

# **FN-CURVES: PRELIMINARY ESTIMATION OF SEVERE ACCIDENT RISKS AFTER FUKUSHIMA**

**Vanderley de Vasconcelos, Wellington Antonio Soares and Antônio Carlos Lopes da Costa**

Centro de Desenvolvimento da Tecnologia Nuclear - CDTN/CNEN  
Caixa Postal 941  
30161-970 Belo Horizonte, MG  
[vasconv@cdtn.br](mailto:vasconv@cdtn.br)  
[soaresw@cdtn.br](mailto:soaresw@cdtn.br)  
[aclc@cdtn.br](mailto:aclc@cdtn.br)

## **ABSTRACT**

Doubts of whether the risks related to severe accidents in nuclear reactors are indeed very low were raised after the nuclear accident at Fukushima Daiichi in 2011. Risk estimations of severe accidents in nuclear power plants involve both probability and consequence assessment of such events. Among the ways to display risks, risk curves are tools that express the frequency of exceeding a certain magnitude of consequence. Societal risk is often represented graphically in a FN-curve, a type of risk curve, which displays the probability of having N or more fatalities per year, as a function of N, on a double logarithmic scale. The FN-curve, originally introduced for the assessment of the risks in the nuclear industry through the U.S.NRC Reactor Safety Study WASH-1400 (1975), is used in various countries to express and limit risks of hazardous activities. This first study estimated an expected rate of core damage equal to  $5 \times 10^{-5}$  by reactor-year and suggested an upper bound of  $3 \times 10^{-4}$  by reactor-year. A more recent report issued by Electric Power Research Institute - EPRI (2008) estimates a figure of the order of  $2 \times 10^{-5}$  by reactor-year. The Fukushima nuclear accident apparently implies that the observed core damage frequency is higher than that predicted by these probabilistic safety assessments. Therefore, this paper presents a preliminary analyses of the FN-curves related to severe nuclear reactor accidents, taking into account a combination of available data of past accidents, probability modelling to estimate frequencies, and expert judgments.

## **1. INTRODUCTION**

The nuclear accident at Daiichi at Fukushima in 2011 showed that the observed Core Damage Frequency (CDF) is higher than that predicted by Probabilistic Safety Assessments (PSA) and their FN-curves [1, 2]. This paper analyses the FN-curves related to nuclear reactors, taking into account a combination of available past accidents data, probability modelling to estimate frequencies, and expert judgments. The influence of the occurrence of Fukushima accident on such curves is also included in the analysis.

## **2. THE FN-CURVE**

FN-curve is a type of risk curve that displays the probability of having N or more fatalities per year, as a function of N, on a double logarithmic scale. It may be used for presenting information about societal risks and to depict at least three different types of information [3]:

- Historical record of incidents;
- Results of a Probabilistic Safety Assessment (PSA);
- Criteria for judging the tolerability of risk.

## 2.1. Construction of FN-Curves

FN-curves display frequency-consequence data. During the analysis to estimate societal risk, various hypothetical events are assessed. Each of these events will have a predicted annual frequency of occurrence,  $f$ , and a predicted number of persons harmed,  $N$ , normally the number of fatalities associated with the event. The associated frequency of occurrence is expressed in events per year. These data are presented in log-log plot, with the  $x$ -axis representing the consequences and the  $y$ -axis representing the frequency of occurrence. Log-log scales are used because the high range of values for  $f$  can span multiple orders of magnitude. Societal risks may be plotted in two ways: non-cumulative frequency basis, the so-called  $fN$ -curves, where the values plotted on the  $y$ -axis are the discrete frequency of experiencing exactly  $N$  fatalities; and cumulative frequency basis, the so-called FN-curves, where the values plotted on the  $y$ -axis are the cumulative frequency of experiencing  $N$  or more fatalities.

In order to construct a FN-curve, a list of all events ( $E_i$ ) and their both associated frequencies ( $f_i$ ) and consequences ( $N_i$ ) has to be compiled and sorted by decreasing  $N_i$  values. In Table 1, event  $E_1$  is the most severe event and has a predicted consequence  $N_1$ , which occurs at a predicted frequency  $f_1$ .  $E_2$  is the next event less severe than  $E_1$ , with a predicted consequence  $N_2$ , and occurs at a predicted frequency  $f_2$ , and so forth.  $F_i$  is the cumulative frequency of events resulting in  $N_i$  or more fatalities. Figure 1 shows a typical FN-curve, expressing the probability of having  $N$  or more fatalities per year, as function of  $N$  [4].

**Table 1: Framework for FN Calculations [3]**

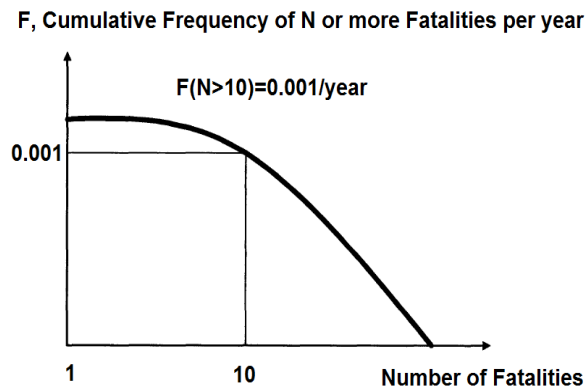
Event	Event Frequency, $f_i$ (per year)	Event Consequence, $N_i$ (number of fatalities)	Cumulative Frequency, $F_i$ (per year)
$E_1$	$f_1$	$N_1$	$F_1=f_1$
$E_2$	$f_2$	$N_2$	$F_2=f_1+f_2$
$E_3$	$f_3$	$N_3$	$F_3=f_1+f_2+f_3$
$E_4$	$f_4$	$N_4$	$F_4=f_1+f_2+f_3+f_4$
...	...	...	...
$E_n$	$f_n$	$N_n$	$F_n=f_1+f_2+f_3+f_4+...+f_n$

