2007 International Nuclear Atlantic Conference - INAC 2007
Santos, SP, Brazil, September 30 to October 5, 2007
ASSOCIAÇÃO BRASILEIRA DE ENERGIA NUCLEAR - ABEN
ISBN: 978-85-99141-02-1

A STUDY ON DOMINO EFFECT IN NUCLEAR FUEL CYCLE FACILITIES

Jean–Claude Bozzolan and José Messias de Oliveira Neto

Instituto de Pesquisas Energéticas e Nucleares (IPEN / CNEN - SP)
Av. Professor Lineu Prestes 2242
05508-000 São Paulo, SP
jcbozzol@ipen.br
messias@usp.br

ABSTRACT

Accidents caused by domino effect are among the most severe accidents in the chemical and process industry. Although the destructive potential of these accidental scenarios is widely known, little attention has been paid to this problem in the technical literature and a complete methodology for quantitative assessment of domino accidents contribution to industrial risk is still lacking. The present study proposes a systematic procedure for the quantitative assessment of the risk caused by domino effect in chemical plants that are part of nuclear fuel cycle plants. This work is based on recent advances in the modeling of fire and explosion damage to process equipment due to different escalation vectors (heat radiation, overpressure and fragment projection). Available data from literature and specific vulnerability models derived for several categories of process equipment had been used in the present work. The proposed procedure can be applied to conversion and reconversion plants of the nuclear fuel cycle. The top-events and escalation vectors are identified, their consequences estimated and credible domino scenarios selected on the basis of their frequencies.

1. INTRODUCTION

The present study defines domino effect as an accident in which a primary event occurring in primary equipment propagates to nearby equipment, triggering one or more secondary events with severe consequences for industrial plants. So three elements characterize the domino effect: a primary accidental scenario which triggers the phenomenon, a propagation effect event (“escalation vector”) due to the consequences of the primary event and one or more secondary accidental scenarios affecting the same or different industrial plants.

The present methodology will consider only secondary accidental events. Historical data analysis show that only 5% of industrial accidents in which domino effect takes place cause tertiary accidental events. Only 1% of the accidents higher order accidental events occur.

Nuclear fuel cycle facilities have numerous chemical plants producing and processing radioactive materials and hazardous substances similar to those found in conventional chemical process industries and storage sites. The processes employed and materials manipulated and stocked are potential sources of hazard causing accidents as fire, explosion, fragments projection and toxic material release.

2. RISK QUANTITATIVE ANALYSIS AND DOMINO EFFECT

2.1. Introduction

Taking the domino effect into consideration when executing a quantitative risk analysis permit the identification of the accidental scenarios susceptible to generate the escalation of the event over the plant or neighboring plant and justify the implementation of specific measures to prevent this escalation. Legislations and technical patterns, worried about the eventuality of major accidents, suggest measures for the assessment, control and prevention of domino effect. The European legislation (Directive "SEVESO II" 96/82/EC) [1] requires the assessment of the domino effect hazard to large industrial area involving plants, at which substantial amounts of dangerous substances are produced, stored or processed.

2.2. A methodology for assessing domino effect

A complete methodology for assessing the domino effect is not yet available despite the attention given by governments to the assessment and prevention of domino effect. Some previous studies had mainly involved qualitative methodologies assessments [2, 3, 4] but a quantitative analysis is still lacking.

2.3. The ARAMIS Methodology

The overall objective of ARAMIS Methodology is to build up a new Accidental Risk Assessment Methodology for Industries that combines both deterministic and risk-based approaches. This methodology is in harmony with the implementation of the European legislation SEVESO II.

ARAMIS is divided into four major steps:

1. Definition of the reference scenarios

    - identification of the major accident hazards (MIMAH)
    - definition of safety systems
    - definition of the reference accident scenarios (MIRAS)

2. Assessment of the management efficiency
3. Risk severity mapping from the set of Reference Accident Scenarios
4. Vulnerability mapping representing the sensitivity of one plant's surrounding environment

These are assessment tools which can be integrally or partially extracted and used in conjunction with other methodologies such as a comprehensive Quantitative Risk Assessment (QRA) for major accidents.

3. METHODOLOGY FOR A DOMINO EFFECT ANALYSIS

The methodology proposed for the assessment of the Domino Effect follows four main stages: (1) identification of primary accidental events; (2) assessment of the consequences of the primary accidental events; (3) identification of the secondary accidental events; and (4) assessment of the consequences and frequencies of the secondary accidental events.

