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COMPARATIVE STUDY OF NEUTRON SHIELDING MATERIALS USED FOR TRANSPORTABLE STORAGE CASK

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ABSTRUCT

Concerning gamma shielding materials used for a transportable storage cask, technical and economical comparison was performed at PATRAM 2010 between a single wall cask which uses carbon steel for gamma shielding, and multi-wall cask which uses lead for gamma shielding. As the next step of the comparison study, neutron shielding materials for the transportable storage cask are compared on both technical and economical viewpoints.
One of the main neutron sources in spent fuels is Cm-244 and Cm-242. The neutrons are produced at their decay process. The other one is fission neutrons, which are produced at fission reaction of fissile materials in the spent fuels. The former neutrons are acting as a primary source of the fission reaction. As generation of both Cm-244 and Cm-242 in the spent fuels increases by the involution of the fuel burn-up, neutron source intensity of high burn-up fuels becomes stronger. Moreover, the half life of Cm-244 is longer comparing to those of dominate gamma sources in the spent fuel, neutron source is sometimes main radiation source for the shielding design of the transportable storage cask, which will contains high burn-up and longer cooling time spent fuels comparing to a transport cask.
The typical neutron shielding materials used for the transportable storage cask are water and resin. Water is economical material and good for neutron shielding because it contains lots of hydrogen atom. However, careful consideration shall be paid against vapour pressure when water temperature becomes higher, which affect very much to structural design. Resin is solid and also contains lots of hydrogen atom. No consideration is necessary for pressure as water, but degradation by high temperature shall be considered during long storage period.
Assuming water and resin as the neutron shielding materials, comparative study is carried out on material property, the influence to the cask design and manufacture, and economy. To make the comparison simpler, forged steel mono-wall cask is selected in this study.

INTRODUCTION

Neutron shielding materials for a transportable storage cask (here after call “the cask”) are compared on both technical and economical viewpoints. A main neutron source in spent fuels is Cm-244 and Cm-242. The neutrons are produced at their decay process and fission reaction. The former neutrons are acting as a primary source of the fission neutron. As Cm-244 and Cm-242 in the spent fuels increases by a power of fuel burn-up, neutron source intensity of high burn-up fuels becomes stronger. The typical neutron shielding materials used for the cask are water and resin. Water is economical material and good for neutron shielding because it contains large number of hydrogen. Resin is solid and also contains large number of hydrogen. Assuming water and resin as typical neutron shielding materials, comparative study is carried out on material property, its influence to the cask design, and economy.

LAYOUT OF NEUTRON SHIELDING

The outline structure of a typical transportation cask is shown in Figure 1. The cask body consists of a inner shell and bolted closure lids with seals that form the containment boundary, a radiation shielding and outer shell. Spent fuels are contained in the cavity of the cask in a fuel basket to allocate the fuels to their individual positions to keep the cask sub-critical. Trunnions and shock absorbers are equipped on the outside of cask. Decay heat from the fuels is dissipated from cask surface to ambient through the basket and cask body. The cask is designed to conform to the regulatory requirements of each country, most of which are established based on the IAEA Regulation (TR-R-1) [1]. The main neutron shielding is usually allocated to the outer annulus part of the cask in order to save total weight of the cask as much as possible. In addition to the circumferential shielding, neutron shielding are sometimes allocated to top and bottom of the cask.