## 2.2. Societal Risks

Traditionally, the term societal risk has been associated with the number of fatalities in the case of an accident. It is based on the principle that often fatalities are the best way to express the seriousness of an accident and provides a simplified basis for risk evaluation. Societal risk is defined as the relationship between frequency and the number of fatalities in a given population from an undesired event [3]. Societal risk evaluation is concerned with estimation of the chances of more than one individual being harmed simultaneously by a same accident.

In the context of this paper, societal risk is associated with risks from substances and processes located on a major hazard facility. A key factor when estimating societal risk is the population around the site, in particular its location and density. The major accident concerned about nuclear reactor is core meltdown, since societal risks is expressed in terms

of core damage frequency (per reactor-year or GWe-year) and number of fatalities. FN-curves are the most common tool for assessing societal risks.



**Figure 1: Typical FN-Curve, expressing the probability of having  $N$  or more fatalities per year, as function of  $N$  (adapted from [4])**

### 2.3. Safety Goals

Any facility should be built or operated in such a way to satisfy a given set of safety goals. This is called a goal-oriented approach where goals are first specified, and then the facility or item is designed, created, operated and maintained accordingly. However, two questions must be first answered before conducting a goal-oriented approach [5]:

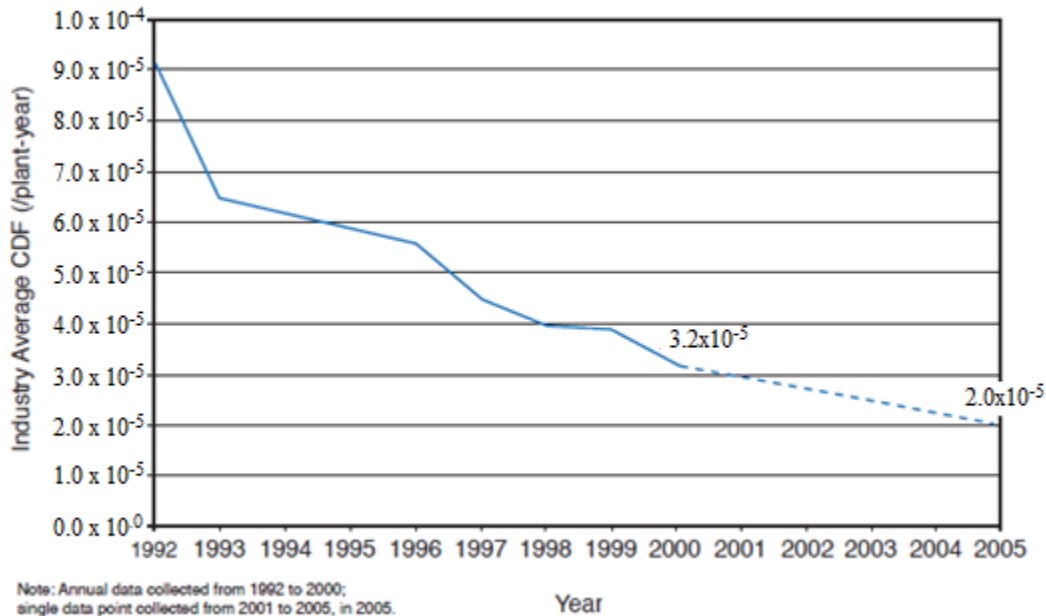
1. How safe is safe enough? This requires a set of safety goals to be satisfied.
2. How to deal with uncertainties? The current risk quantification involves significant uncertainties.

The outcome of a nuclear power plant PSA analysis is a combination of qualitative and quantitative results. Quantitative results are usually presented as the Core Damage Frequency (CDF) or the frequency of occurrence of an unacceptable radioactive release. In order to evaluate the acceptability of PSA results, quantitative criteria need also to be defined.

Safety goals for PSA results, both for CDF and for radioactive releases, are in use in most countries having nuclear power plants. Ultimately, the goals are intended to define an acceptable level of societal risk from the operation of a nuclear reactor. The levels of the safety goals differ from country to country. In some countries, they are mandatory, while in others they are not [5].

Thus, the scope, level of detail and areas of use of PSA have changed considerably since the time the safety goals were originally defined. This is a change both in quality and in maturity of the PSA technique. At the same time, PSA applications are becoming more and more important. This has led to an increased interest and need to use of PSA results, and thus to make judgments concerning the acceptability of risk contributions calculated with PSA. While the FN-curve represents a high-level safety goal, the CDF criteria used for interpreting PSA results can be regarded as an alternative for these high-level safety goals [5].

The Nuclear Regulatory Commission (NRC) in 1975, when the so-called WASH-1400 was carried out [6], estimated a CDF equal to  $5 \times 10^{-5}$  per reactor-year and suggested an upper bound of  $3 \times 10^{-4}$ . Lessons from Three Mile Island accident and the experience of NRC in performing PSA found, in 1990, an average CDF of nearly  $9 \times 10^{-5}$  per reactor-year. In 2008, the EPRI report on the U.S. nuclear power plants [7] pointed out that this metric has shown a decreasing trend from 1992 to 2005 due to safety enhancements that have induced significant reductions in the risk of core meltdown. An average CDF value of  $2 \times 10^{-5}$  per reactor-year was estimated at the end of 2005 (Figure 2). Table 2 shows examples of numerical safety goals defined in different countries, as well as by IAEA and EUR guidelines [5].