3.1. Identification of primary accidental events

MIMAH is the ARAMIS method for the identification of major accident hazards. It is based mainly on the use of “bow-tie” diagrams composed of a fault tree and an event tree. The major input of ARAMIS was to define a precise bow tie structure and to define the list of equipment, potential critical events and their consequences. The critical events were defined to be either loss of containment for fluids or loss of physical integrity for solids. From a description of the plant including the chemical substances used, produced or stored, it is possible from MIMAH to list of all the critical events susceptible to occur in the plant. Then, for each of these critical events, MIMAH allows to identify all their consequences in terms of secondary events and dangerous phenomena.

MIMAH involved 7 main steps:

- Step 1: Collection of needed information
- Step 2: Identification of potentially hazardous equipment in the plant
- Step 3: Selection of relevant hazardous equipment
- Step 4: Association of critical events for each selected equipment
- Step 5: Construction of a fault tree for each critical event
- Step 6: Construction of an event tree for each critical event
- Step 7: Construction of the complete bow-ties for each selected equipment.

This first stage of the proposed methodology allows really the identification of potentially hazardous equipment in the plant and to select relevant hazardous equipments susceptible to generate major accidents and the domino effect. A complete description of the steps to be followed can be extracted from the ARAMIS User Guide [5].

3.2. Identification of secondary accidental events

3.2.1 Introduction

After the identification of the primary accidental events (stage 1), the escalation vectors associated to each scenario should be defined (stage 2).

This stage of the methodology overall objective is to check the likelihood of the secondary accidental events and to quantify the resultant consequences of primary accidental events, characterized by the dangerous phenomena (primary accidental events) associates to each dangerous equipment selected in the previous stage. Models are used to quantify the consequences of fires and explosions and fragments impacts. Computational codes for physical Quantitative Consequence and Risk Analysis, such as the DNV SAFETI® or similar softwares can be used in support. These codes, used in conventional Chemical Process Industries, are appropriate for the objectives of the present methodology for the assessment of domino effect in nuclear fuel cycle facilities.

Effect Models predicts effects of the outcomes due to thermal radiation, overpressure and fragments impacts with respect to property damage. For the purpose of this study effect models with respect to human injury and fatality are not considered.

The methodology is followed for the calculation of risk due to the accidental scenarios caused by domino effects. In particular, the expected frequency of the secondary scenario is calculated by means of the following equation:

$$f_{D} = f_{I} . P_{D} \qquad (1)$$

where f_D is the resulting frequency of the domino event, f_I the expected frequency of the primary top event, P_D the probability of occurrence of the domino effect.

$$P_D = P_S . P_d . P_e \quad (2)$$

where P_s is the probability of the scenario causing the propagation, P_d the equipment damage probability, and P_e the probability of the secondary scenario given the failure of the target unit.

V.Cozzani e E.Salzano [6, 8] used a simplified model to assess the process equipment damage probability caused by blast wave and thermal radiation. The authors defined a probability function called "probit function" (Y) to relate equipment damage to the peak static overpressure or time to failure of the target equipment under fire:

$$Y = k_1 + k_2 \ln(V) \quad (3)$$

where Y is the probit for equipment damage, V is the damage variable, ie the overpressure Ps on the target equipment or time to failure (ttf) of the secondary equipment involved in the fire, k_1 and k_2 are the probit coefficients.

3.2.2 Escalation vectors and threshold values

Accidental event sequences where a relevant domino effect takes place have at least three features: (1) a primary accidental scenario due to a lost of containment, which initiates the domino accidental escalation; (2) the propagation of the primary event, due to an "escalation vector" generated by the physical effects of the primary scenario resulting in the damage of at least one secondary equipment; (3) one or more secondary events (ie fire, explosion and fragment flight), involving the damaged equipment.

Escalation vectors are the physical effects responsible of the escalation that start the secondary scenarios. Three escalation vectors are considered: radiation/fire impingement, overpressure and fragment projection. Toxic release was considered as a possible escalation vector by some authors [7], but this release may cause escalation effects due only to errors in emergency procedures and/or in emergency management following the primary accident.