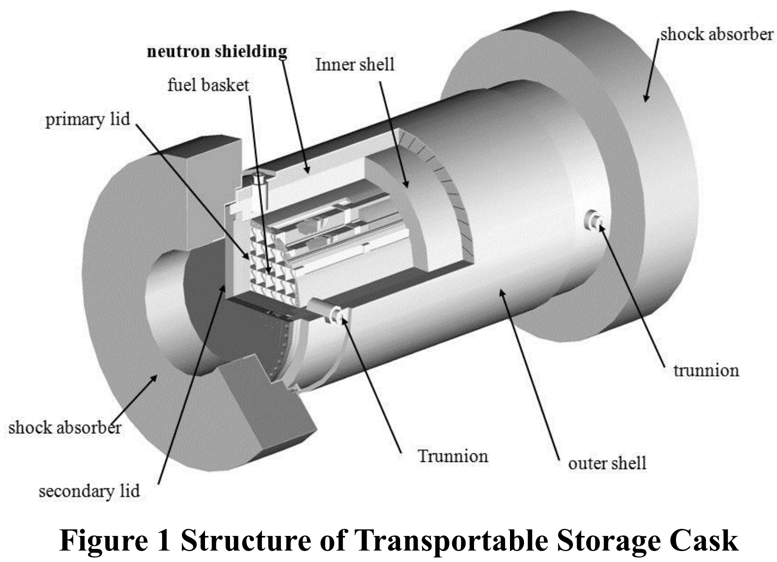

Figure 1 Structure of Transportable Storage Cask

PHYSICAL PROPERTIES OF NEUTRON SHIELDING MATERIALS

According to the IAEA Regulation, it requires attention to be given to freezing temperatures for liquid. To conform to the requirement, 55% of ethylene-glycol solution is assumed as typical water type of neutron shielding material (here after call "ethylene-glycol water"). The ethylene-glycol depresses the freezing point below -40ºC. NS4-FR is selected as a typical resin type of neutron shielding material. It is world widely known fire resistant neutron shielding material based on epoxy for use in moderately high temperature applications (hereafter call “NS4-FR”). NS4-FR is hardened a little at -40ºC. However, it is still solid and does not need any special consideration against above mentioned IAEA requirement. Physical properties of these two materials are compared in Table 1.

Table 1 Physical Properties (at 100ºC)

		ethylene-glycol water	NS4-FR	remarks
density	kg/m^3	1.01×10^3	1.67×10^3	
specific heat	kJ/kg·K	3.56	1.34	
solidify point	ºC	-46	solid	
coefficient of thermal expansion (at 100ºC)	1/ºK	8.03×10^{-4}	$1.18\times10^{-4*}$	*linear expansion
thermal conductivity	W/m·K	3.84×10^{-1}	9.8×10^{-1}	
coefficient of heat transfer by convection	W/m^2·K	640×10^3	-	Δt=20ºC
H-density	g/m^3	0.111	0.0959	
B4C density	g/m^3	0	0.0194	

Heat Transfer Characteristics

The thermal conductivity of both materials is rather small as shown in the table. However, heat transfer by natural convection is expected for ethylene-glycol water, which is a function of temperature difference at film layer. The heat transfer coefficient at 20ºC temperature difference is shown in table 1, which is larger than its conduction. On the other hand, NS4-FR is solid, and no heat transfer by convection can be expected, so that design idea is necessary to compensate its low heat conductivity.

Thermal Expansion

Coefficient of thermal expansion for ethylene-glycol water is more than twice larger than that of NS4-FR. As ethylene-glycol water is needed to contain in the vessel to keep necessary shielding thickness, pressure increase by compression and vapor pressure at the operating temperature shall be considered to the design of containment vessel. NS4-FR is solid so that necessary shielding thickness can be kept even if it is not contained in the vessel. No special design consideration is necessary against thermal expansion.

Hydrogen Density

Hydrogen is effective to neutron shielding. The atomic number density of hydrogen in ethylene-glycol water is higher than that of NS4-FR as shown in Table 2, so that the neutron shielding performance of ethylene-glycol water is basically better than that of NS4-FR. However, NS4-FR is a compound consists of several materials as shown in Table 2. These materials other than hydrogen, especially B-10 are also effective for neutron shielding. Attenuation of dose equivalent for both materials calculated based on typical cask structure is shown in Figure 2, which shows the shielding performance of both materials is equivalent.

