*Safety, Reliability and Risk Analysis: Theory, Methods and Applications – Martorell et al. (eds)*
*© 2009 Taylor & Francis Group, London, ISBN 978-0-415-48513-5*

# Environmental reliability as a requirement for defining environmental impact limits in critical areas

E. Calixto & Emilio Lèbre La Rovere
*UFRJ-COPPE, Rio de Janeiro, Brasil*

ABSTRACT: The main objective of this study is to define reliability requirements in relation to environmental impacts in critical areas in terms of environmental resource sensitivity. Nowadays many enterprises in Brazil are evaluated in this area in term of many different environment requirements, but the environmental impact of the enterprise or the group of enterprises as a whole are not assessed, and nor are their future modifications.

When the number of enterprises in a specific area increases the risk of accidents is also rises. In other words reliability over time gets worse. Unfortunately most of cases in Brazil do not take into account the entire enterprise risk impact in a specific area and the decrease of reliability over time.

The methodology in question takes into account all the critical events which cause a serious environmental impact for each enterprise in the same area that take place over time. By taking into account all relevant events, it is possible to produce the Environment Diagram Block which covers all related events and their probability of occurring over time. This means that failures in any block represent accidents with potential environment impacts.

The environmental reliability target is associated with the tolerable number of environmental impacts in a specific area, taking into account all events over a specific period of time. The tolerable number of accidents depends on social perception and environmental sensitivity.

For this analysis the Monte Carlo simulation has to be carried out over a period of time in order to define the Environmental Availability and Environmental Reliability related to the number of tolerable events. Moreover, in the case of any enterprise modifications or an increase in the number of enterprises a new block will be inputted in the Environmental Block Diagram and the new results will be assessed.

## 1 INTRODUCTION

Nowadays many environmental requirements are imposed on enterprises in order to preserve environmental conditions and avoid serious environmental impacts. In Brazil there are specific laws which stipulate specific risk analyses, procedures and waste limits for enterprises depending on their characteristics and potential environmental impacts.

In the Oil and Gas industry, the law is even more strict due to previous catastrophic events, such as accidents in Guanabara Bay, the P-36 platform incident, and so on.

Even regarding the worst possibilities of accidents and environmental impacts, no methodology takes into account groups of enterprises and analyzes their impact on the environment over time. Therefore, there is no strategy to evaluate a specific area regarding the overall potential environmental impact.

Tolerable environmental sensitivity is related to the ability of ecosystems to adapt or react to the number of potential environmental impacts over time in relation to all the enterprises in a specific area. Therefore, based on environmental sensitivity it is possible to define a limit in terms of the number and types of environment accidents in order to set the reliability target for a specific area taking all enterprises as a single system. The reliability target is environmental reliability and the protection level will be stipulated both for each individual enterprise and for the group of enterprises in a specific area in order to preserve the environment over time.

To clarify the methodology a case study will be carried out of a group of enterprises with an environmental impact in a specific area.

## 2 ANALYSIS METHODOLOGY

In order to perform this analysis a number of important steps have to be followed to achieve consistent results which can provide support for decision making about enterprise limits and environmental reliability targets for specific areas.

The first step is to discover the sensitivity of the ecosystem in terms of environmental impacts. For this the characteristics of the ecosystem have to be analyzed and its limits estimated. This is very difficult in many cases and almost impossible in others due to complex features of ecosystems. Therefore, it is advisable that ecosystems be compared with others to estimate limits regarding environmental impacts. In this case, it is important to be conservative as regards the tolerable limits of events in order to preserve the environment.

After the environmental impact limits have been defined, the enterprises and their potential environmental accident impacts have to be studied. In this case historical accident data has to be analyzed and the density probability function established to discover accident frequency over time. In many cases accident frequency is considered constant over time, but this is not true in all situations. This concept significantly influences the analysis because some accidents increase in frequency in a specific period of time, which in turn allows these accidents to be discussed and in some cases leads to the discovery of their causes and the consequent proposal of preventive action in order to avoid future accidents.

