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Studying the Impact of a Nuclear-Powered Naval Ship Severe Accident on Aquatic Biota using Resrad Code

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Abstract: Naval ships are designed to function under very difficult circumstances. The most common cases of nuclear ship incidents/accidents are collisions, problems with the nuclear power reactor, groundings, fires and explosions as well as leaks in the sea-water systems of submarines. Accidental release to air caused by criticality or core melt is considered a real radiological hazard. This study consists of two parts; first part aims at estimating the core inventory of the suggested accident due to melting of nuclear fuel in the ship's power reactor using a Radiological Assessment System for Consequence Analysis (RASCAL) code. The behavior control of accidental released radionuclides on surface water body was calculated using mathematical equation. The radionuclides concentrations which have been evaluated in the marine environment are ^{241}Am, ^{239}Pu, ^{137}Cs, ^{90}Sr, and ^{13}1I. In the second part: The aquatic biota dose rate was evaluated using the RESRAD-BIOTA code. The radiological impact assessment of accidental releases of ^{90}Sr and ^{137}Cs to marine biota was found to be high. It is higher than International Commission on Radiation Protection (ICRP) dose limit by a factor about 10^3 for 100 m and by factor ten over the 4 km from the release point. Also, the radiological impact of accidental release of ^{131}I to marine biota increases by factor 10^4 at 100 m and by factor ten for 4 km from release point.

Keywords: -Nuclear powered ship incidents/accidents, Biota, Radiation dose assessment, naval ship, and nuclear accident.

1 Introduction

Nuclear power ships are progressively becoming more popular in advancing ship technology, where those are using reactors have lower fuel costs and last for many years and have almost zero [1].

The accidents related to nuclear ships include; collisions, groundings, sinking, leaks in sea-water systems, fires or explosions problems with the nuclear power reactor, and serious radiation exposures [2].

Regarding accidents involving the nuclear propulsion plant in nuclear naval ship, the Loss of Coolant Accidents (LOCAs) and criticality are of the interest. For Russian nuclear Navy, there have been 6-LOCAs and 5-criticalities [3].

Little radioactivity was detected in Atlantic Ocean water due to LOCA in a Soviet Echo-II class submarine, 1989 [2].

The exposure of aquatic biota to radiation from accidental releases of radionuclides is considered a real radiological Hazard [4].

Radiation from radionuclides released as a result of the Chernobyl accident caused numerous acute adverse effects on the biota located at a distance of a few tens of kilometers from the release point [5]. For example, In Sweden, fish with up to 4.8 X 10^4 Bq/kg, where the maximum permitted concentrations of 137-Cs in food products is 300 Bq/kg fresh weight [6]. Aquatic organisms are no more sensitive than other organisms; Embryo development in fish and the process of gametogenesis appear to be the most radiosensitive stages of all aquatic organisms tested [7].

This work aims at studying the effect of radiological release from a hypothetical nuclear naval ship accident on aquatic biota as a result of core melt. Sever accident scenario was assumed. Core inventory due to the accident calculated using RASCAL code. RASCAL is a Radiological Assessment System for Consequence Analysis. It is software developed and used by the U. S. Nuclear

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Regulatory Commission (NRC). Then applied an equation (1) the longitudinal dispersion of radionuclides to calculate activity concentrations at various distances down-current. Finally, these values have been used as input to, RESRAD Biota -code to calculate, the dose-rates for aquatic biota. The RESRAD-BIOTA code provides a complete spectrum of biota dose evaluation capabilities, from methods for general screening, to comprehensive receptor-specific dose estimation.

2 Materials and Method

A postulated core meltdown caused by a loss of coolant accident in a nuclear power ship Pressurized Water Reactor (PWR) was considered with power 200 MW. It was assumed that the reactor was operating at full power during passing through a water body "Channel body". RASCAL code is used to calculate the core inventory due to core melting. RASCAL is a Radiological Assessment System for Consequence Analysis. It is software developed and used by the U. S. Nuclear Regulatory Commission (NRC). RASCAL consists of two main tools: The Source Term to Dose model and the Field Measurement to Dose model. RASCAL adjusts the inventory of radionuclides that have a half-life exceeding one year to account for peak-rod burnup [8]. Radionuclide core inventory using RASCAL code was presented in Table 1. Controlling the behavior of the longitudinal dispersion of accidental released radionuclides in surface water bodies is determined using the following mathematical equation [9].