Table 2 Atomic number density of ethylene-glycol water and NS4-FR (at 100ºC)

($\times 10^{24}$atoms/cm3)

	ethylene-glycol water	NS4-FR
H	6.23×10^{-2}	4.99×10^{-2}
B-10	-	1.20×10^{-4}
C	1.07×10^{-2}	2.20×10^{-2}
N	-	1.38×10^{-3}
O	2.58×10^{-2}	2.51×10^{-2}
Al	-	7.59×10^{-3}

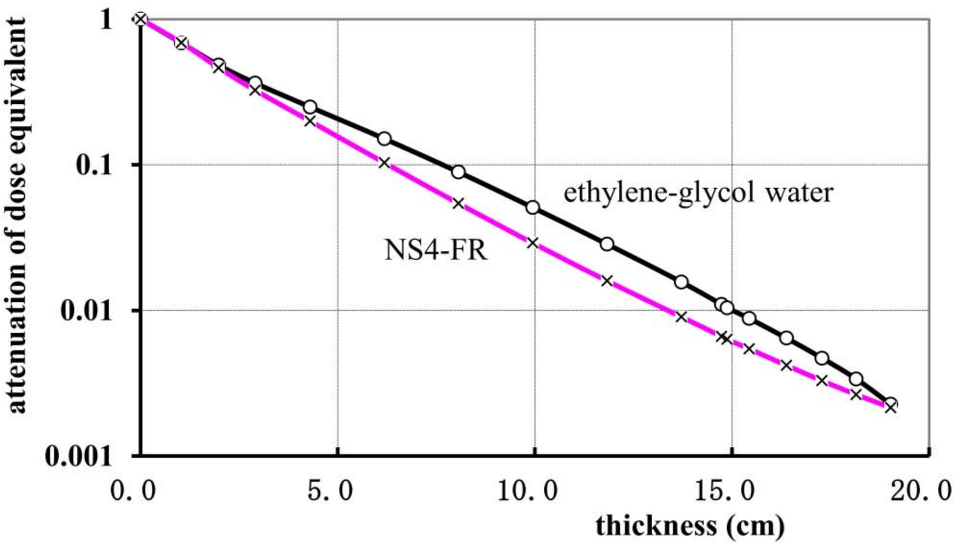

Figure 2 Attenuation of neutron dose equivalent

NEUTRON SHIELDING CONFIGURATION OF SPENT FUEL CASK

The main neutron shielding is usually allocated to the outer annulus part of the cask in order to save total weight of the cask as much as possible, which is shown in Figure 3. In addition to the circumferential shielding, neutron shielding is sometimes allocated to top and bottom of the cask. However, comparative discussion is focused to the circumferential shielding to make the discussion simple.

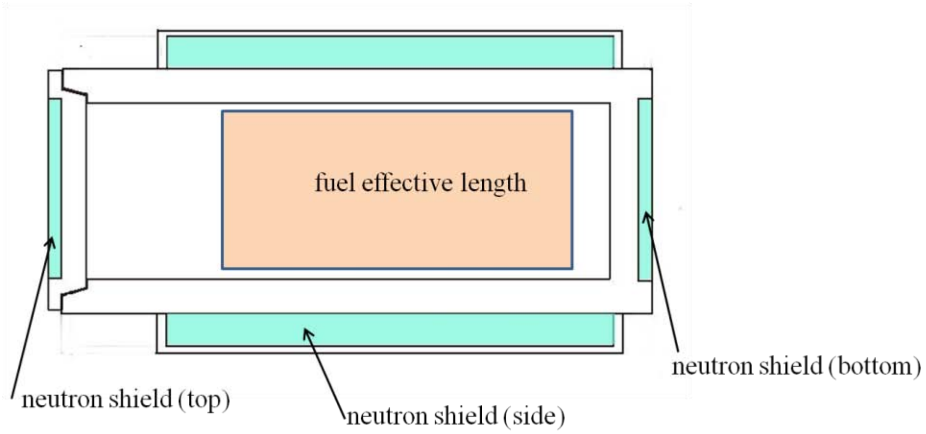

Figure 3 General configuration of main neutron shielding

<u>Configuration of Ethylene-glycol Water Neutron Shielding</u>

Ethylene-glycol is contained in the annular shielding tank. The tank is usually divided into two and sometimes three rooms. They are called, an expansion room, a shielding room and auxiliary expansion room, as shown in Figure 4. When temperature is rising after loading spent fuels into the cask, the expanded water is pushed into the expansion room through small holes located at the lower part of annulus tank in horizontal position. The holes are sealed by water in order that air does not enter into the shielding room. The rotation angle, α in the figure, at handling and transportation is limited to keep the water seal. The auxiliary expansion room is prepared for accident conditions. A rupture disk is equipped at the partition plate between the shielding room and the auxiliary room. The expansion and the auxiliary rooms occupy the space for trunnions that makes the design more complicate.