The final step is group all the enterprises and simulate events over time. The Monte Carlo simulation will be used, with the group of enterprises being represented by the Block Diagram Methodology. This analysis requires that the group of enterprises be taken as a single system. Each enterprise will be represented by a specific block and all blocks will be in series. This means that in the case of accidents the system will impact the environment and the reliability of system environments will be influenced by enterprises' reliability.

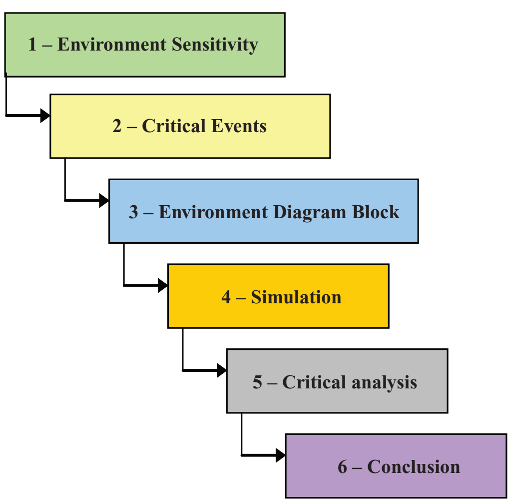


Figure 1. Environmental reliability analysis methodology.

After the simulation the system reliability will be analyzed and it will be possible to discover if the target has or has not been achieved and whether the number of accidents is higher or not. In negative cases, it is also possible to find out how much improvement is necessary to achieve the reliability target. The methodology is summarized below in Figure 1.

## 3 ENVIRONMENTAL SENSITIVITY

Environmental sensitivity in some specific areas can involve issues with social, economic and environment impacts in the case of accidents. To facilitate the understanding of environmental sensitivity ESI maps were drafted to serve as quick references for oil and chemical spill responders and coastal zone managers. They contain three kinds of information:

Shorelines are ranked based on their physical and biological character, then color-coded to indicate their sensitivity to oiling.

Sensitive biological resources, such as seabird colonies and marine mammal hauling grounds, are depicted by shaded polygons and symbol icons to convey their location and extent on the maps.

ESI maps also show sensitive human-use resources, such as water intakes, marinas, and swimming beaches.

In the USA at present project scientists have created collections of ESI maps, called ESI atlases, for most coastal areas, including Alaska. To do this, vulnerable coastal locations have to be identified before a spill happens, so that protection priorities can be established and cleanup strategies identified. To meet this need, NOAA OR&R researchers, working with colleagues in state and federal governments, have produced Environmental Sensitivity Index (ESI) maps. An example section from an ESI map appears in Figure 2 below.

The Environmental Sensitivity Index (ESI) project team has developed a systematic method for creating ESI maps. Others are welcome to adopt this method when it proves useful to them. This section gives an introduction to the basic elements of ESI maps. ESI maps include three kinds of information, delineated on maps by color-coding, symbols, or other markings:

- Shoreline Rankings: Shorelines are ranked according to their sensitivity, the natural persistence of oil, and the expected ease of cleanup.
- Biological Resources: Oil-sensitive animals, as well as habitats that either (a) are used by oil-sensitive animals, or (b) are themselves sensitive to spilled oil (e.g., coral reefs).

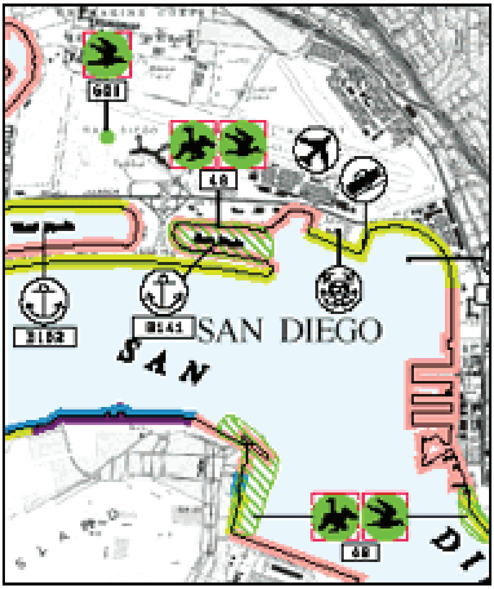


Figure 2. Environmental sensitivity.