$$C_{(x,t)} = \frac{C_o}{WH\sqrt{4\pi K_{lt}}} exp^{\left[-\frac{(x-vt)^2}{4K_l} - \lambda t\right]} \qquad (1)$$

Where:

C_o is the initial concentration of the respective radionuclide (Bq), from RASCAL code result

λ is the radioactive decay = $\ln 2/t_{1/2}$

W is the mean width of the water body (m),

H is the mean depth of the water body (m),

v is the shear velocity (ms-1)

K: Longitudinal dispersion coefficient m^2/s

x: Release distance (m)

Mainly radionuclides concentration, which have been evaluated in the marine environment using equation (1) are ^{241}Am, ^{239}Pu, ^{137}Cs, ^{90}Sr, and ^{131}I. The calculation obtained at certain time for deferent release distances. The radionuclide concentration for ^{131}I, ^{137}Cs, ^{90}Sr, ^{241}Am and ^{239}Pu in water at different distances from release point are the input RESRAD-BIOTA code.

The code was designed to be consistent with and provide a tool for implementing the "Graded Approach for Evaluating Radiation Doses to Aquatic and Terrestrial Biota". The RSRAD-BIOTA code is a tool for implementing a graded approach to biota dose evaluation. Each level corresponds to a specific step of the graded approach. Level 1 corresponds to Step 2, General Screening; Level 2 corresponds to Step 3a, Site-Specific Screening; and Level 3 corresponds to Step 3b, Site-Specific Analysis [10]. Figure 1 represents RESRAD-BIOTA Levels of Analysis Corresponding to the Graded Approach. External and internal dose rates due to the input radionuclides for aquatic animal, Riparian animal and fish are the code output.

Table 1: Radionuclide core inventory using RASCAL code:

^{88}Kr	2.88×10^{6}	133Xe	6.83×10^{6}
^{89}Sr	6.92×10^{6}	135Xe	8.30×10^{5}
^{90}Sr	2.99×10^{5}	134Cs	8.31×10^{5}
^{95}Zr	9.50×10^{6}	137Cs	3.12×10^{5}
^{97}Zr	5.90×10^{6}	140Ba	7.35×10^{6}
^{95}Nb	1.02×10^{7}	140La	8.07×10^{6}
^{97}Nb	6.09×10^{6}	141Ce	8.02×10^{6}
^{99}Mo	6.26×10^{6}	144Ce	6.13×10^{6}
^{99}Tc	5.53×10^{6}	156Eu	1.91×10^{6}
^{103}Ru	4.56×10^{6}	157Eu	1.91×10^{6}
^{106}Ru	4.39×10^{5}	239Np	1.58×10^{6}
^{132}Te	4.44×10^{6}	239Pu	1.23x10
^{131}I	3.01×10^{6}	241Am	8.24×10^{-1}

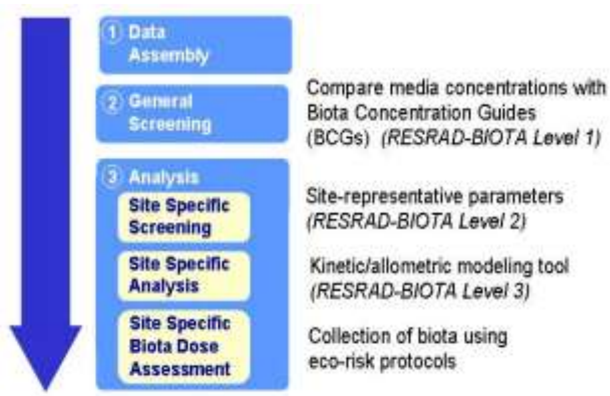

Fig.1: RESRAD-BIOTA Levels of Analysis Corresponding to the Graded Approach.

