A probabilistic model of environmental safety of ship power plant

Roman Liberacki, M.Sc., Eng.

ABSTRACT

In the paper a probabilistic model of environmental risk of ship power plant is presented. This is a linear strategy model with an additional restraint. It can be used for assessing risk to marine environment, which results from ship power plant operation. The risk is a sum of component probabilities of exceedance of the limits assigned - by MARPOL convention - to particular kinds of pollution discharged from ships, multiplied by weight factors. The factors determine a degree of harmfulness of a discharge for the environment. The restraint concerns the case of exceedance of the limits assumed unacceptable by the convention. A risk value is be contained within (0,1) interval. Moreover a criterion for environmental safety of ship power plant was propsed. This is the criterion of the ALARP class, in which an intolerable risk level and acceptable one is distinguished. Suggestions concerning determination of the levels are submitted.The considerations are illustrated by results of example computer investigations of influence of reliability of technical elements of the systems responsible for environmental safety of a hypothetical ship power plant on environmental risk value. Three qualification levels of ship's crew were accounted for : high, average and low.

Keywords : environment protection, environment safety, risk, reliability, ship power plant

INTRODUCTION

Ships are technical objects which produce serious hazards to the seas and atmosphere. Importance of the problem is supported by the fact of establishment of IMO MEPC Committee which deals with problems of pollution from ships to the seas. It has been estimated that maritime economy and shipping share in 20% in total pollution amount discharged to the marine environment [3].

When analyzing safety of a technical object one assumes that the object is a component of the man-technology-environment system, and that losses which may be generated by the object within the system, are considered. The losses are unavoidable, however one can influence a level of risk of their appearance. It should be reduced to a size which one would be willing to tolerate or even to accept [1]. Different safety criteria which define permissible risk levels for different categories of losses, are proposed. It also concerns the ships and risk involved to the marine environment. The risk mainly arises due to harmful substances released from ships to the seas and atmosphere. It is obvious that environmental safety of a ship should be shaped when designing the ship. During its operation it can be only maintained at a certain level or corrected.

International conventions adopted by IMO and ratified by member states, as well as other legal instruments of a lower rank impose definite limits upon harmful substances discharged from ships. They impose necessity of installing special anti-pollution devices and complying with appropriate procedures of action to be undertaken by ship crews. The main legal instrument in this respect is the 73/78 MARPOL Convention [11].

Norway is especially active in the area of marine environment safety. This state elaborated a procedure called Environmental Indexing of Ships, submitted to IMO and implemented in the waters of its state responsibility [9]. The procedure makes different kinds of dues paid by a ship, dependent on pollution-preventing systems installed on it.

Both the requirements of the MARPOL Convention and the Norwegian procedure have one important drawback: they do not account for a random nature of risk created by ships to marine environment. The pollution-preventing systems are anthropotechnical, and their technical and human components have definite reliability. The fact that a ship is equipped with devices complying with the standards imposed by the Convention does not show itself that the standards are also fulfilled during ship's operation because the devices can be unserviceable, wrongly used or simply switched off. Therefore a proposal is to supplement the deterministic requirements with probabilistic methods for assessing reliability and environmental risk of ships. The probabilistic model of environmental safety of ship power plant, elaborated by this author and presented in the paper, may serve as such a tool.

PROBABILISTIC MODEL OF ENVIRONMENTAL SAFETY OF SHIP POWER PLANT

In the environmental safety model of ship power plant the kinds of pollutions which are dealt with by the MARPOL Convention standards, were taken into account. These are : oil pollutants, sewage, noxious components of exhaust gas emitted by piston diesel engines and waste incinerators, as well as cooling media (freons).

The environmental safety of ship power plant is expressed by risk level it creates for the environment. The lower risk the greater safety. The risk measure associates probabilities of causing hazards to environment and their consequences into a single numerical value. A caused hazard is the emission of such pollution amount which exceeds its limit value imposed by the MARPOL Convention.