**Figure 2: Core Damage Frequency of nuclear industry trend (adapted from [7])**

**Table 2: CDF as safety goals in different countries and organizations [5]**

Country/Organization	Core Damage Frequency – CDF per year
Finland	$1 \times 10^{-5}$
Netherland	$1 \times 10^{-5}$
Russia	$1 \times 10^{-5}$
Switzerland	$1 \times 10^{-5}$
United Kingdom	$1 \times 10^{-4}$
USA	$1 \times 10^{-4}$
IAEA	$1 \times 10^{-4}$
EUR	$1 \times 10^{-5}$

### 3. HISTORICAL USE OF FN-CURVE

WASH-1400 and NUREG-1150 are U.S. documents regarding severe accidents and FN-curves. Such curves, as well as FN-curves from German Risk Study, and comparison among frequency-consequence curves for full energy chains, based on historical experience on severe accidents, are discussed in the next items.

### 3.1. WASH-1400

WASH-1400 [8], the so-called “The Reactor Safety Study” (updated and replaced by NUREG-1150 [4]), is a study from 1975 that introduced probability into the analysis of reactor accidents. Figure 3a taken from this report plots the “probability per reactor-year” versus “early fatalities.” A worst-case reactor accident, resulting in fatalities, initiated by a worst-case earthquake, would only occur in U.S. about once in a billion reactor-years of operation. The report puts this risk into context by comparison: "Based both on worldwide experience and estimates such as described above, extrapolation indicates that up to 100,000 fatalities might occur for a severe earthquake occurring in the U.S.". If one nuclear power plant were put into the same geographic location, it would add 1,000 to 2,500 additional fatalities, a one-percent increase. Figure 3b shows the probability per reactor-year for latent cancer fatalities.

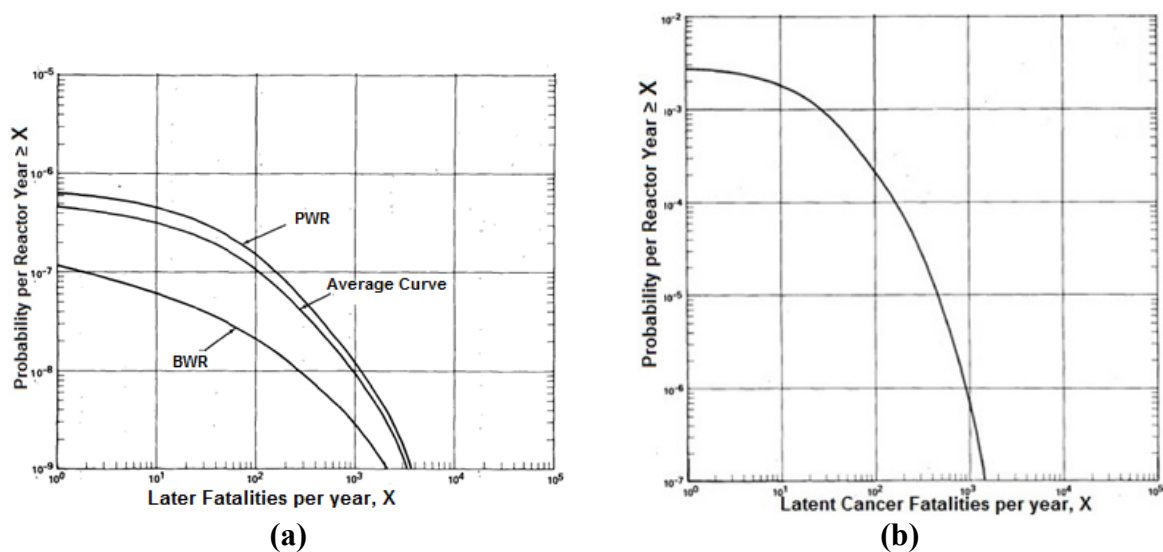


Figure 3: Probability per reactor-year for early (a) and latent cancer fatalities (b) [6]