3 Results and Discussion

Figure 2 represents the radionuclides concentration in water body at different distances up to 16 Km from the release point. Radionuclides concentrations are decreasing by a factor of approximately 10^3 over the 16 km from the release point. The highest concentration was the short half-life ^{131}I. In the first 7-days, radiation exposures were essentially acute because of the large quantities of short-lived radionuclide ^{131}I (Its half-life about 8 days), which after one month had been largely disappeared. There is no significant concentration for ^{241}Am, but ^{137}Cs-, ^{90}Sr and ^{239}Pu have been the dominant radionuclides.

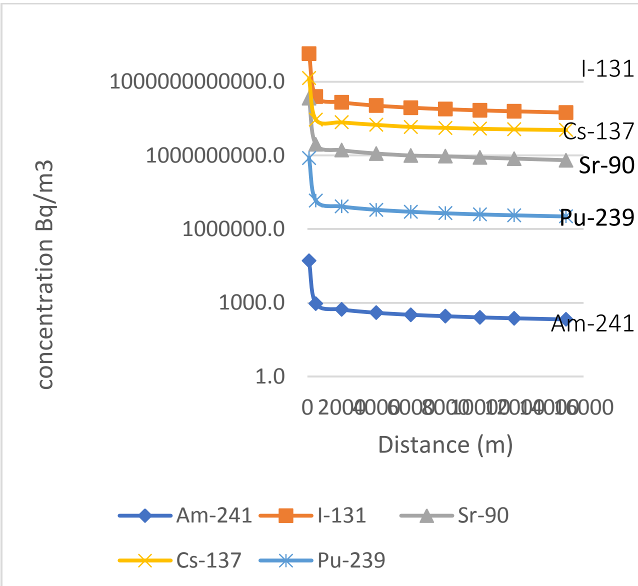

Fig. 2: Radionuclides concentrations with distance.

The RESRAD Aquatic Biota (Aquatic animals, Riparian animals and fish) output dose rates (external and internal) are represented in the Table 2 at different distances up to four kilometers from the release point. It is obvious internal high dose rate from ^{131}I and ^{137}Cs at distance 100m from the release point. This dose rate would cause significant effect in most organisms on a timescale of minutes. It is shown that, the dose rate decreases by about factor 10^2 for whole radionuclide at distance 4 km from the release point. For external or internal dose, there are no significant effects from ^{241}Am. Its released into water from nuclear facilities will tend to stick to particles in the water or the sediment. Ultimately, most americium ends up in soil or sediment. fish may take up ^{241}Am, the amount that builds up in the flesh is very small [11]. For ^{131}I 4-weeks aftermath the accident there is no significant effect due to its short half live time. The principal focus was for long-lived radionuclides such as ^{137}Cs, ^{239}Pu and ^{90}Sr isotopes. Figure 3 represents the behavior of ^{131}I concentration for water speed value 0.5 m s^{-1} and 1m s^{-1}. It is obvious that radionuclide concentration decreases about its half value when the water speed increases to its double value.

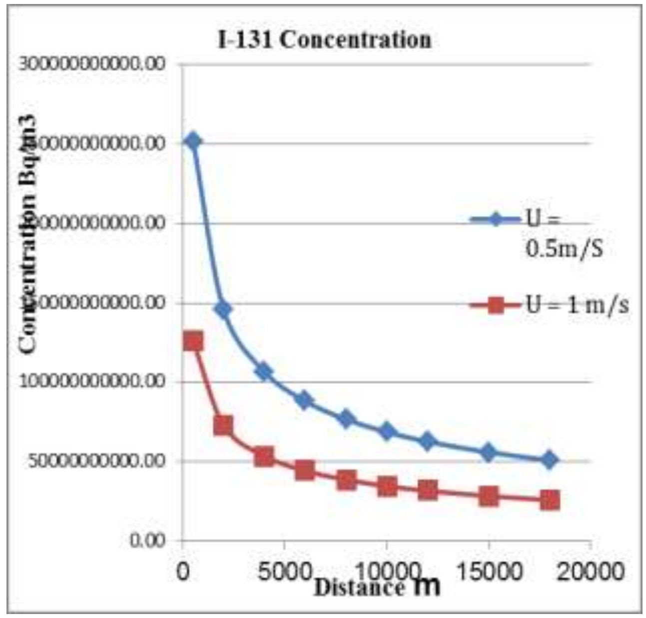

Fig. 3: I-131 concentration with distance for two different water speeds.

