



Original Article

Comparison between NaI(Tl) and CsI(Tl) detectors in detection of flooded flexible risers using MCNP6

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Abstract: Flexible risers are multilayer pipes used in offshore oil production, combining flexibility and mechanical strength through several layers of different materials. Although designed to withstand severe operating conditions, loss of watertightness may occur, allowing seawater ingress that can lead to corrosion of metallic components, degradation of thermal insulation, and mechanical failure, ultimately compromising riser integrity and operational safety. Regular inspection is therefore essential to ensure facility's operation without riser's repair interruption. Gamma transmission is a promising technique for this purpose. This study proposes a methodology to detect seawater ingress using two NaI(Tl) scintillation detectors and compares its performance with an array of twenty-three CsI(Tl) scintillation detectors. The results showed excellent agreement between I/I_0 and seawater ingress percentage for both detector configurations. However, NaI(Tl) detectors presented approximately 25 times higher detection efficiency, leading to improved counting statistics, shorter acquisition time, or reduced source activity, depending on operational requirements. In addition, NaI(Tl) detectors enable gamma-ray spectrometry using simpler electronic instrumentation. The results were obtained by simulations with the MCNP computer code.

Keywords: MCNP; gamma transmission; flexible risers; NaI(Tl) detectors.



Comparação entre detectores NaI(Tl) e CsI(Tl) na detecção de alagamento em risers flexíveis utilizando MCNP6

Resumo: Os *risers* flexíveis são tubos multicamadas utilizados na produção de petróleo offshore, combinando flexibilidade e resistência mecânica através de diversas camadas de diferentes materiais. Embora projetados para suportar condições operacionais severas, podem apresentar perda de estanqueidade, permitindo a entrada de água do mar, o que pode levar à corrosão de componentes metálicos, degradação do isolamento térmico e falha mecânica, comprometendo, em última instância, a integridade do *riser* e a segurança operacional. Inspeções regulares são, portanto, essenciais para garantir a operação da instalação sem interrupções para reparos no *riser*. A transmissão gama é uma técnica promissora para esse fim. Este estudo propõe uma metodologia para detectar a entrada de água do mar utilizando dois detectores de cintilação de NaI(Tl) e compara seu desempenho com um conjunto de vinte e três detectores de cintilação de CsI(Tl). Os resultados mostraram excelente concordância entre a razão I/I_0 e a porcentagem de entrada de água do mar para ambas as configurações de detectores. No entanto, os detectores de NaI(Tl) apresentaram uma eficiência de detecção aproximadamente 25 vezes maior, resultando em melhores estatísticas de contagem, menor tempo de aquisição ou menor atividade da fonte, dependendo dos requisitos operacionais. Além disso, os detectores de NaI(Tl) permitem a espectrometria de raios gama usando instrumentação eletrônica mais simples. Os resultados foram obtidos por meio de simulações com o código computacional MCNP.

Palavras-chave: MCNP; transmissão gama; *risers* flexíveis; detectores de NaI(Tl).

1. INTRODUCTION

Flexible risers are critical components in offshore oil and gas production systems, designed to transport fluids between subsea installations and surface facilities. Their multilayered structure is typically composed of polymeric barriers, metallic armors, and insulation layers providing mechanical strength and fluid containment under harsh dynamic conditions according to the fluid transport specification [1]. Due to their flexibility and ability to accommodate vessel motions and seabed movements, they are widely employed in deepwater developments.

However, over time, these risers are subject to environmental and operational stresses such as pressure, temperature cycling, mechanical loading, and chemical exposure. One of the key integrity threats is seawater ingress, which refers to the penetration of seawater between the layers of the risers. This may occur through several mechanisms, including damage to the external sheath, failure of sealing systems at end fittings, delamination between polymer layers, or degradation of internal pressure barriers [2] [3].

The presence of seawater inside the riser structure can lead to corrosion of metallic reinforcements, loss of thermal insulation efficiency, and eventual mechanical failure. Therefore, understanding the causes and consequences of water ingress is essential for ensuring the long-term integrity and safe operation of flexible riser systems.

Due to the risers' high cost and, also, the possible financial loss due to plant shutdown, periodic inspections aimed at preventive maintenance are necessary.