### 3.2. NUREG-1150

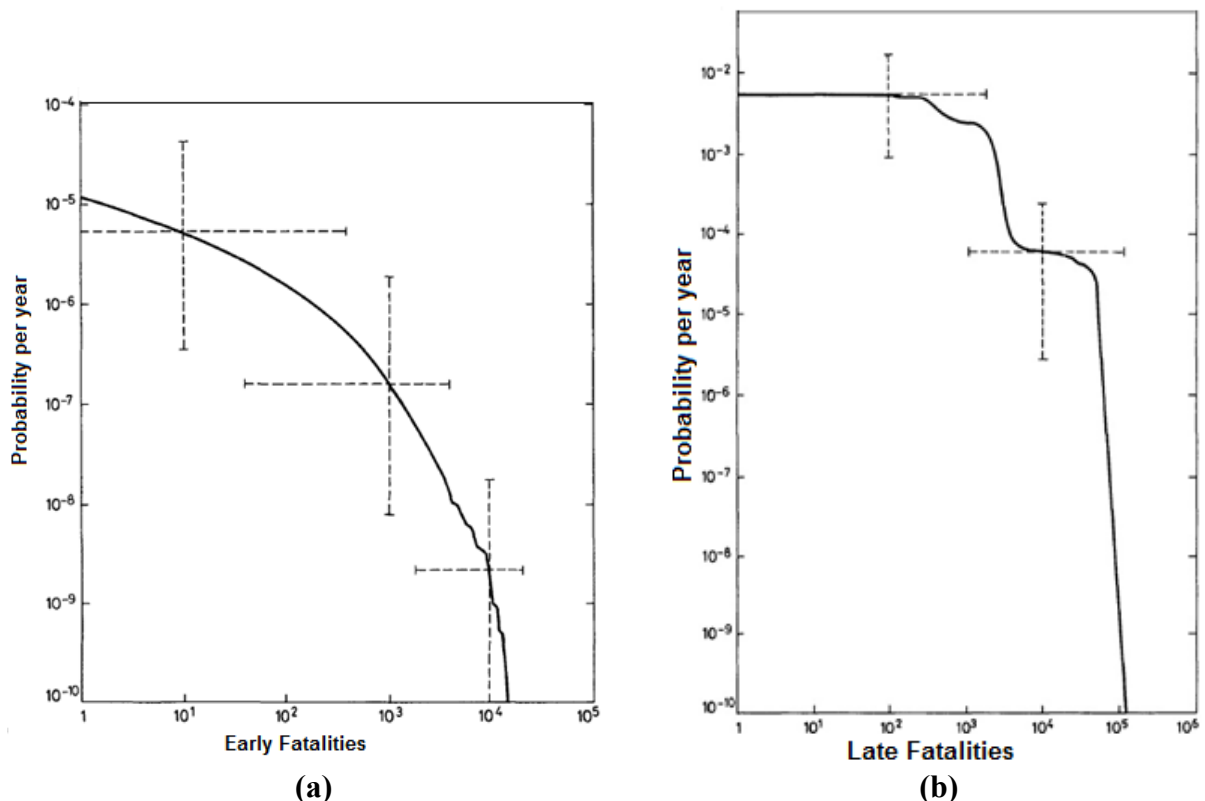
NUREG-1150 [8] “Severe Accident Risks: An Assessment for Five U.S. Nuclear Power Plants,” was issued in 1990. It reviews the two reactor types considered in WASH-1400, using improved methods of analysis and expanding the analysis to include three more specific plant designs. It evaluates two BWRs and three PWRs, which operated sufficiently long time to provide a valid database. Considering the features of the analysed plants, and how the plant-specific differences in design make difference in the calculated mean frequency core damage, risk comparison obtained are shown in Table 3. It was verified the need to be meticulous when comparing numbers for the five different technologies, all with different types of containment that resulted in different values for the core damage frequency.

**Table 3: Nuclear Power Plants risks comparison [8]**

Attribute	Surry	Peach Bottom	Sequoyah	Grand Gulf	Sion
CDF per reactor-year	$3 \times 10^{-5}$	$3 \times 10^{-6}$	$4 \times 10^{-5}$	$3 \times 10^{-6}$	$2 \times 10^{-4}$
Possible internal accident sequences	5	4	5	2	6
Range of time to core damage	5 min to 8 hours	15 min to 13 hours	Not provided	205 min to 12 hours	Not provided
Maximum early fatalities	1,000	3	3,000	30	10,000

### 3.3. German Risk Study

Results of the “German Risk Study for Nuclear Power Plants” [9] were published in 1979. The main objective of such report was to apply as far as possible the methods of “U.S. Reactor Safety Study” to German plants and site conditions. To calculate the societal risk resulting from reactor accidents, a total of 25 plants at 19 different sites in the Federal Republic of Germany were considered. The probability per year for early and late fatalities for these 25 German plants are presented in Figures 4a and 4b, respectively.