- Human-Use Resources: Resources and places important to humans and sensitive to oiling, such as public beaches and parks, marine sanctuaries, water intakes, and archaeological sites.

The Shoreline Rankings have been defined on the basis of factors that influence sensitivity to oiling, including substrate grain size, permeability, trafficability, and mobility; the slope of the intertidal zone; relative degree of exposure of the physical setting; ease of cleanup; and biological productivity and sensitivity. A ranking of 1 represents the shorelines least susceptible to damage by oiling, and 10 represents the locations most likely to be damaged.

Habitat is the single most important influence on impacts of oil in marine ecosystems (API 1985; NAS 1985). Intertidal habitats are exposed to much higher concentrations of oil than subtidal habitats (Ballou et al. 1987). Benthic (sea bottom) habitats are generally more affected by contact with oil than pelagic (open water) habitats. The two key intertidal habitat variables are exposure to wave action and substrate (Baker 1991). Table 1 below lists sensitivity rankings of marine habitats (excluding tropical) to oil augmented from the American Petroleum Institute (API 1985).

Sheltered habitats with fine-grained sediments are highly sensitive whereas exposed rocky shores have a relatively low sensitivity to oil pollution. In sheltered, fine-grained habitats oil tends to linger whereas on exposed rocky shores oil is subject to rapid removal

Table 1. Sensitivity rankings of marine habitats.

| Sensitivity ranking | Habitat type |
|---|---|
| High | Saltmarsh |
| | Sheltered Rocky Intertidal |
| | Sheltered Rocky Intertidal |
| | Special Use (endangered species/marine protected areas) |
| Medium – High | Seagrass Meadow (low intertidal to shallow subtidal) |
| Medium | Open Water Enclosed Bays and Harbours |
| Low – Medium | Exposed Sand/Gravel/Cobble Intertidal |
| Low | Exposed Rocky Intertidal |
| | Kelp Forest Subtidal |
| | Open Water, Non-enclosed Nearshore and Offshore |
| | Soft Bottom to Rocky Subtidal |

by wave action. Moreover, rocky intertidal species are adapted to counteracting the stressful effects of desiccation and these adaptations can help them against oil. The importance of habitat is also reflected in the Vulnerability Index and habitat recovery generalizations (excluding tropical habitats) listed in Table 2.

In relation to Biological Resources, certain animal and plant species are especially vulnerable to the effects of oil spills. Under the ESI method, these species have been classified into seven categories, each further divided into sub-categories of species similar in their sensitivity to spilled oil. Many species that are vulnerable to oil are wide-ranging, and may be present over large areas at any time. These species can be especially vulnerable at particular times and places. ESI maps show where the most sensitive species, life stages, and locations exist, but do not necessarily show the entire area where members of a sensitive species occur.

In Human-Use Resources exact locations of some archaeological and cultural resources cannot be disclosed because of the risk of vandalism. Either these locations are shown within a polygon enclosing a larger area, or a map symbol is placed near to, but not at the exact location. People using the ESI method to map human-use resources are encouraged to denote not only surface water intakes, but also groundwater recharge zones and well fields.

Although this methodology defines the most critical areas in the case of accidents, it is not enough to know the exact environmental limits of accident impacts. Also necessary is specialist knowledge of environmental behavior in the case of accidents or to carry out a simulation of environmental effects. The most usual means is to look for a similar environment area that was affected by similar accidents and to evaluate its effects and environment behavior in order

Table 2. Vulnerability index and habitat recovery generalizations.

| Vulnerability index 1 | Shoreline type | Comments |
|---|---|---|
| 10 | Marine Wetlands | Very productive aquatic ecosystems; oil can persist for decades |
| 9 | Sheltered Tidal Flat Boulder Barricade Beach | Areas of low wave energy-high biological productivity; oil may persist for decades |
| 8 | Sheltered Rocky Coast | Areas of reduced wave action; oil may persist for over a decade |
| 7 | Gravel Beach | Same as Index 6; if asphalt pavement forms at high spring tide level it will persist for decades |
| 6 | Mixed Sand/Gravel Beach | Oil may undergo rapid penetration/burial under moderate to low-energy conditions; oil may persist for decades |
| 5 | Exposed Compacted Tidal Flat | Most oil not likely to adhere to or penetrate the compacted sediments |
| 4 | Course Sand Beach | Oil may sink and/or be buried rapidly; under moderate to high-energy conditions oil likely removed naturally within months |
| 3 | Fine Sand Beach | Oil does not usually penetrate far into the sediment; oil may persist several months |
| 2 | Eroding Wavecut Platform | Wave-swept; most oil removed by natural processes within weeks |
| 1 | Exposed Rocky Headland | Wave reflection keeps most oil offshore |