Damage propagation models developed by *Valerio Cozzani* [8, 9, 10, 11, 12], *Ernesto Salzano* [8, 9, 12], *Severino Zanelli* [10, 11], *Gianfilippo Gubinelli* [10, 11, 12], *Giacomo Antonioni* [10] and *Gigliola Spadoni* [10] in the framework of the quantitative assessment of domino effects are used to assess the credibility of escalation and to obtain specific threshold values for the different accidental scenarios. A threshold value is defined as the maximum value of the escalation vector below which the reference damage is not credible. Only radiation/fire impingement, overpressure and fragment projection are considered by these authors analysis, as escalation vectors. Toxic release is excluded because this physical effect does not result directly in a loss of containment or in the damage of secondary equipment.

The authors study focused on the revision and on the improvement for this escalation credibility. First, the threshold criteria for different categories of process equipment were obtained with respect to the escalation vectors of concern. Finally revised threshold values were proposed, and specific escalation criteria were obtained for the primary scenarios more frequently considered in the risk assessment of industrial sites.

3.2.3 Escalation vectors, threshold values and frequencies with respect to overpressure

V. Cozzani and E. Salzano [8] defines 3 threshold values $P_{L,\ ED1\_IP1}$; $P_{L,\ ED2\_IP2}$ and $P_{L,\ ED2\_IP3}$ related to the escalation of accidental scenarios due to overpressure. The expected damage due to overpressure is usually assessed considering the peak static overpressure on the target item, but many other factors may influence the damage due to blast waves. In fact, the likelihood of escalation following the damage is dependent on structural damage states (DS) and of loss intensities (LI). For the purposes of the authors study, the structural damage state DS of equipment items was described by two classes: DS1, light damage to the structure or to the auxiliary equipment and DS2, intense damage or even total collapse of the structure. Three loss intensity categories were defined: (1) LI1, "minor loss", defined as the partial loss of inventory, or the total loss of inventory in a time interval higher than 10 min from the impact of the blast wave; (2) LI2, "intense loss", defined as the total loss of inventory in a time interval between 1 and 10 min and (3) LI3, "catastrophic loss", defined as the "instantaneous" complete loss of inventory (complete loss in a time interval of less than 1 min).

Table 1 summarizes the expected secondary scenarios for the different damage states and loss intensities for different equipment categories. Elongated equipments are atmospheric, long, vertical and elongated vessels. Auxiliaries are "small" process equipment which ranges from pump to heat exchangers, to small volume reactors.

Table 2 summarizes the peak overpressure threshold values related to various equipment categories.

The peak overpressures obtained during the consequence analysis, eg using a computational code, will be compared with the threshold values. As a result the damage states, loss intensities and expected secondary scenarios will be defined. The expected frequency of a single escalation event, ie a primary event triggering a secondary accidental scenario, may be calculated. The quantitative assessment of domino effect requires the estimation of the escalation probability.

Table 3 summarizes the models used in the present study for the assessment of escalation probability.

Table 1. Expected secondary scenarios for the different damage state and loss intensities [8]

Damage State	Loss Intensity	Expected secondary scenarios			
		Equipment category			
		Atmospheric	Pressurized	Elongated	Auxiliary
DS1	LI1, flammable	Minor pool fire	Minor jet fire	Minor pool fire	Minor pool fire
				Minor flash fire	Minor flash fire
DS1	LI1, toxic	Minor evaporation pool	Boiling pool	Minor boiling pool	Minor evaporating pool
			Jet toxic dispersion	Toxic dispersion	
DS2	LI2, flammable	Pool fire	Jet fire	Pool fire	Minor pool fire
		Flash fire	Flash fire	Flash fire	Minor flash fire
		VCE	VCE	VCE	
DS2	LI2, toxic	Evaporating pool	Boiling pool	Boiling pool	Minor evaporation pool
		Toxic dispersion	Jet toxic dispersion	Toxic dispersion	
DS2	LI3, flammable	Pool fire	BLEVE / Fireball	Pool fire	Minor pool fire
		Flash fire	Flash fire	Flash fire	Minor flash fire
		VCE	VCE	VCE	
DS2	LI3, toxic	Evaporating pool	Boiling pool	Boiling pool	Evaporating pool
		Toxic dispersion	Jet toxic dispersion	Toxic dispersion	Minor toxic dispersion

VCE, vapour cloud explosion; BLEVE, boiling liquid evaporating vapour explosion. “Flammable” and “toxic refer to the substance in the secondary vessel damaged by the blast wave

Table 2. Peak overpressure threshold values related to various equipment categories (kPa) [8]