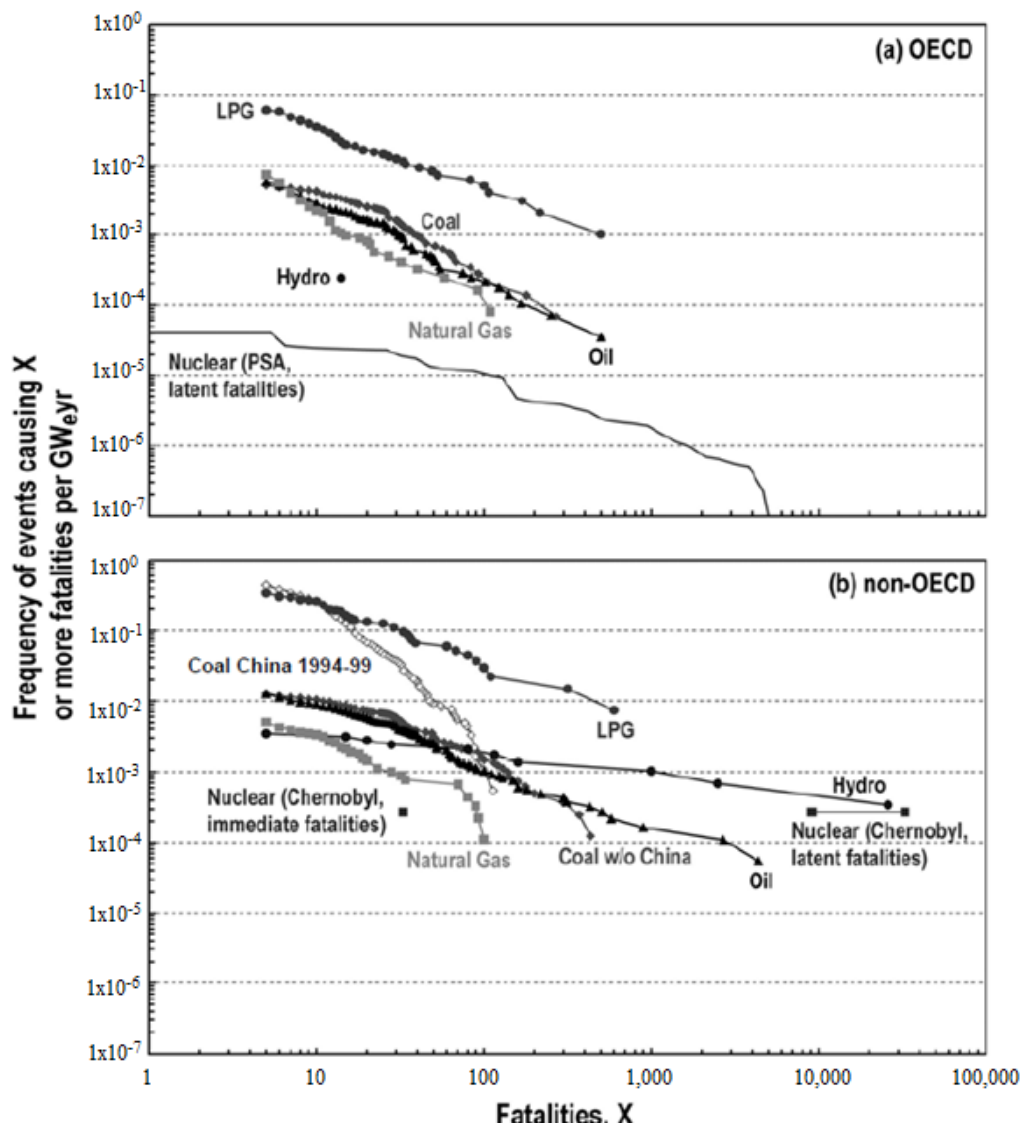


**Figure 4: Probability per year for early (a) and late (b) fatalities (a) for 25 German plants [9]**

### 3.4. Comparisons among Frequency-Consequence Curves in the Energy Sector

Figure 5 shows a study comparing frequency-consequence curves for full energy chains. It is based on historical experience on severe accidents ( $\geq 5$  fatalities) in OECD and non-OECD countries [1]. For OECD countries (Figure 5a), fossil energy chains show higher historical frequencies of severe accidents than hydro, with Liquefied Petroleum Gas (LPG) exhibiting the greatest risks and natural gas minors

According to that study, nuclear energy in OECD countries is very safe in comparison with fossil chains; there were no accidents resulting in five or more prompt deaths. The comparisons shown in Figure 5a refer to latent fatalities for a Swiss nuclear power plant. For non-OECD countries (Figure 5b) there were 31 immediate fatalities related to Chernobyl accident. The estimated latent fatalities ranging from 9,000 to 33,000 for this accident are also included in the analysis. It should be noticed that these comparisons were carried out in 2010, before the Fukushima accident.



**Figure 5: Comparisons among frequency-consequence curves for full energy chains, based on historical experience on severe accidents ( $\geq 5$  fatalities) (adapted from [1])**

#### 4. ANALYSIS OF FN-CURVE FOR SEVERE ACCIDENTS AFTER FUKUSHIMA

In order to analyse the FN-curve for severe nuclear reactor accidents in light of Fukushima events it is at first necessary to compare the theoretical distribution of CDF along time with core damage historical data.

##### 4.1 Core Damage Frequency Trend

The consequences of Fukushima accident are far worse than the reported two early fatalities. Excess lifetime cancer incidents were estimated to be between 360 and 850, whereas 220–520 of them will be fatal [10, 11]. On the other hand, the latent fatalities are much lower than that resulting from the tsunami itself (nearly 20,000, and also smaller than the accident of Chernobyl (9,000-33,000). Table 4 shows reactor accidents involving partial core meltdown in the nuclear power industry [12].

**Table 4: Partial core meltdown accidents in the nuclear power industry [12]**

Year	Unit	Reactor Type	Early Fatalities	Power MWe
1959	USA Sodium Reactor Experiment	Sodium-cooled, graphite-moderated, thermal power reactor	3	6.5
1961	Stationary Low Power Reactor	Experimental, gas-cooled, water moderated	-	0.3
1966	Enrico Fermi Unit 1	Liquid metal fast breeder reactor (LMFBR)	-	61
1967	Scotland Chapelcross Unit 2	Gas-cooled, graphite-moderated	-	50
1969	Saint-Laurent A-1	Gas-cooled, graphite moderated	-	390
1979	Three Mile Island Unit 2	Pressurized Water Reactor (PWR)	-	776
1980	Saint-Laurent A-2	Gas-cooled, graphite moderated	-	450
1986	Chernobyl Unit 4	RBKM-1000	31	925
1989	Greifswald Unit 5	Pressurized Water Reactor (PWR)	-	408
2011	Fukushima Daiichi Units 1, 2 and 3	Boiling Water Reactor (BWR)	2	439-760-760