*Note*: 10 = most vulnerable, 1 = least vulnerable, index is a qualitative rank order.

to define limits for accident impacts. When doing this it is necessary to be conservative in defining limits in order to preserve environments because in most cases environment limits are not easy to define.

## 4 ENVIRONMENTAL RELIABILITY

The concept of reliability is known in industry and has many different applications. It means the probability of a system, subsystem or equipment to work properly for a specific period of time. The reliability function requires historical data and uses methods like the minimum square to establish the PDF (density probability function) that best fits the historical data. The reliability function is as follows:

$$R(t) = 1 - \int_0^t f(t)dt$$

Depending on the PDF function the reliability format can differ.

The reliability concept can be used in environmental analysis in order to establish the probability of an environment impact not occurring in a specific period of time. It is possible to stipulate environmental reliability targets to limit the quantity of environmental impacts and increase the level of safety protection in one or more enterprises. Figure 3 represents the environment reliability of oil spills in Japan, in relation to the worst events. Most of the events have occurred in the last 30 years, due to the increase in oil transport. The best PDF that represents the events is Gumbel, with a correlation of 0.9484.

The remarkable aspect is that the frequency of this event is not constant, as is usually assumed in most risk analyses, but changes over time. The frequency index is:

$$\lambda(t) = \frac{f(t)}{R(t)}$$

Figure 4 below show the frequency index, which is almost constant until 10 years and then starts to increase.

Environmental reliability can be used to prioritize critical areas or enterprises in terms of environmental impact risk, which can provide useful support for decision making related to the allocation of emergency resources. It should be noted that priorities will change over time depending on the PDF of the critical events

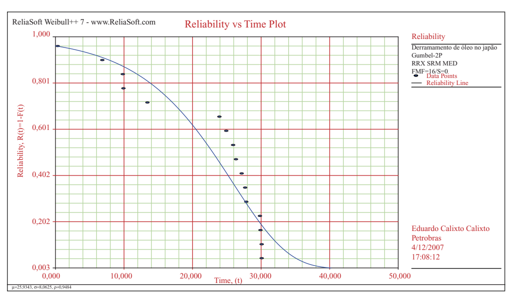


Figure 3. Environmental reliability of oil spills in Japan.

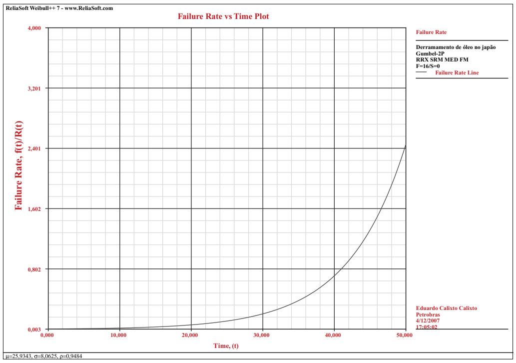


Figure 4. Event frequency.

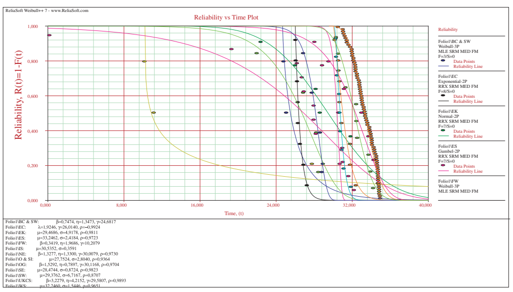


Figure 5. Environmental reliability of oil spills in the UK.

analyzed. Figure 5 below shows the environmental reliability curve for different oil spill areas in the UK. In relation to environmental reliability it can be seen that oil spills in UKCS, represented by the red curve, are the most reliable event along time. This means that it is not a critical area requiring the investment of emergency resource allocations during the first thirty years.