Marinho et al. [4] describe a methodology that employs gamma-ray transmission based on an array of twenty-one CsI(Tl) detectors, sampling an elongated section of the gamma-ray flux. Each detector records the number of incident photons from a ^{137}Cs radiation source according to a preset energy window. It does not consider insulation layers for the risers and

there is no information on the detectors' dimensions, nevertheless, it is presented in another reference by the same author and, supposedly, the same detector as a 5x15x20 mm crystal [5].

This study presents a comparison of the expected results for two types of detectors, NaI(Tl) and CsI(Tl), for a typical riser structure, including the insulation layers. Because of the complexity of the riser's structure and the impossibility of determining the amount of water within the material layers, the MCNP computer code proved to be an asset for this comparison.

2. MATERIALS AND METHODS

The multilayered structure of a typical riser composed of, among others, insulation and metallic layers not evenly distributed, suggests that, for gamma-ray transmission measurements, two main regions are expected: one of lower attenuation (insulation layers) and another of higher attenuation (stainless-steel grid type layers) levels of the incident radiation.

Therefore, the methodology presented in this paper proposes two NaI(Tl) detectors, one for the insulation layers and another for the stainless-steel layers. A similar approach was used for the CsI(Tl) detectors, dividing the array into two subsets, which was considered more feasible for better results than the approach of Marinho et al. [4]. In addition to that, two more detectors, making a total of twenty-three, were used in this work to cover the same length as the two NaI(Tl) detectors for a fair comparison of the two types of detectors.

The two regions approach, higher and lower attenuation, is essential because the counts on the detectors aiming at the stainless-steel layers can be highly affected in case of seawater ingress in the insulation layers.

Even though there might be oil ingress in the inner stainless-steel layers; to minimize the variables and to simplify the results' analysis, seawater was considered in the simulation for both insulation and stainless-steel layers' water ingress.

2.1. The risers

Literature lacks comprehensive descriptions of risers due to industrial confidentiality and all the effort to get permission to use real data proved to be unfruitful. Therefore, based on general information compiled from various pieces and bits from online information and other sources, a generic riser's data was generated and is presented in Table 1.

Table 1: The generic riser's data generated for this work.

LAYER	MATERIAL	DENSITY (g/cm ³)	INNER RADIUS (cm)	THICKNESS (cm)
1	Stainless-steel 304	4.330	8.00	1.10
2	Nylon type 11	1.425	9.10	0.80
3	Stainless-steel 304	6.500	9.90	0.80
4	Nylon type 11	1.425	10.70	0.20
5	Stainless-steel 304	6.500	10.90	0.60
6	Nylon type 11	1.425	11.50	0.20
7	Stainless-steel 304	6.500	11.70	0.50
8	Polyethylene	0.930	12.20	0.10
9	Extruded Polypropylene	0.700	12.30	3.00
10	Nylon type 11	1.425	15.30	0.05
11	Extruded Polypropylene	0.700	15.35	3.00
12	Polyethylene	0.930	18.35	0.08
13	Polyethylene Terephthalate	1.380	18.43	1.00

Two distinct regions can be identified: insulation and stainless-steel layers. Due to the low density of the material, extruded polypropylene, used in two thick insulation layers, the attenuation is expected to be much smaller compared to the stainless-steel layers, with much higher density values. Therefore, these two regions were treated individually for transmission measurements purposes.

The maximum amount of seawater in each layer in case of seawater ingress is calculated based on the difference of densities between the nominal density (raw material)

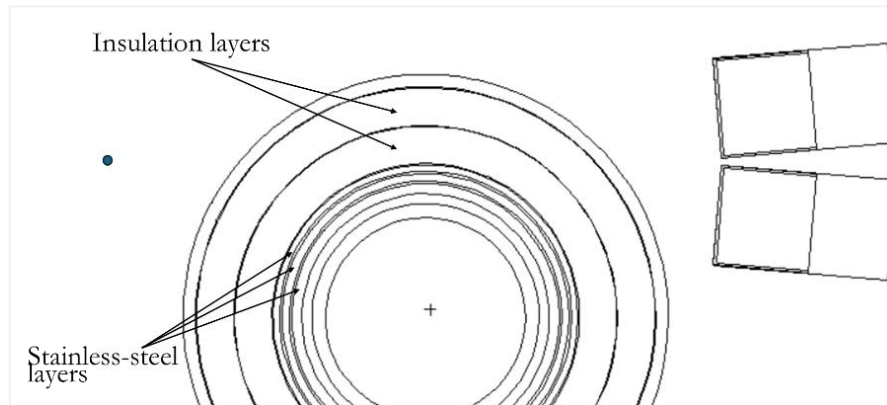
and the density for the layer of a given material (manufactured product). This approach estimates the space available within the layer which can accommodate seawater.