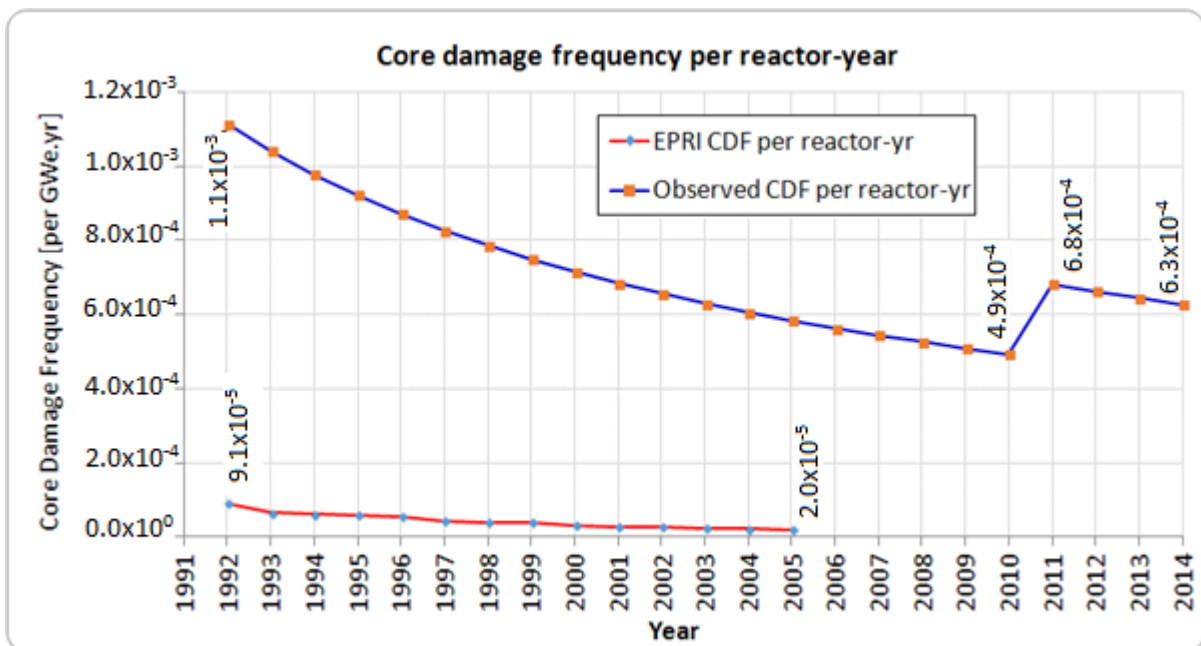
Preliminary statistical analysis of CDF historical data apparently shows that the Fukushima accident results in a significant increase in the expected frequency of severe accidents in nuclear reactors. According to EPRI [7], the estimated average CDF is of the order of  $2 \times 10^{-5}$  per reactor-year. This means that an average of one accident per 50,000 reactor-years was expected. That seems to be an optimistic estimation when compared to the observed nuclear power historic data. Considering the end of 2014, approximately 16,000 operating years of nuclear reactors (Table 5) and 10 core meltdowns (see Table 4, discarding the accidents in experimental reactors), this implies an observed frequency of nearly one accident per 1,600 reactor-year. This is a higher rate than that predicted by the PSA studies (examples in Table 3) and by the nuclear industry trend (Figure 2). Figures 6a and 6b show the estimated CDF using historical data of accidents per GWe-year and per reactor-year, respectively, for the period 1992-2014.



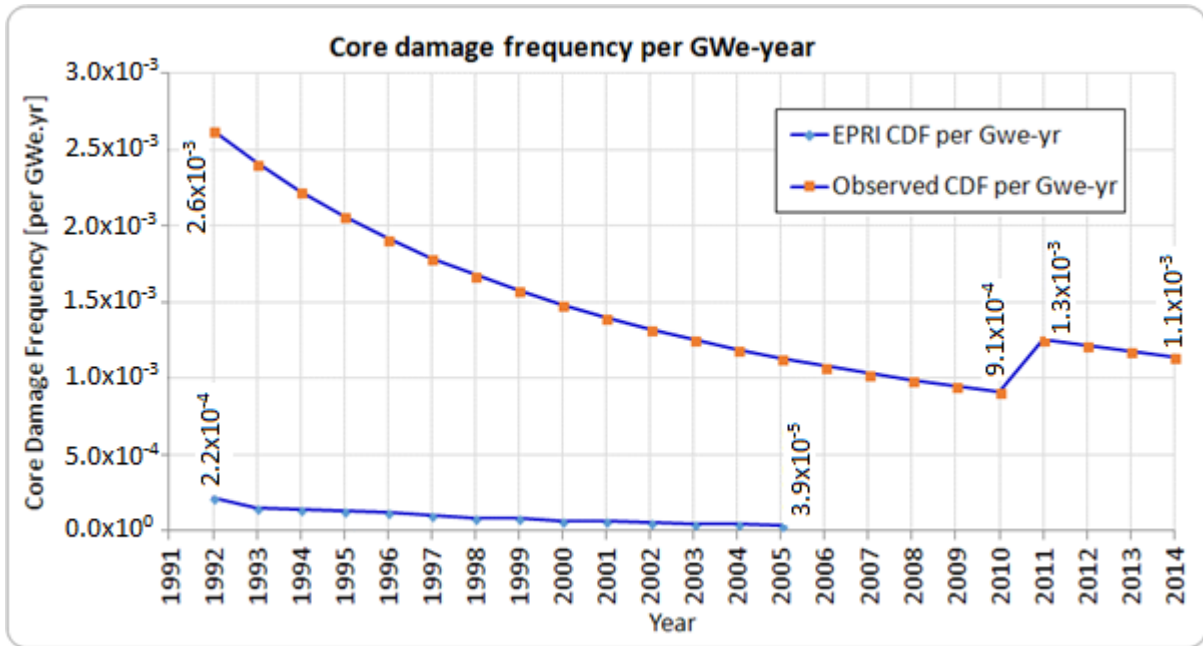
**Table 5: Trend in electricity supplied by nuclear reactor for the period 1989-2014 [13]**