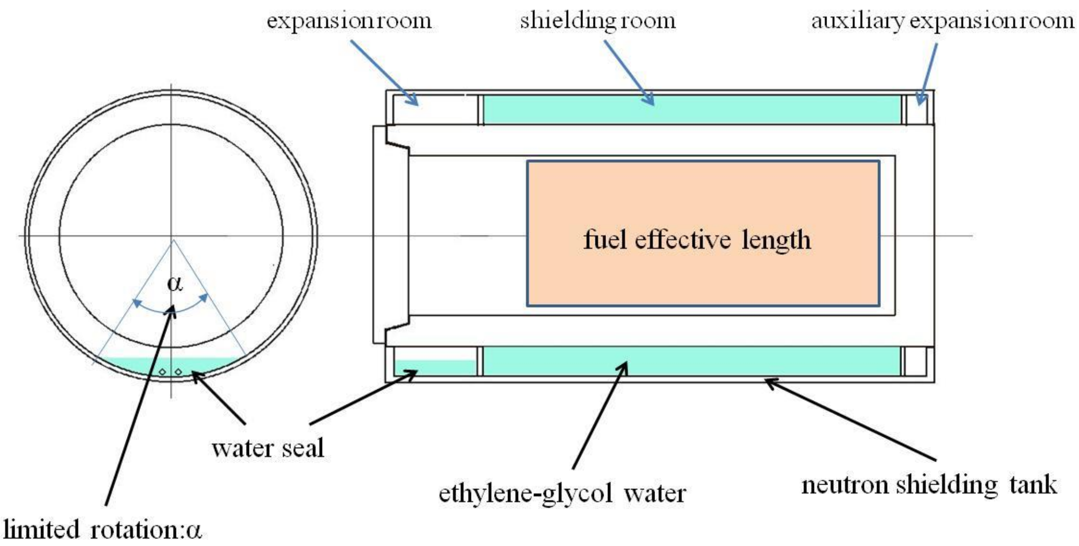

Figure 4 Structure of annular shielding tank for ethylene-glycol water

Configuration of NS4-FR Neutron Shielding

NS4-FR is allocated to the annual part of a cask as shown in Figure 5. An expansion room is also allocated, but it is less than half of expansion room for the ethylene-glycol water. No auxiliary expansion room is needed . This is a great advantage for the design of the casks, because it is easier to obtain the space for trunnions.

To secure heat removal path in the shield is the most important when NS4-FR is used for neutron shielding material. One of the solutions is to use inner fins. This is shown in Figure 6. The number of the fin and its thickness is determined by the heat load. The inner fins are welded to the inner shell and outer shell as shown in the figure.