Figures 3 illustrate the calculated internal dose rate for different aquatic biota due to each radioisotope. The maximum internal dose rate is 3.6x10^5 Gy d^{-1} due to ^{137}Cs. It is eight times greater than generic dose rate according to United Nations Scientific Committee on the Effects of Atomic Radiation Sources and Effects of ionizing radiation ((UNSCEAR), which is 10 mGy d^{-1}/) [12]. Where the external dose rates for fish and aquatic animals from ^{137}Csand ^{90}Sr are about 79 mGy d^{-1} and 12 mGy d^{-1} respectively at distance 2 km from the release point. This is due to the complex interaction of radioisotopes chemical properties with the chemical, physical and biological process of aquatic environment. It can also, leading to non-uniform distribution of the radioactivity input to the aquatic environment [13]. There is an acute internal dose rate result from contamination with ^{137}Cs, ^{90}Sr and ^{239}Pu greater than generic dose by factor 10^3. The International Commission on Radiological Protection (ICRP) has proposed a 'derived consideration reference level' of (0.1-1m Gyd^{-1}) for the most sensitive Reference Animals and Plants (RAPs) [14]. Fish are more radiosensitive than other aquatic biota and proposed to a reference dose rate of about1.6 mGy d^{-1} [15]. The Department of Energy (DOE) adopt a dose rates corresponding to expected safe levels of (populations exposure) of biota based on reviews of the acute and chronic radiation exposure effects. The expected safe levels were a dose rate of 10 mGy d^{-1} to populations of aquatic animals, 10 mGy d^{-1} to populations of terrestrial plants and 1.0 mGy d^{-1} to populations of terrestrial animals [12]. The DOE indicated that, the population should be protected if the dose rate does not exceed the expected safe dose rate to the most individual population exposed [16]. ICRP suggested that, some reductions in reproductive capacity might occur in frogs and possibly in fish species, for a range of 1–10 mGy d^{-1} dose rates. It had been concluded that significant effects on fish gonads from chronic radiation exposure would be unlikely at dose rates less than 24 mGyd^{-1} [17, 18]. The dose rates to fish depended on their trophic positions. In general, radionuclide levels in marine water returned to pre-accident values within a few months after the accident. This is mainly due to dilution with non-contaminated water and also to convection processes that have efficiently transported the radionuclide to depth [19]. During fish migration, radioactive cesium will decline when fish leaves contaminated waters. Cesium will gradually be excreted, as it is not bound to the body. The biological half-life of cesium in sea fish is typically between 5 to 100 days [20, 21].

Table 2: RESRAD aquatic biota output dose rate:

Distance (m)	Nuclide	Aquatic animal Dose Gy/d	
		Water dose	
		External	**Internal**
100	^{241}Am	2.01x10^{-8}	3.11x10^{-2}
	^{137}Cs	7.67	3.61x10^{5}
	^{131}I	5.52x10	2.41x10^{4}
	^{239}Pu	3.04x10^{-7}	1.15x10
	^{90}Sr	1.65	1.06x10^{3}
		Riparian Animal	
	^{241}Am	2.01x10^{-8}	9.32x10^{-4}
	^{137}Cs	7.67x10	8.86x10^{5}
	^{131}I	5.52x10	2.73x10^{4}
	^{239}Pu	3.04x10^{-7}	3.44x10^{-1}
	^{90}Sr	1.65	2.05x10^{4}
		Fish	
	^{241}Am	2.01x10^{-8}	3.11x10^{-2}
	^{137}Cs	7.67	3.61x10^{5}
	^{131}I	5.52x10	2.41x10^{4}
	^{239}Pu	3.04x10^{-7}	1.15x10
	^{90}Sr	1.65	1.06x10^{3}
500	**Aquatic animal Dose Gy/d**		
	^{241}Am	3.63x10^{-10}	5.63x10^{-4}
	^{137}Cs	1.56x10^{-1}	7.33x10^{3}
	^{131}I	5.52x10	2.41x10^{4}
	^{239}Pu	5.48x10^{-7}	2.07x10
	^{90}Sr	1.65x10	1.06x10^{3}
		Riparian Animal	
	^{241}Am	3.63x10^{-10}	1.69x10^{-5}
	^{137}Cs	1.56x10^{-1}	1.80x10^{4}
	^{131}I	5.52x10	2.73x10 4
	^{239}Pu	5.48x10^{-7}	6.21x10^{-1}
	^{90}Sr	1.65	2.05x10^{4}
		Fish	
	^{241}Am	3.63x10^{-10}	5.63x10^{-4}
	^{137}Cs	1.56x10^{-1}	7.33x10^{3}
	^{131}I	5.52x10	2.41x10^{4}
	^{239}Pu	5.48x10^{-7}	2.07x10
	^{90}Sr	1.65	1.06x10^{3}
2,000	**Aquatic animal Dose Gy/d**		
	^{241}Am	2.11x10^{-10}	3.27x10^{-4}
	^{137}Cs	7.95x10^{-2}	3.74x10^{3}
	^{131}I	5.80x10^{-1}	2.53x10^{2}
	^{239}Pu	3.19x10^{-7}	1.20x10
	^{90}Sr	1.27x10^{-2}	8.16
	Riparian Animal		
	^{241}Am	2.11x10^{-10}	9.78x10^{-6}
	^{137}Cs	7.95x10^{-2}	9.18x10^{3}
	^{131}I	5.80x10^{-1}	2.86x10^{2}
	^{239}Pu	3.19x10^{-7}	3.61x10^{-1}
	^{90}Sr	2.11x10^{-10}	1.58x10^{2}
	Fish		
	^{241}Am	2.11x10^{-10}	3.27x10^{-4}
	^{137}Cs	7.95x10^{-2}	3.74x10^{3}
	^{131}I	5.80x10^{-1}	2.53x10^{2}
	^{239}Pu	3.19x10^{-7}	1.20x10
4,000	**Aquatic animal Dose Gy/d**		
	^{241}Am	1.55x10^{-10}	2.40x10^{-4}
	^{137}Cs	5.92x10^{-2}	2.79x10^{3}
	^{131}I	4.25x10^{-1}	1.86x10^{2}
	^{239}Pu	2.34x10^{-7}	8.84
	^{90}Sr	9.39x10^{-4}	6.00x10^{-1}
	Riparian Animal		
	^{241}Am	1.55x10^{-10}	7.20x10^{-6}
	^{137}Cs	5.92x10^{-2}	6.84x10^{3}
	^{131}I	4.25x10^{-1}	2.10x10^{2}
	^{239}Pu	2.34x10^{-7}	2.65x10^{-1}
	^{90}Sr	9.39x10^{-4}	1.16x10
	Fish		
	^{241}Am	1.55x10^{-10}	2.40x10^{-4}
	^{137}Cs	5.92x10^{-2}	2.79x10^{3}
	^{131}I	4.25x10^{-1}	1.86x10^{2}
	^{239}Pu	2.34E-07	8.84
	^{90}Sr	9.39x10^{-4}	6.00x10^{-1}

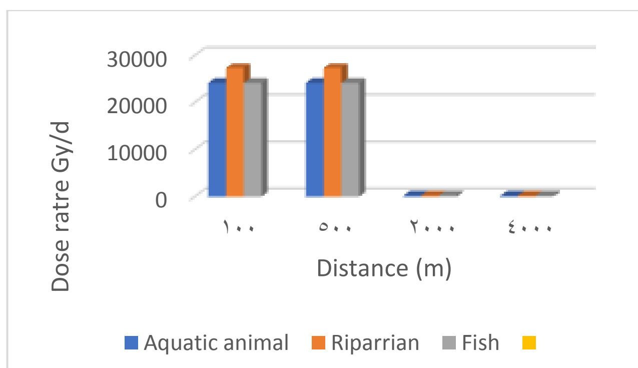

Fig.4: The internal dose rate with distances for the aquatic biota due to I-131**.**

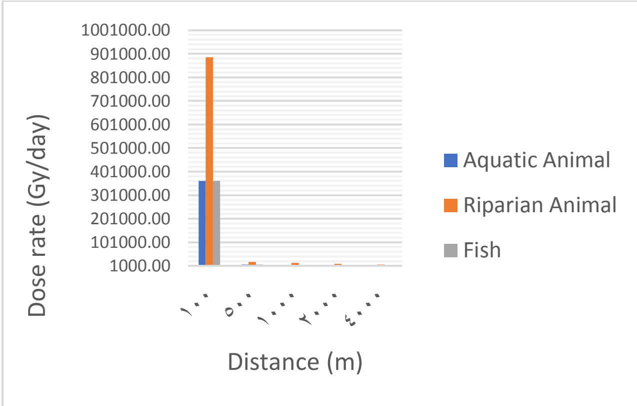

Fig. 5: Internal dose rate with distances for the aquatic biota due to Cs-137.