On the other hand, it is also necessary to analyze what the historical data represents and if the behavior will remain the same over time. In the UK oil spill area, the first events are related to accidents with ships, while the final one involve platform accidents and other types of occurrence. In this particular case, it is most advisable to consider the last ten years.

## 5 ENVIRONMENTAL AVAILABILITY

Environmental availability is the part of total time when there is no environmental impact in an area. The concept takes into account the number of environmental impacts and their duration as shown in the equation below (D(t) = availability).

$$D(t) = \frac{\sum_{i=1}^{n} t_i}{\sum_{i=1}^{n} T_i}$$

Where D(t) is environmental availability, t is the duration of the event, T lifetime duration and i represents the time when the undesired event occurred.

It is possible in this way to represent the actions of emergency teams to alleviate environmental impacts and to assess their performance in relation to various aspects, such as time taken for emergency team to reach the accident area and the duration of emergency actions to control the accident and eliminate the environmental impact.

To represent a group of events or enterprises an environmental block diagram is used covering the whole system or group of events that cause the environmental impact. The main idea is to take into account a single group of events that can occur in a specific area or a group of enterprises which have a potential environmental impact.

In Brazil the total environment impact of a group of enterprises in critical environmental areas is not taken into account. Nevertheless, the ecosystem can only support a limited number of environmental impacts and this number has to be taken into account when a group of enterprises is being evaluated.

## 6 CASE STUDY

To find out the maximum number of environmental impacts and their intensity, ecosystems and their characteristics have to be analyzed. The result is related to environment reliability and can be estimated using Monte Carlo Simulation Methodology. Figure 6 represents the Santos Basin which is considered to be a sensitive environmental area. Therefore, no catastrophic events in this area are tolerable and to find out if enterprises are reliable the Environmental Reliability Methodology has to be followed.

There are many different types of enterprises and oil spill resources, but in relation to drilling activities the worst events are surface, submarine and underground blowouts. The probability that events are constant over time is shown in Table 3 below.

When carrying out the Monte Carlo Simulation if it is intended not to permit any kind of catastrophic event, the maximum level of drilling in the area has to keep the number of catastrophic events below one.


Figure 6. Area of santos basin.

Table 3. Blowout events.

| Blowout | Probability |
|---|---|
| Underground Blowout | 1,50E-04 |
| Submarine Blowout | 1,80E-04 |
| Surface Blowout | 1,62E-06 |
| Blowout | 3,33E-04 |

The main objective of the methodology is to estimate the period of time when the event analyzed happen based on its PDF characteristics. In this direct simulation it is possible to analyze the life of the system as a whole and to find out which event occurred, when it happened and to have an idea about its direct and indirect impacts and the environment reliability and availability for a specific period of time. For instance, a group of events involving drilling activity in the Campos Basin is represented in an Environmental Diagram Block where each block takes into account blowout events over the lifetime of the drilling. Each drilling activity has three catastrophic events that are represented in Figure 7 below. The events are in series in the Block Diagram because the occurrence of any event represents an environmental impact on the system as a whole.

The next step is to represent the group of enterprises located in same area and to estimate environmental availability and reliability limits. In the same way that each event is in a series in an individual enterprise, groups of enterprises are also in series. Figure 8 below represents the drilling group of the Campos Basin. The same block is also used for the analysis.

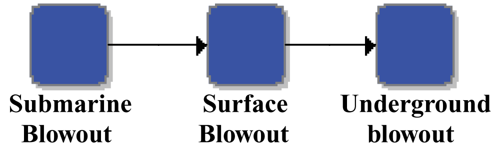


Figure 7. Drill block diagram.

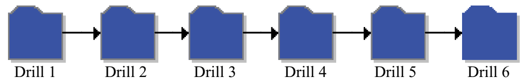


Figure 8. Drill block diagram.

The Direct Simulation will take into account three catastrophic events for all drilling activities over time. As a result it is possible to show the number of drilling activities in this area over a lifetime of 20 years as illustrated in Table 4 below.