As an example, the nominal density of Polypropylene is 0.90 g/cm^3 [6]; the density considered for layers 9 and 11 is 0.70 g/cm^3 . The difference between the density values shows that there is room for the presence of seawater in a significant quantity, more precisely a total flooding of 22.2% in volume. The Polypropylene $(\text{C}_3\text{H}_6)_n$ is composed of 66.666...% H and 33.333...% C in number of atoms. Considering a flooding percentage of 25% of the total possible flooding, that is, 25% of the 22.2% of total flooding, the chemical composition becomes 66.6667% of H, 31.3545% of C and 1.9788% of O in number of atoms and density of 0.7568 g/cm^3 . The other elements present in seawater were not considered in the simulation due to their very low concentration.

2.2. NaI(Tl) detectors

The proposed configuration consists of two 3"x3" NaI(Tl) detectors. One detector faces the insulation layers and another the stainless-steel layers as shown in Figure 1. The proposed use of NaI(Tl) detectors is because of the possibility of performing gamma ray spectrometry and a much higher counting efficiency. The simulation considers the photon interactions within the active volume of the detector. The simulated detectors include the aluminum cover and the MgO layer covering the crystal; the photomultiplier tube was considered as an aluminum slab [7][8].

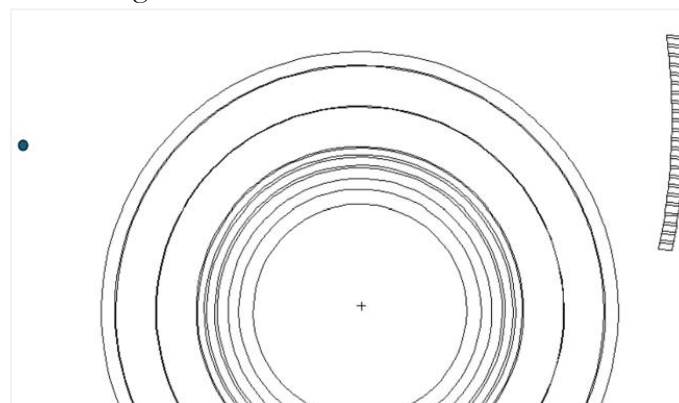
Figure 1: Simulation set up for seawater ingress in risers using NaI(Tl) detectors. The source is positioned at 12.45 cm high and 25.46 cm to the left of the center of the riser. The layers subject to flooding are indicated.



2.3. CsI(Tl) detectors

The detectors counting geometry consists of twenty-three CsI(Tl) detectors arranged orthogonally to the tube's axis, displaced to one side, as shown in Figure 2. Even though each detector was simulated individually, including the aluminum cover, the array was treated as two sets: the upper set, facing the insulation layers, composed of thirteen detectors; and the lower set, facing the stainless-steel layers, composed of ten detectors.

Figure 2: Simulation set up for seawater ingress in risers using CsI(Tl) detectors. The source is positioned at 12.45 cm high and 25.46 cm to the left of the center of the riser.



Because of the small individual volume and, consequently, the low detection efficiency, to simplify the simulation and, hence, diminish the computer time, these detectors were simulated as gamma-ray counters for the photons striking the face of the detector

exposed to the incidence of the radiation. This approach could be implemented because the measurement methodology is based on the I/I_0 ratio and the counting efficiency and other effects are canceled out. Another reason for this approach is that Marinho et al. [4] used a preset energy window as the detectors' output.