Year	Reactors	Accumulated reactor-year	Accumulated GWe-year	Year	Reactors	Accumulated reactor-year	Accumulated GWe-year
1989	424	5,029	1,675	2002	444	10,660	5,301
1990	420	5,449	2,002	2003	443	11,103	5,587
1991	418	5,867	2,332	2004	443	11,546	5,886
1992	421	6,288	2,665	2005	443	11,989	6,186
1993	430	6,718	2,902	2006	443	12,432	6,490
1994	433	7,151	3,143	2007	439	12,871	6,787
1995	436	7,587	3,393	2008	439	13,310	7,084
1996	440	8,027	3,652	2009	440	13,750	7,376
1997	441	8,468	3,910	2010	442	14,192	7,676
1998	438	8,906	4,173	2011	448	14,640	7,963
1999	434	9,340	4,444	2012	440	15,080	8,231
2000	438	9,778	4,723	2013	441	15,521	8,501
2001	438	10,216	5,010	2014	439	15,960	8,776

Even though the reported accidents are related to different reactor technologies and countries, with different levels of safety and licensing requirements, the observed CDF values are more than one order of magnitude higher than the severe accidents expected rate in the EPRI report for the period 1992-2005 (Figures 6a and 6b).



**Figure 6a: Estimated CDF using historical data of accidents per reactor-year (1992-2014) compared with EPRI CDF expected rate (1992-2005)**



**Figure 6b: Estimated CDF using historical data of accidents per GWe-year (1992-2014) compared with EPRI CDF expected rate (1992-2005)**

#### 4.2 FN-Curves Analysis

The FN-curves analysis was done considering historical of severe accidents in nuclear reactors, including Fukushima events. A GWe-year reference was adopted instead of reactor-year, in order to take into account different reactor powers. As illustrated in Figure 7a, when adopting such reference the apparent differences disappear between the FN-curves of Wash-1400 (average curve in Figure 3a) and the German Risk Study (Figure 4a) for early fatalities. Considering Chernobyl and Fukushima accidents for both early (Table 6a and Figure 7a) and late (Table 6b and Figure 7b) fatalities, the PSA studies seems also to be very realistic compared with historical data .

**Table 6 – FN calculations for early (a) and late (b) fatalities**

Event	Frequency [per GWe-year]	Fatalities	Cumulative Frequency [per GWe-year]
Fukushima	$1.3 \times 10^{-4}$	2	$7.2 \times 10^{-4}$
Chernobyl	$6.0 \times 10^{-4}$	31	$6.0 \times 10^{-4}$

(a)

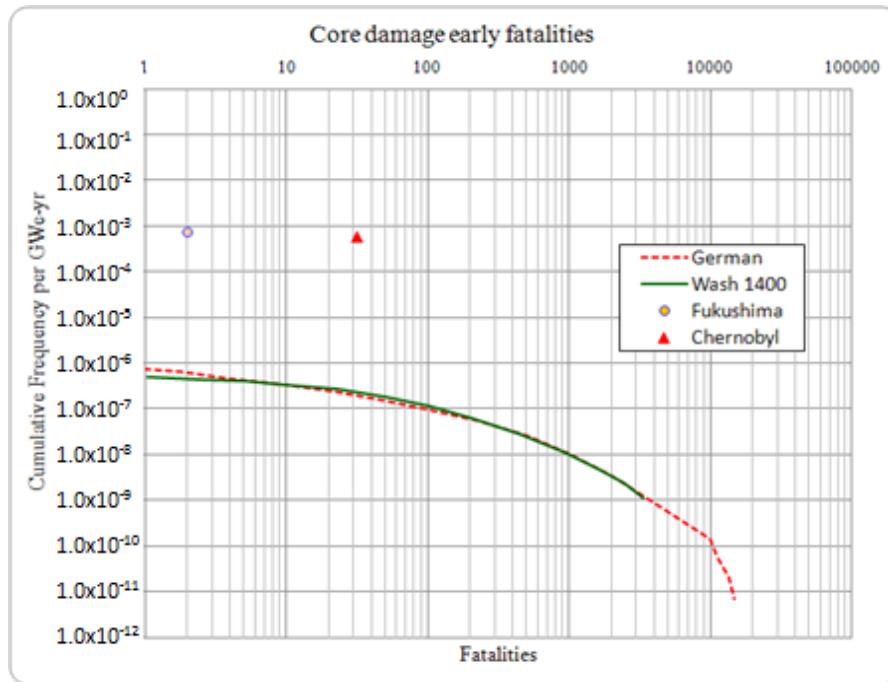
Event	Frequency [per GWe-year]	Fatalities	Cumulative Frequency [per GWe-year]
Fukushima	$1.3 \times 10^{-4}$	220-520	$7.2 \times 10^{-4}$
Chernobyl	$6.0 \times 10^{-4}$	9,000 - 33,000	$6.0 \times 10^{-4}$

(b)