The first column represents the number of drilling activities and the second environment availability. Environmental reliability is given in the fourth column, while the number of expected catastrophic events is stated in column five. Finally, column six gives the emergency team capacity. The maximum number of drilling activities in this area is ten because the number of expected catastrophes is lower than one and there is one hundred percent emergency team availability. The emergency availability capacity represents the total time that a catastrophic event takes place and the availability of the emergency team to respond. Unavailability to respond to events represents worse damage to the environment.

It is important to state that drilling is only one part of the oil production chain. Therefore, it is advisable to take into account all platform and ship transport in the area and related catastrophic events.

In this case the probabilities were considered to be constant over time due to the lack of historical data. This is an important assumption which is very influential in the analysis because it considers that the density of events is random over time, However, this is actually not the case, in fact blowout events have a high probability of occurring early in drilling life. Therefore, the PDF lognormal distribution would represent better this kind of event and indicates that it is advisable to be more careful at the beginning. Figure 9 shows the blowout frequency index.

The other important aspect is to know which events are the most critical to the system as a whole. In the case in question it is the underground blowout as shown in Figure 10 below. To be able to identify the most critical events with the greatest impact on environmental availability, it is essential to assess environmental availability events. In fact, the event which has the lowest environment availability will impact more on

Table 4. Monte Carlo simulation results.

| Monte Carlo Simulation (20 years) | | | | | | |
|---|---|---|---|---|---|---|
| Drills | Env Avail | Env Unavail | Env Reliab | CE | ETC | EIT |
| 1 | 99,99% | 0,01% | 96,80% | 0,03 | 100% | 23 |
| 5 | 99,92% | 0,08% | 82,00% | 0,20 | 100% | 141 |
| 10 | 99,84% | 0,16% | 64,40% | 0,40 | 100% | 283 |
| 20 | 99,69% | 0,31% | 46,00% | 0,74 | 99,47% | 523 |
| 40 | 99,42% | 0,58% | 25,20% | 1,41 | 99,44% | 1017 |
| 80 | 98,81% | 1,19% | 6,40% | 2,86 | 98,77% | 2082 |

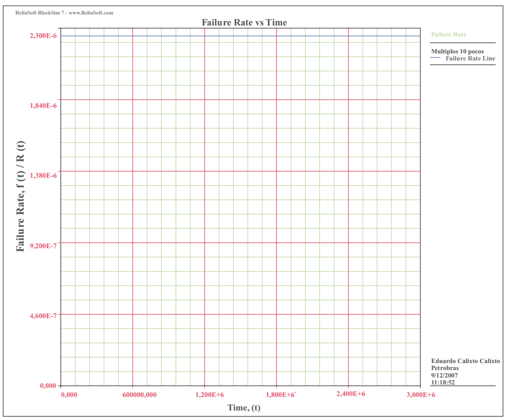


Figure 9. Drill blowout frequency.

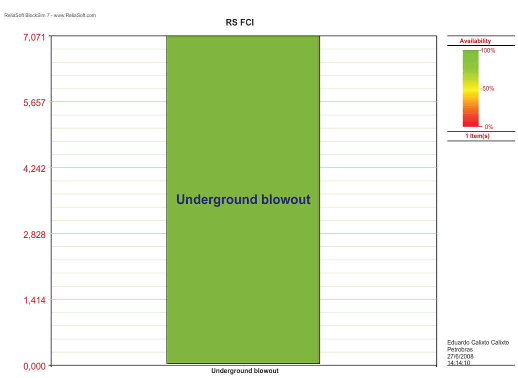


Figure 10. Critical system events.

the whole system. This happens because in the Block Diagram when a group of blocks is in a series, the system availability will be lower than the lowest block availability, in which case the event which has the lowest environmental availability will impact more on the environmental availability system.

In some cases certain events will happen many times but will not impact over time like others which happen much less frequently.

## 7 CONCLUSION

Environmental reliability is a powerful tool to support decision making related to environmental protection, defining limits for enterprises with reliability requirements, numbers of enterprises and establishing the most vulnerable areas for the location of emergency teams.

Unlike the usual methodology, it is possible to consider a group of enterprises and critical events in simulation over a specific period of time. The difficultly is obtaining historical data about events and defining environments limits for specific areas.