2.4. MCNP

The Monte Carlo method is broadly used for photon and particle transport [9][10][11]. It is a powerful tool for simulating radiation transport; it is very flexible and enables the analysis of a wide energy range. When applied together with a spectrometry system, Monte Carlo methods provide means to determine the detector's response function, optimizing both time and financial resources.

This work is a very good example as its use under difficult situation; the experimental set-up demands containment of the detectors and very large tanks to submerge the riser sample and the detector system in a watertight container. Apart from that, there is still the impossibility of determining the precise amount of water ingress.

Among the available Monte Carlo computer codes, the MCNP - Monte Carlo N-Particle Code, developed by the Los Alamos National Laboratory, has been widely used for all kinds of purposes involving radiation transport [12][13][14]. It is well documented, broadly validated, and the results obtained from its use are equally widely accepted if the calculation methodology applied is adequate [15].

The MCNP6 computer code was used to simulate the transport of gamma radiation within matter. The F8 tally was used to record the pulse height distributions (PHDs) for the NaI(Tl) detectors, while the F1 tally was used to record the number of photons crossing the front face of the CsI(Tl) detectors relative to the energy of 661.66 keV. The relative errors were kept below 0.5% by adjusting the number of photons.

Table 2 presents the nominal densities and the atomic compositions of the selected materials used to generate the riser for the simulations. The nominal densities refer to the raw material.

Table 2: Nominal densities and atomic compositions of the raw material used in the riser's manufacture [6].

MATERIAL	DENSITY (g/cm ³)	HEAD ATOMIC COMPOSITION	
		ELEMENT	FRACTION
Stainless steel 304	8.03	C	0.003635
		Mn	0.019870
		P	0.000793
		S	0.000511
		Si	0.019434
		Cr	0.199443
		Ni	0.088343
		Fe	0.667971
Nylon type 11	1.425	H	0.617647
		C	0.323529
		N	0.029412
		O	0.029412
Polyethylene	0.93	H	0.666667
		C	0.333333
Polyethylene Terephthalate	1.38	H	0.363636
		C	0.454545
		O	0.181818

The simulated radiation source consists of a point gamma ray source, positioned at 12.45 cm high and 25.46 cm to the left of the center of the riser, with an energy of 661.66 keV and a collimation angle of 20°.

The riser's layers subjected to flooding were simulated as a homogeneous mixture, considering the change in both density and chemical composition. This approach has been validated by Salinas et al. [16].

Another detector's feature which needed to be assessed was the detection efficiency for the counting geometry to evaluate their adequacy to the task. For this purpose, an adjusted set of simulations was performed for a better comparison of the detector types.

The simulation, in this case, featured the complete CsI(Tl) detectors, with all the details. For an adequate efficiency comparison, it was necessary to consider the photons interactions within the CsI(Tl) crystal and its response to the incident radiation.

To counterbalance for the small volume of the CsI(Tl) detectors, the source-detector system was simulated in vacuum. The source to detectors distances and positions were kept the same, but, for this comparison, there was no need for the riser and the water to be considered in the simulations if both were simulated under the same conditions.

For both detector types the outputs were recorded by the F8 tally - pulse height distributions (PHDs).

3. RESULTS AND DISCUSSIONS

Simulations were carried out for both detector types with partial and total seawater ingress of layers 9 and 11 (insulation layers), and layers 3, 5 and 7 (stainless-steel grid type layers). Layer 1 is also made of stainless steel, but it is in contact with the fluid being transported and is not in the pathway of the radiation from the source to the detectors.

At first, only the insulations layers were simulated with seawater and, afterwards, only the stainless-steel layers were simulated with seawater. This procedure was adopted because flooding in the insulation layers affects the measurements for the stainless-steel layers. This analysis is only possible because of the control over the amount and layers of flooding provided by Monte Carlo simulations.

The value for " I_0 " was determined by a complete simulation of all the components in the counting geometry without seawater ingress. Therefore, the ratio I/I_0 is 1 for 0%

of seawater ingress. The shielding effect of the material present in the counting geometry is cancelled out.

Figure 3 shows the value of I/I_0 for seawater ingress in the insulation layers as a function of the percentage of the seawater relative to the maximum possible amount of seawater ingress for the NaI(Tl) detector on the top. The adjustment of the data to a third-degree function leads to equation $y = -62.686x^3 + 347.6x^2 - 732.19x + 447.27$ with a correlation value of 1.