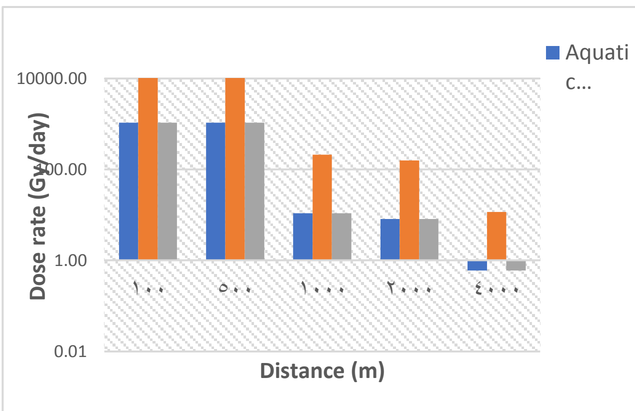

Fig. 6: Internal dose rate with distances for the aquatic biota due to Sr-90**.**

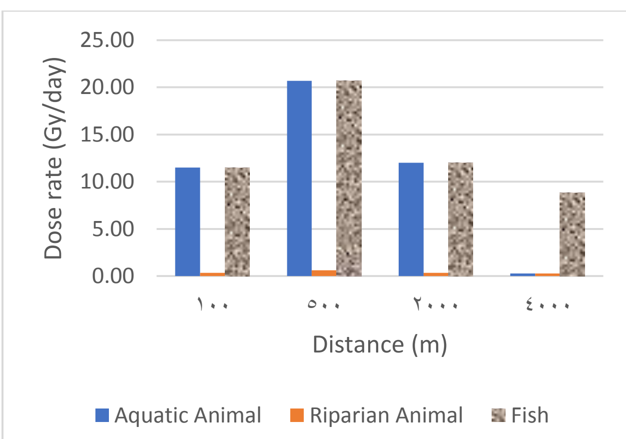

Fig.7: Internal dose rate with distances for the aquatic biota due to Pu-239.

4 Conclusion and Recommendations

This study discusses the impact of a nuclear-powered naval ship sever accident on marine biota. The most effects on aquatic biota were found at the 100 m from the release point. The maximum dose rates to aquatic organisms (excluding fish) were found in the first two weeks aftermath the accident. This is due to ^{131}I dose contribution that disappeared largely after one month. No expectation to long-term impact from ^{131}I because of it is rapidly decay and is not expected to be transported over long distances by marine water currents. The longer half - lives ^{137}Cs, ^{90}Sr and ^{239}Pu have been the dominant radionuclides and could be transported over long distances by marine water currents. It is concluded that, based on the water body's current speed, the diffusion and dilution of radionuclides activity concentrations will be affected, the radiation levels may be returned to the pre-accident levels after few months depending on the contamination levels. The great quantity of water, as well as, the increasing of water speed will rapidly disperse and mitigate the existence of radioactive materials to the pre-accident levels. Therefore, the severity of the impact of the accident in the ocean or the sea differs from that of the canals, where low speed water. Accident where the water speed is low the pre-accident return will be taken more time. Emergency protective measures are needed for the first 4Km. Regular sampling of seawater at 2, 4 and 16Km must be taken as well as monitoring for the presence of ^{131}I, ^{137}Cs, ^{239}Pu and ^{90}Sr in local seafood. It is important to enhance the preparedness and response to nuclear and radiological emergencies in the coastal ports and sea. When the coastal state which an emergency has occurred and has not the enough capabilities to assess the impact of the accident for taking the decisions on protective and other response actions, should request the necessary information, advice and assessments from the Consignor or other IAEA Member States [22].

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