Noxious substances released to the environment during ship's power plant operation are of different forms of harmful influence on the environment. Due to complexity of the problem, to use weight factors for determining the consequences of released pollutions is most suitable. To each kind of pollution a weight factor reflecting seriousness of environmental losses due to its discharge, was assigned.

The probabilities and weight factors were joined together into a single value by means of the linear strategy model [5], to which a restraint was added. The strategy is of a compensating character. A high value of one component of the model is capable to compensate a low value of the other. Whereas the restraint has to select the ship power plants not complying with the Convention's requirements as those hazardous. An additional advantage of the assumed linear strategy is the simplicity resulting from its additive character. The environmental **risk measure** of ship power plant can be expressed as follows :

$$\begin{cases} R = \sum_{i=1}^{m} w_i \cdot P_i(X_i > x_{il}) \ , \ \sum_{i=1}^{m} w_i = 1 \\ \exists i \ \ P_i(X_i > x_{il}) = 1 \Rightarrow R = 1 \end{cases} \qquad (1)$$

where :

- X_i – amount of discharge of i-th kind of pollution (random variable)
- x_{il} – limit amount of discharge of i-th kind of pollution, imposed by the Convention
- m – number of kinds of pollution, taken into account
- w_i – weight factor for i-th kind of pollution
- $P_i(Xi > x_{il})$ – probability that the discharge amount of i-th kind of pollution will exceed the yearly limit amount of discharge permitted by the Convention.

It is worth observing that :

$$\exists i \ \ P_i(X_i > x_{il}) = 1 \Rightarrow R = 1$$

$$\forall i \ \ P_i(X_i > x_{il}) = 0 \Rightarrow R = 0$$

The first relationship corresponds with the situation when a ship does not comply with any of the Convention's requirements, i.e. it is not fitted with appropriate devices and systems. The maximum risk value is then equal to R = 1.

The second relationship corresponds with the situation when a ship and its crew are beyond reproach regarding environmental safety. The situation is obviously not real; then R = 0. Therefore the risk measure R is contained within the interval between 0 and 1.

The probabilities $P_i(X_i > x_{il})$, i = 1,2,...,m, which appear in (1) can be determined on the basis of singular models of environmental safety of ship power plant. 12 such models were elaborated :

★ for operation of fuel oil delivery to ship
★ for operation of fuel oil pumping between tanks onboard the ship
★ for operation of lubricating oil delivery to ship
★ for operation of lubricating oil pumping between tanks onboard the ship
★ for operation of transferring oily substances out of the ship
★ for packing (sealing) of stern tube,controllable pitch propeller boss, and controllable pitch propeller boss of thruster
★ for bilge water deoiling system
★ for ship sewage system
★ for ship diesel engines regarding their NO_x emission
★ for ship diesel engines regarding their SO_x emission
★ for ship incinerator
★ for ship refrigerating system.

For every kind of pollution a review of design, features, structure and modes of operation of a relevant technical system, was performed with taking into account crew's actions. Next, appropriate unserviceability and event trees were elaborated. This way cause - effect models were obtained. Each of the models contains – in its structure comprising the above mentioned trees - description of a scenario of events leading to triggering a hazard. A triggered hazard is the emission of such pollution amount which exceeds its limiting value imposed by the MARPOL Convention. The specific models make it possible to determine probabilities of violating the Convention conditions, i.e. of triggering the considered hazards. In the models any conscious, deliberate, unlegal pollution discharges by ship crews were not taken into account. Input values to the singular models are the unserviceability events of technical elements and human errors. The model tree structures are compliant with recommendations of the FSA method being developed within IMO activity [2, 12, 13].

To determine numerical values of the weight factors the Norwegian report on the Environmental Indexing of Ships was used [9]. However the there given values of weight factors were not applied in this work, because such pollutions as bilge water, lubricating oils, and oil residues were not accounted for in it. The report's authors asssumed that if the discharging to the sea a given kind of pollution is prohibited then it is not discharged in fact. They also assumed that the pollutions subjected to treatment (bilge water) are always cleaned up to a sufficient degree. They do not take also into account oil leakage from stern tube as it should be prevented by packing. This approach results from a deterministic viewpoint on the environment protection systems, without accounting for reliability of technical elements and human relability.