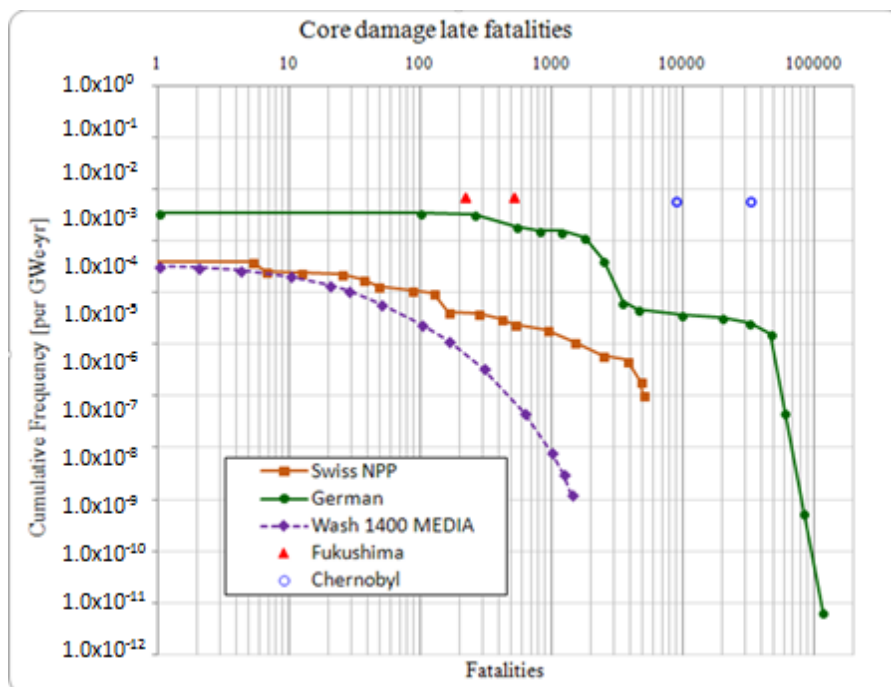
## 5. CONCLUSIONS

This work reviews the FN-curves related to severe accidents in nuclear reactors in light of historical accidents, including Fukushima events. A GWe-year reference basis was adopted in

order to take into account different reactor powers. It was noticed that Wash-1400 and German risk studies present nearly the same estimates for early fatalities, which was not so clear in a reactor-year basis. Both frequency-consequence and CDF studies show that PSA studies seem to be very optimistic faced to historical data of severe accidents. This preliminary study shows that FN-curves, CDF trends and safety goals related to current nuclear reactors needs to be reviewed taking into account historical data.



(a)



(b)

**Figure 7: FN curves for early fatalities (a) and late fatalities (b) per GWe-year (including Chernobyl and Fukushima points)**

## ACKNOWLEDGMENTS

The authors would like to thank the following institutions, which sponsored this work: CDTN/CNEN (Centro de Desenvolvimento de Tecnologia Nuclear/Comissão Nacional de Energia Nuclear), FINEP (Financiadora de Estudos e Projetos) and FAPEMIG (Fundação de Amparo à Pesquisa do Estado de Minas Gerais).

## REFERENCES

1. NEA/OECD, Nuclear Energy Agency/Organization for Economic Co-Operation and Development, *Comparing Nuclear Accident Risks with Those from Other Energy Sources*, NEA 6861, Paris, France (2010).
2. L. E. Rangel, F. Lévêque, *How Fukushima-Daiichi Core Meltdown Changed the Probability of Nuclear Accidents?* CERNA Mines ParisTech, Paris, France (2013).
3. CCPS - Center for Chemical Process Safety, American Institute of Chemical Engineers, *Guidelines for Developing Quantitative Safety Risk Criteria*, John Wiley & Sons, Inc., New Jersey, USA (2009).
4. L. Debesse, *The Use of Frequency-Consequence Curves in Future Reactor Licensing*. (Submitted to the Engineering Systems Division of the Department of Nuclear Science and Engineering in partial fulfilment of the requirements for the Degree of Master Science in Technologies and Policies), Echole Polytechnique, Paris, France (2007).
5. J. E. Holmber, M. Knochenhauer, *Probabilistic Safety Goals. Phase 1 – Status and experiences in Sweden and Finland*. SKI report 07/06-SE, Roskilde, Denmark, (2007).
6. USNRC, U.S. Nuclear Regulatory Commission, *WASH-1400 – Reactor Safety Study*, NUREG-75/014, Washington, USA (1975).
7. EPRI, Electric Power Research Institute, *Safety and Operational Benefits of Risk-Informed Initiatives*. Technical Report, Washington, USA (2008).
8. USNRC, U.S. Nuclear Regulatory Commission, *Severe Accident Risks: An assessment for five U.S. Nuclear Power Plants*, NUREG-1150, Washington, USA (1990).
9. A. Birkhofer, “The German Risk Study for Nuclear Power Plants”, *IAEA Bulletin*, **Vol. 22**, N. 5/6, pp.13-22 (1980).
10. WHO, World Health Organization, *Health Risk Assessment from the Nuclear Accident after the 2011 Great East Japan Earthquake and Tsunami based on a Preliminary Dose Estimation*, Geneva, Switzerland (2003).
11. N. Evangelidou, Y. Balkanski, A. Cozic, A. P. Møller, “Global and Local Cancer Risks after the Fukushima Nuclear Power Plant Accident as Seen from Chernobyl: A modelling study for radio-caesium ( $^{134}\text{Cs}$  &  $^{137}\text{Cs}$ )”. *Environment International*, **Vol. 64**, pp.17–27 (2014).
12. T. Cochran, *Fukushima Nuclear Disaster and its Implications for U.S. Nuclear Power Reactors*, Natural Resources Defense Council, Washington, USA (2011).
13. IAEA, International Atomic Energy Agency, “Trend in Electricity Supplied - Sum of electricity supplied from reactors connected to the grid”, PRIS - Power Reactor Information System, <http://www.iaea.org/PRIS/WorldStatistics/WorldTrendinElectricalProduction.aspx> (2015).