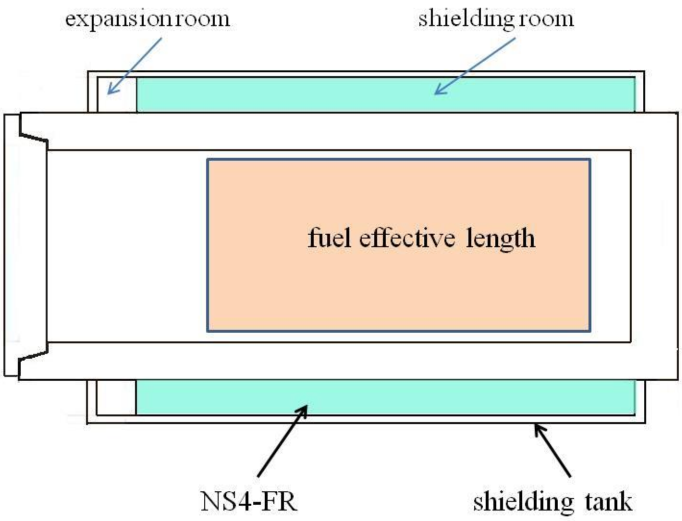

Figure 5 Structure of NS4-FR neutron shielding

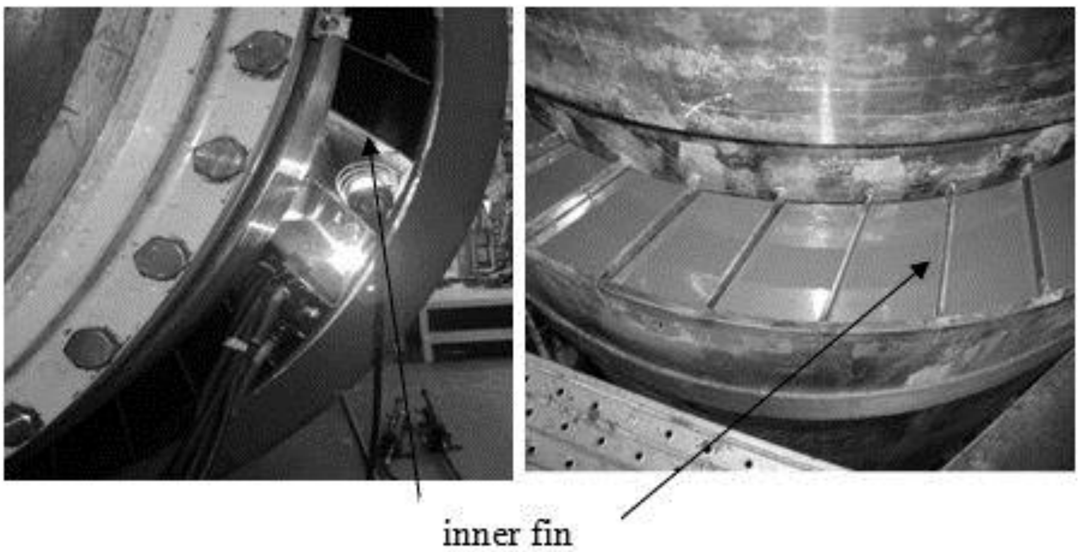

Figure 6 Inner fins

CONSIDERATION OF ECONOMY

Ethylene-glycol water is cheaper than NS4-FR. However, when ethylene-glycol is used for the neutron shielding, sophisticate and robust containment tank with expansion and auxiliary expansion rooms shall be designed. Required space for trunnions makes it more sophisticate not only design but fabrication. They increase the cost of a neutron shielding with ethylene-glycol water. On the other hand, design of neutron shielding with NS4-FR is simpler, even if it requires inner fin and complicate pouring work. If these are added to the material costs, it can be said that there is no significant cost difference between ethylene-glycol water shielding and NS4-FR shielding.

CONCLUSION

Comparative discussion between ethylene-glycol water neutron shielding and NS4-FR neutron shielding is summarized in Table 3. The superior part is shown in bold fonts in the table.

It can be said that NS4-FR neutron shielding is superior to ethylene-glycol water shielding. Week point of NS4-FR shielding is lower heat transfer performance, but it can be solved by design innovation.

In the case that the heat load from loaded spent fuels is higher, or the fuel surface temperature is required to keep lower for special purpose such as a post irradiation examination, ethylene-glycol should be adopted for heat transfer performance reason.

Table 3 Discussion summarized

discussion	ethylene-glycol water	NS4-FR
thermal expansion		
espansion space	large	**SMALL**
water seal	required	**NO**
required tank strength	robust	**NO**
heat transfer		
conduction	low	low
natural convection	**YES**	no
inner fins	**NO**	required
neuton shielding performance	even	
rotation during handling	limited	**NOT LIMITED**
economy	even	

REFERENCES

[1] IAEA Safety Standards, "Regulations for the Safe Transport of Radioactive Material 2009 Edition, Safety No. TS-R-1"