However in the Norwegian report in question, a very detail analysis of influence of different pollutants on the environment, was performed. Their impact to the environment, which results from their destructive mechanisms to the environment, range of influence and potential amount of discharge, was there linguistically described.

Values of the weight factors of detrimental influence of pollutants on the marine environment are given in Tab.1. The factors were determined by changing the linguistic variables characterizing the environmental impact into appropriate numerical values (col. 4 and 5). Next, for each kind of pollution the assigned numerical values (col.5) were summed up for particular destructive impacts as shown in col. 6. Finally, the values of col. 6 for particular kinds of pollution were divided by the total sum of the numerical values determined for all kinds of pollution ($\Sigma = 72$). This way the searched values of the weight factors, w_i , (col. 7) were found. The sum of all weight factors equals one in accordance with the formula (1).

Incinerators are only used at high sea, far from land. Hence their influence is very limited. Amount of their exhaust gases is small relative to that emitted from the combustion engines.

INVESTIGATION OF THE MODEL

The investigating subject was a hypothetical ship power plant of a typical technical structure complying with contemporary solutions. Its operational process also complied with that presently applied. To perform calculations the following assumptions were made :

➲ **Regarding risk of NO_x excessive emission** :
in the power plant 4 combustion piston engines are installed : 1 main engine, and 3 auxiliary engines driving independent electric generating sets; no systems for purifying exhaust gas from NO_x are applied.

Tab.1. Values of weight factors of harmful influence of polluting agents on marine environment Σ = 72 Σ = 1

Polluting agent	Pollution symbol i	Environmental exposure	Environmental impact	Numerical value of environmental impact	Sum of numerical values	Weight factor w_i
1	2	3	4	5	6	7
NO_x	I	Climatic changes Acid rains Production of ozon Limitation of plant vegetation	Mean High Very high High	3 4 5 4	16	**0.223**
SO_x	II	Acid rains	Very high	5	5	**0.069**
CFC and HCFC	III	Destruction of ozone layer Climatic changes	Very high Very high	5 5	10	**0.139**
Exhaust gases from incinerators	IV	Local air pollution	Low	1	1	**0.014***
Heavy fuel oil	V	Pollution of beaches Pollution of sea	High to very high High to very high	4 to 5 (4.5) 4 to 5 (4.5)	9	**0.125**
Fuel oil (diesel)	VI	Pollution of beaches Pollution of sea	Mean to high Mean to high	3 to 4 (3.5) 3 to 4 (3.5)	7	**0.097**
Lubricating oil	VII	Pollution of beaches Influence on sea organisms	Moderate Moderate	2 2	4	**0.056**
Oil residues	VIII	Pollution of beaches Influence on sea organisms	Low to high Low to high	1 to 4 (2.5) 1 to 4 (2.5)	5	**0.069**
Oily bilge water	IX	Pollution of beaches Influence on sea organisms	Low to high Low to high	1 to 4 (2.5) 1 to 4 (2.5)	5	**0.069**
Sewage	X	Pollution of beaches Influence on sea organisms	Very high Very high	5 5	10	**0.139**
					Σ = 72	**Σ = 1**

* Harmfulness of exhaust gases from incinerators was not determined by the Norwegian authors. For needs of the model a low value of environmental impact was assumed.