In the case of emergency teams it is considered that they will be in the correct position and that all procedures and actions will happen correctly avoiding any delay. In real life this does not happen, therefore the specific model has to be evaluated taking into account the performance of emergency teams.

The remarkable point about historical data is understanding why accidents happens and if the data fits well enough to be used in the current simulation case.

In this case study only drilling activities which affected a specific area where taken into account, but in addition all enterprises and the lifetimes of platforms and ships have also to be considered.

The next step in the case study is to consider all enterprise data which has an influence on environmental sensitivity in the area in question. Because of the environmental effects of other enterprises drilling limits will probably be reduced in order to keep the number of catastrophic accidents lower than one during the lifetime in question.

## REFERENCES


A.M. Cassula, "Evaluation of Distribution System Reliability Considering Generation and Transmission Impacts", Master's Dissertation, UNIFEI, Nov. 1998.

API (American Petroleum Institute). 1985. Oil spill response: Options for minimizing ecological impacts. American Petroleum Institute Publication No. 4398. Washington, DC: American Petroleum Institute.

Ballou, T.G., R.E. Dodge, S.C. Hess, A.H. Knap and T.D. Sleeter. 1987. Effects on a dispersed and undispersed crude oil on mangroves, seagrasses and corals. American Petroleum Institute Publication No. 4460. Washington, DC: American Petroleum Institute.

Barber, W.E., L.L. McDonald, W.P. Erickson and M. Vallario. 1995. Effect of the Exxon Valdez oil spill on intertidal fish: A field study. Transactions of the American Fisheries Society 124: 461–476.

Calixto, Eduardo; Schimitt, William. Análise Ram do projeto Cenpes II. ESREL 2006, Estoril.

Calixto, Eduardo. "The enhancement availability methodology: a refinery case study", ESREL 2006, Estoril.

Calixto, Eduardo. "Sensitivity analysis in critical equipments: the distillation plant study case in the Brazilian oil and gas industry". ESREL 2007, Stavanger.

Calixto, Eduardo. "Integrated preliminary hazard analysis methodology regarding environment, safety and social issues: The platform risk analysis study". ESREL 2007, Stavanger.

Calixto, Eduardo. "The safety integrity level as hazop risk consistence. the Brazilian risk analysis case study". ESREL 2007, Stavanger.

Calixto, Eduardo. "The non-linear optimization methodology model: the refinery plant availability optimization case study". ESREL 2007, Stavanger.

Calixto, Eduardo. "Dynamic equipments life cycle analysis". 5° International Reliability Symposium SIC 2007, Brazil.

IEEE Recommended Practice for the Design of Reliable Industrial and Commercial Power Systems–IEEE Std. 493–1997.

Kececioglu, Dimitri, and Sun, Feng-Bin, Environmental Stress Screening–Its Quantification, Optimization and Management, Prentice Hall PTR, New Jersey, 1995.

Lafraia, João R. Barusso, Manual de Confiabilidade, Mantenabilidade e Disponibilidade, Qualimark, Rio de Janeiro, Petrobras, 2001.

Monteiro, Aline Guimarães. Metodologia de avaliação de custos ambientais provocados por vazamento de óleo: O estudo de caso do complexo REDUC-DTSE. Rio de Janeiro, 22/12/03–COPPE/UFRJ.

Moraes, Giovanni de Araujo. Elementos do Sistema de Gestão de segurança meio ambiente e saúde ocupacional. Gerenciamento Verde Consultoria Rio de Janeiro: 2004

R. Billinton, and R.N. Allan, "Reliability Evaluation of Engineering Systems: Concepts and Techniques", 1st Edition, Plenum Press, New York, 1983.

ReliaSoft Corporation, *Weibull++* 6.0 *Software Package*, Tucson, AZ, www.Weibull.com.

Rolan, R.G. and R. Gallagher. 1991. Recovery of intertidal biotic communities at Sullam Voe following the Esso Bernica oil spill of 1978. Proceedings of the 1991 Oil Spill Conference, San Diego. American Petroleum Institute Publication No. 4529: 461–465. Washington, DC: American Petroleum Institute.

W.F. Schmitt, "Distribution System Reliability: Chronological and Analytical Methodologies", Master's.