Figure 4 shows the value of I/I_0 for seawater ingress in the stainless-steel layers as a function of the percentage of the seawater relative to the maximum amount possible of seawater ingress for the NaI(Tl) detector on the bottom. The adjustment of the data to a linear function leads to equation $y = -1011.9x + 1012.1$ with a correlation value of 0.9998.

Figure 3: I/I_0 relationship for insulation layers flooding using NaI(Tl) detectors.

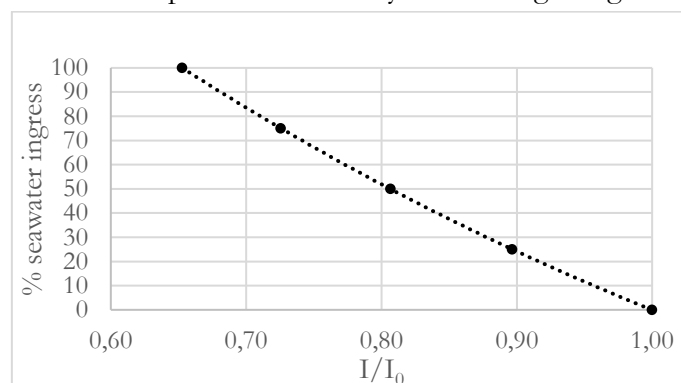


Figure 4: I/I_0 relationship for stainless-steel layers flooding using NaI(Tl) detectors.

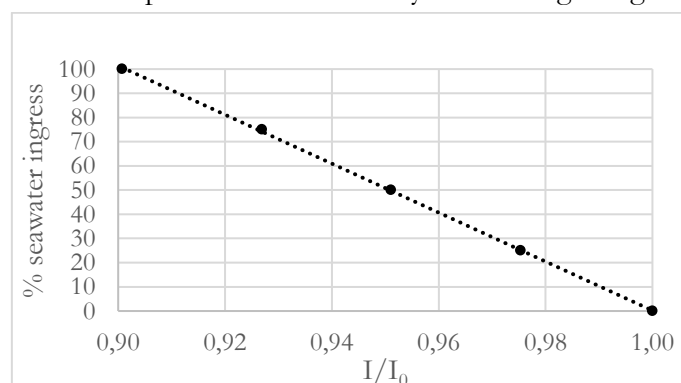


Figure 5 shows the value of I/I_0 for seawater ingress in the insulation layers as a function of the percentage of the seawater relative to the maximum possible amount of seawater ingress for the array of thirteen CsI(Tl) detectors on the top. The adjustment of the data to a third-degree function leads to equation $y = -125.13x^3 + 481.91x^2 - 819.71x + 462.92$ with a correlation value of 1.

Figure 6 shows the value of I/I_0 for seawater ingress in the stainless-steel layers as a function of the percentage of the seawater relative to the maximum amount possible of seawater ingress for the ten CsI(Tl) detectors on the bottom. The adjustment of the data to a linear function leads to equation $y = -990.94x + 991.75$ with a correlation value of 0.9993.

Figure 5: I/I_0 relationship for insulation layers flooding using CsI(Tl) detectors.