- **Regarding risk of SO_x excessive emission** :
the ship in question 24 times a year enters a protected region in which using a fuel oil having sulphur mass content lower than 1,5% is required; beyond the region a fuel oil of sulphur content exceeding 1,5% is used on the ship; no systems for purifying exhaust gas from SO_x are applied; ship's fuel system is common for all the engines (a change of fuel oil kind for one engine simultaneously applies to the remaining engines); hence the set of engines of the power plant in question should be considered as a single engine.
- **Regarding risk of freon release to the atmosphere** :
in the ship's refrigerating system a freon of HCFC group is used; repair and maintenance operations are carried out once a year, during which a release of freon may happen.
- **Regarding risk of of excessive emission of noxious substances resulting from the use of a waste incinerator** :
waste combusting operations by means of the incinerator are performed 15 times a year.
- **Regarding risk of heavy fuel oil release to the sea** :
the heavy fuel oil bunkering operations are carried out 12 times a year on the ship; the heavy fuel oil pumping operations between the ship's tanks are performed 300 times a year.
- **Regarding risk of (diesel) fuel oil release to the sea** :
the fuel oil bunkering operations are carried out 2 times a year on the ship; the fuel oil pumping operations between the ship's tanks are performed 24 times a year.
- **Regarding risk of lubricating oil leakage to the sea** :
the lubricating oil bunkering operations are carried out 4 times a year by means of oil supply piping; the filled tank is fitted with an air-escape pipe reaching over the deck; the oil pumping operations between the ship's tanks do not involve any risk of oil leakage to the sea; the ship is equipped neither with a controllable pitch propeller nor thrusters; oil leakage may only occur through stern tube packing.
- **Regarding risk of leakage of oil residues to the sea** :
the operations of transferring oil derivatives out of the ship are carried out 4 times a year; the ship is fitted with the oil/bilge water separator NEPTUN made by Warma, Grudziądz (Poland); the separated oil collected in the separator may be released to the sea due to a failure of oil discharge system of the 2nd chamber of the separator.
- **Regarding risk of release of bilge water containing more than 15 ppm of oil** :
the ship is fitted with the bilge water/oil separator NEPTUN; in the engine room cleaning operations with the use of detergents are performed 6 times a year.
- **Regarding risk of sewage pollution of coastal waters** :
the ship is fitted with LK biological-chemical sewage treatment plant, Warma, Grudziądz; the probability of ship's sailing over sea waters up to 12 NM from the nearest land amounts to 30 % ; the seawage treatment plant is operated in accordance with DTR recommendations.

Way of performing the model investigation

Three levels of crew qualification were assumed: high, average and low. Probabilities of making human errors were determined by using tables elaborated on the basis of the THERP method [8] as well as calculations performed by using ASEP – – HRAP method [4] and TESEO method [6], [14].

The same reliability level R_{te} was assumed for all technical elements of the investigated systems. For elements of the singular operation models of : bunkering, pumping, transferring out fuel oils, lubricating oils and oil derivatives, of combusting wastes as well as of entering a region protected against SO_x emission, the reliability level concerns a single operation only. For technical elements of singular models of : packing, bilge water treatment system, sewage system, combustion engines regarding NO_x emission, as well as refrigerating system, the yearly reliability level is assumed. For elements of automation and signalling systems the so called **reliability on demand** is assumed.

The investigation consisted in simultaneous changing reliability levels of all technical elements within the range from 0,9 to 1. On the basis of relevant singular models as well as values of the weight factors of harmfulness of pollution impact onto the environment, values of yearly environmental risk were calculated in function of the reliabilities of technical elements and crew qualification levels. Results of the calculations are shown in Fig.1.

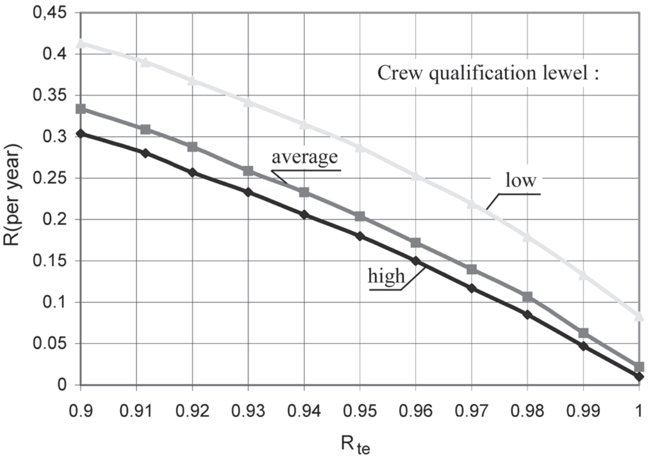

Fig. 1. *Influence of the reliability level of technical elements, R_{te} , and crew qualification levels on the yearly environmental risk of ship power plant, R.*

