [cm]	λ neutron [cm]	λ total [cm]
Fe	7.8	4.6	1.1	17
Pb	11.4	2.2	14	14
Typical ordinary Portland concrete	2.3	17	7-13	17
H_2O	1	39	2.8	39
Polyethylene	0.9	25	3	25

As shown in Table 1, it can be confirmed that water as a shielding agent should be thickened by about 2.3 to 2.7 times to achieve the same performance as iron or lead. Therefore, the shielding method of MRX used water instead of iron or lead to reduce the weight of the shielding material by about 50~70%, but it would have reduced the space utilization of the ship by increasing the size of the shielding body. However, economical utilization of space is as important as weight reduction for space-limited ships. Therefore, in order to shield the reactor, it is not preferable to use only water for the shielding to minimize volume.

Thus, the authors propose the following shielding materials to further improve the efficiency by mixing iron or lead with water and polyethylene containing hydrogen. The calculated relaxation lengths of the mixture shielding materials based on the reference [9] are the following:

Table. 2. Mixture shielding material of relaxation lengths

Material	Volume of metal [%]	λ gamma [cm]	λ neutron [cm]	λ total [cm]
Fe-Polyethylene	66	6.6	2	6.6
Fe-H_2O	61	6.8	2	7
Pb-Polyethylene	21	8.7	4	8.7
Pb-H_2O	71	9.6	4	9.6

As shown in Table 2, it can be confirmed that the shielding performance of the mixture is much better than single shielding material. If the mixed shielding materials are used as a shielding agent, the weight of the shielding will be reduced, and the space utilization efficiency can be improved by reducing the shielding volume.

6. Conclusions

Nuclear-powered ships have spatial and load restrictions compared to land-base nuclear power plants due to the characteristics of the ships. Therefore, a shielding concept meeting these limitations must be devised to successfully apply nuclear energy for ship propulsion.

A land-base nuclear power plant has relatively less space constraints and is not subjected to load constraints, so they use multiple layers of concrete walls to shield neutron and gamma rays from the core. In particular, gamma rays are shielded with high density and heavy elements in concrete, and neutrons are shielded with water in concrete.

In the early days of nuclear-powered ships, the primary shielding surrounding the pressure vessel and the secondary shielding outside the containment vessel were constructed with heavy concrete. The concept is similar to the shielding method of a land-base nuclear power plants. Due to this shielding method, the nuclear reactor facility of the nuclear-powered ship was considerably large, and the load of the nuclear reactor facility became heavy, and it was difficult to perform the original role of a cargo ship.

So the MRX (Marine Reactor X) reactor was devised to use water to shield the periphery of the reactor to make a more compact and lightweight nuclear-powered ship. It was possible to lower the load by 50~70%. It was effective nuclear reactor by lowering the radiation dose to 1/50 level of the previous nuclear reactors in ships.

However, as a result of reviewing the shielding performance of water mainly used for MRX through relaxation lengths(λ), it may be effective for neutron shielding, but overall shielding efficiency including gamma rays is inefficient compared to other shielding materials. In other words, the shielding method of MRX using water instead of heavy concrete to reduce the weight of the shielding material by about 50~70%, but increases the volume of the shielding body and reduces the space in a ship.

In conclusion, for the shielding of nuclear powered ships having space limitation, if a metal-water or metal-polyethylene mixed shielding material is used as a shielding agent, it is shown that the weight of the shielding agent will be reduced as well as the size of the shielding body potentially. This will lead to the reduction of the overall reactor compartment and effectively utilizing the space of the ship. As further study, more evaluation using neutron and photon transport analysis code will be followed to fully optimize the mixture's constituents and compositions.

REFERENCES

[1] John R.Lamarsh, Introduction to nuclear engineering 3Th, 2014
[2] Akio YAMAJI and SAKO, Shielding Dsign to obtain compact marine reactor, p.14-20
[3] Y.kawai and I.KATAOKA, Shielding experiment for the first nuclear ship in japan, p.170-171
[4] Y.G.Jaeger, Engineering Compendium on radiation shielding Volume 3, p.427-428
[5] 길영미, 김하용, 유병용, 우일국, 오영태, 김교윤, 선박용 원자로 차폐체의 재료 특성에 관한 연구
[6] 한국수력원자력㈜, 신고리 3, 4 호기 예비안전성분석 보고서(PSAR) 제 12 장 방사선 방호
[7] 한국수력원자력㈜, 신고리 5, 6 호기 예비안전성분석 보고서(PSAR) 제 12 장 방사선 방호
[8] IAEA, Safety Standards Design of the reactor containment and associated systems for nuclear power plants No. SSG-53