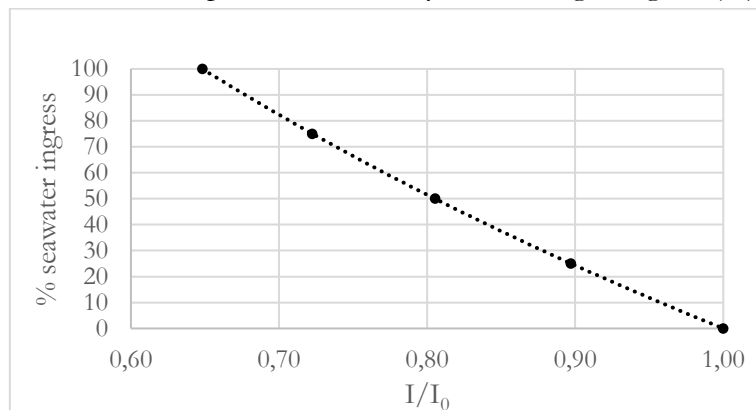
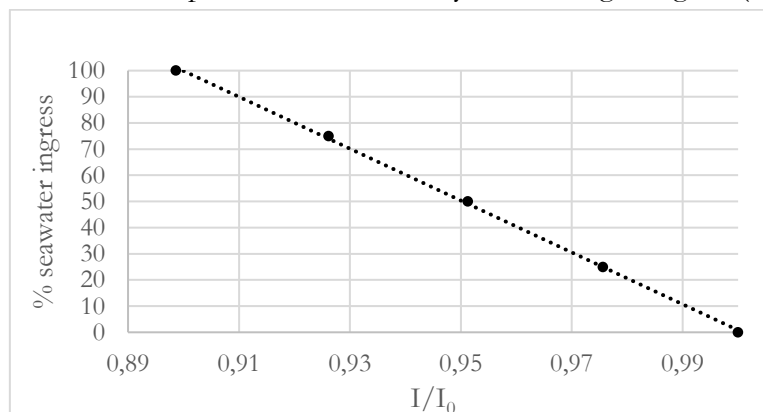


Figure 6: I/I_0 relationship for stainless-steel layers flooding using CsI(Tl) detectors.



Figures 3, 4, 5 and 6 show a very good curve fit for both detector types, that is, the relationship between I/I_0 versus seawater percentage are, as expected, equivalent.

Nevertheless, it is a completely different case when it comes to counting efficiency. A simulation of the source-detector system in vacuum for the same source-detector geometry has shown that the counting efficiency is about 25 times higher for the upper and lower NaI(Tl) detectors when compared to the upper and lower CsI(Tl) detector sets respectively. For this test, the crystals of the CsI(Tl) detectors were considered in the simulation and the efficiency refers to the gamma ray interaction within the crystal itself.

Therefore, working with the NaI(Tl) detectors would lead to either a lower activity of the ^{137}Cs source or lower counting time or, still, higher precision, depending on operational requirements.

It must also be considered that it is not uncommon to have the presence of radioactive scales in risers due to natural radioisotopes. The presence of the radioisotopes ^{208}Tl (2614 keV) and ^{214}Bi (1764 keV) will greatly interfere with the 661.66 keV energy counts due to Compton scattering. This is a major drawback to the methodology proposed with the CsI(Tl) detectors as they will record the number of incident photons, that is, total counts with a threshold of $\pm 15\%$ of ^{137}Cs peak's energy as described by Marinho et al. [4].

In this scenario, the use of two NaI(Tl) detectors will enable gamma ray spectrometry, and the influence of higher energies can be accounted for by Compton scattering subtraction in the 661.66 keV energy photopeak region.

4. CONCLUSIONS

The use of two NaI(Tl) detectors can highly improve the analysis results for seawater ingress evaluation in risers and greatly simplify the detection system compared to an array of twenty-three CsI(Tl) detectors.

The 25 times higher detection efficiency of the NaI(Tl) detectors, when compared to CsI(Tl) detectors, leads to higher precision on the I/I_0 ratio.

The possibility of performing gamma ray spectrometry enables the identification and quantification of the contribution on the 661.66 keV energy region due to Compton interactions of higher-energy photons from other radioisotopes, enabling the analysis in the presence of radioactive scales, which would be impossible otherwise.

The data show that, as expected, the smaller the amount of seawater, the smaller the difference between I_0 and I , resulting in greater difficulties in identifying small percentage of seawater ingress.

Flooding in the insulation layers will affect significantly the results for the stainless-steel layers, but not the other way around. Therefore, in cases of flooding of the insulation layers, the results for the stainless-steel layers must be considered with great care or even completely disregarded.

As a suggestion for future works, the use of artificial neural networks can improve the analysis results and, even, the possibility of getting good results for stainless-steel layers in case of insulation layers flooding.

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CONFLICT OF INTEREST

All authors declare that they have no conflicts of interest.

DATA AVAILABILITY STATEMENT

The authors declare that the data supporting the results of this study and the derived data supporting the conclusions of this study are available upon reasonable request to the corresponding author.

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