Conclusion derived from the example model investigation

- ✶ The environmental risk of ship power plant, defined by the expression (1), obviously depends on the reliability of relevant technical elements as well as on the crew qualification level – the reliability of human operator.
- ✶ The greater reliability of technical elements and human reliability the lower environmental risk from the side of ship power plant, i.e. the higher level of environmental safety.

A PROPOSED CRITERION FOR ENVIRONMENTAL RISK OF SHIP POWER PLANT

The proposed risk criterion follows the proposal elaborated in the frame of FSA method used by IMO. The entire risk range is divided into three categories :

- the intolerated risk
- negligible risk
- the so called ALARP (As Low As Reasonably Practicable) range.

The intolerated risk cannot be accepted in any case. The negligible risk is acceptable and no way of its mitigation is searched for. The risk within the ALARP range is subjected to an analysis. Possible lowering the risk level and costs associated with the possibility are considered. If lowering the risk level is practically possible and its cost is reasonable then actions aimed at its reduction are undertaken [7,13].

The division of the risk range into three categories requires two limit risk values : upper R_u and lower R_l , to be established. IMO carries out work on establishing such limits in the case of human life. They reflects risk produced by ships to human life. As far as the risk to the environment due to ship power plant is concerned such limits still have to be determined. A graphical interpretation of the risk criterion is shown in Fig.2.

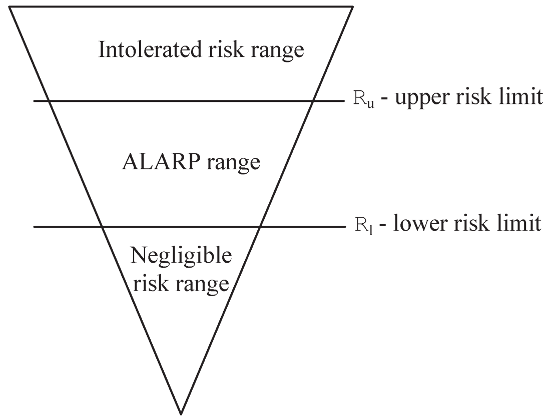

Fig. 2. *A graphical interpretation of the risk criterion*

Here it is proposed the upper risk limit R_u to be a value somewhat higher than the average risk according to the formula (1) for power plants of ships in service, under assumption of the average qualification level of ship crews. The proposal is based on the author's conviction that one should strive for improving present state of environmental safety. On the other hand it cannot be said that the risk level due to existing ship power plants complying with the international requirements, is not admissible.

A value of the lower risk limit R_l can be also determined by using the formula (1), in this case for a ship power plant designed with taking into account possibly proecological solutions and ways of its operation, following the Norwegian ship's class notation Clean Design [10]. The notation does not take into account reliability of technical elements which should be on the level as high as possible. The human reliability would be assumed for the high qualification level.

In this case a proecological ship represents the ship the stern tube of which is filled with water instead of lubricating oil, on which oily bilge water and sewage are collected in tanks and transferred out to land – based stations, only diesel fuel oil containing less than 1.5% of sulphur is used, and freons are not applied to its refrigerating system.

FINAL REMARKS AND CONCLUSIONS

- ❖ Randomness of the event of inadmissible pollution release from ship power plant is obvious. It implicates applying probabilistic approach to its environmental safety. The safety is a feature of the power plant which has to be assessed by using the notion of risk and safety criterion defined in safety engineering.
- ❖ Application of the elaborated models is closely associated with data on reliability of elements of environment protection systems; however they are unavailable in Poland. Perhaps they are saved in databases of Det Norske Veritas or Lloyds Register. Also experts – experienced ship engineers – have not sufficient experience to base on their opinion in

formulating credible assessments. Ship environmental protection systems are considered by ship engineers as auxiliary ones only, moreover they subject to failures rather rarely.

- The elaborated models make it possible to formulate reliability requirements for elements of environmental protection systems. The requirements can be put forward to producers of the elements, which are able to appropriately shape reliability of the elements as well as to verify it by means of laboratory tests or investigations in service. The problem is covered by PN-IEC 60300-3-4 standard. It consists only in formulating appropriate requirements and, certainly, in associated costs of their implementation.
- The models make it also possible to design reliability of the power plant systems responsible for releasing noxious substances – to a given amount only, as well as the entire power plant – to a given level of environmental risk.
- The environmental safety of ship power plant is a partial problem. The environmental safety of the entire ship is that mainly interesting. It seems that just the so defined models have a chance to be applied in the worldwide shipping. Hence the presented models exemplify only a methodical approach to solving the problem of environmental safety assessment.

BIBLIOGRAPHY

1. Brandowski A.: *Science of safety* (in Polish). Warsaw University of Technology. Warszawa, 1993
2. Brandowski A.: *An analysis of the projects on formal asessment of ship safety, carried out by IMO* (in Polish). Int. publ. of Gdynia Maritime University. Gdynia, 1996
3. Fisher W.: *International Protection of the Marine Environment: Land in Sight*. Research Center Julich. Germany, 1988
4. Kosmowski K.T.: *Assessment of operator's reliability during realization of selected control process functions – exemplified on the basis electrical energy generating system on B 488 ships* (in Polish). Gdańsk University of Technology. Gdańsk, 1997
5. Łukasiak - Goszczyńska M.: *Multidimensional decisions and strategies of their making* (in Polish). PAN, 1977
6. Radkowski S.: *Background of safe engineering* (in Polish). Publ. House of Warsaw University of Technology. Warszawa, 2003
7. Skjong R.: *Criteria for estabilishing risk acceptance*. Proceedings Vol.2, European Safety and Reliability (ESREL) Conference, Maastricht. June, 2003
8. Swain A.D., Guttman H.E.: *Handbook of Human Reliability Analysis with Emphasis on Nuclear Power Plant Applications*. Final Report, prepared for U.S. Nuclear Regulatory Commision. August, 1983
9. Det Norske Veritas : *Environmental Differentiation of Dues and Fees for Ships*. Technical Report No. 97-0212.1997
10. Det Norske Veritas: *Environmental Class*. January, 2000
11. IMO (International Maritime Organisation): I*nternational Convention for the Prevention of Pollution from Ships* MARPOL 73/78
12. IMO (MSC 66/INF.8): *A methodology for formal safety assessment of shipping*. 01.03.1996
13. IMO (MEPC 45/13): *Formal Safety Assessment Including Environmental Indexing of Ships*. Report of the joint MSC/MEPC Working Group of the Human Element and Formal Safety Assessment. 27 June 2000
14. Safety and Reliability Directorate UK Atomic Energy Authority: *Human Reliability Assessors Guide*. October, 1988

ACRONIMS

ALARP	- As Low As Reasonably Practicable
ASEP-HRAP	- Accident Sequence Evaluation Program - Human Reliability Analysis
CFC	- (chlorofluorocarbons)
DNV	- Det Norske Veritas
DTR	- technical-operational documentation
FSA	- Formal Safety Assessment
HCFC	- (hydrochlorofluorocarbons)
IMO	- International Maritime Organisation
MARPOL	- International Convention for the Prevention of Pollution from Ships
MEPC	- Marine Environment Protection Committee of IMO
MSC	- Marine Safety Committee of IMO
PN	- Polish Standard
TESEO	- Tecnica Empirica Stima Errori Operatori
THERP	- Technique for Human Error Rate Prediction