Threshold value	Equipment categories			
	Atmospheric	Pressurized	Elongated	Auxiliary
$P_{L,DS1\_LI1}$	7	30	14	12
$P_{L,DS2\_LI2}$	16	38	37	37
$P_{L,DS2\_LI3}$	20	61	45	59

Table 3. Models for escalation probability related to various equipment categories [10]

Escalation vector and primary scenario	Target equipment	Model for escalation probability
Overpressure All overpressure scenarios	Atmospheric vessel	*Ps*: peak static overpressure on the target equipment (kPa)
		Y = - 18,96 + 2,44 ln (*Ps*)
	Pressurized vessel	Y = - 42,44 + 4,33 ln (*Ps*)
	Elongated vessel	Y = - 28,07 + 3,16 ln (*Ps*)
	Auxiliary	Y = - 17,79 + 2,18 ln (*Ps*)

3.2.4 Escalation vectors, threshold values and frequencies with respect to radiation intensity and fire impingement

The assessment of escalation is addressed considering the radiation intensity, the time evolution of the accidental event and the characteristics of the secondary target. The main element to consider is that the duration of the primary scenario should be at least comparable with the characteristic "time to failure" (ttf) of the secondary equipment involved in the fire. This in turn depends on the equipment design (eg pressurized vessels have a higher ttf than atmospheric storage tanks). The vessel may be fully or partially engulfed by a fire, a flame impingement may be present or heat radiation may come from a distant source. Radiation and fire impingement are the escalation vectors and the duration of the primary scenario the damage threshold value of a possible secondary target.

Table 4 summarizes the escalation vectors and expected secondary scenarios for flammable materials for the different primary scenarios.

Table 5 summarizes the models for escalation used in V.Cozzani, E.Salzano, S.Zanelli and G.Gubinelli study derived from the revision of literature data and from the application of equipment damage models, performed in a recent study.

For other target equipment categories some general conclusions may be drawn on the basis of the authors study: (1) for a representative set of unprotected atmospheric vessels, the ttf values result higher than 30 min for radiation intensities lower than 10 kW/m^2; (2) for a representative set of unprotected pressurized vessels, the ttf values result higher than 30 min for radiation intensities lower than 40 kW/m^2.

The time evolution of the accidental event obtained during the consequence analysis, eg using a computational code, will be compared with the time to failure (ttf) of the secondary equipment involved in the fire. As a result the damage states, loss intensities and expected secondary scenarios will be defined. The expected frequency of a single escalation event, ie a primary event triggering a secondary accidental scenario, may be calculated. The quantitative assessment of domino effect requires the estimation of the escalation probability.

Table 6 summarizes the models used in the present study for the assessment of escalation probability.

Table 4. Escalation vectors and expected secondary scenarios for the different primary scenarios [12]

Primary scenario	Escalation vector	Expected secondary scenario
Pool fire	Radiation, fire impingement	Jet fire, pool fire, BLEVE, toxic release
Jet fire	Radiation, fire impingement	Jet fire, pool fire, BLEVE, toxic release
Fireball	Radiation, fire impingement	Tank fire
Flash fire	Radiation, fire impingement	Tank fire

Table 5. Escalation vectors and expected secondary scenarios for the different primary [10]

Escalation vector and primary scenario	Target equipment	Simplified models for ttf vs radiation
Radiation All radiation scenarios	Atmospheric vertical cylindrical vessels	$\ln(\mathrm{tff}) = -1{,}128.\ln(I) - 2{,}667.10^{-5}.V + 9{,}877$ I: radiation intensity on the target equipment (kW/m^2) V: equipment volume (m^3)
	Pressurized horizontal cylindrical vessels	$\ln(\mathrm{tff}) = -0{,}947.\ln(I) + 8{,}835.V^{0{,}032}$ I: radiation intensity on the target equipment (kW/m^2) V: equipment volume (m^3)

Table 6. Models for escalation probability related to various equipment categories [10]

Escalation vector and primary scenario	Target equipment	Model for escalation probability
Radiation All radiation scenarios	Atmospheric vertical cylindrical vessels	tff (s): time to failure of the target equipment
		$Y = 12{,}54 - 1{,}847.\ln(\mathrm{tff})$
	Pressurized horizontal cylindrical vessels	$Y = 12{,}54 - 1{,}847.\ln(\mathrm{tff})$

3.2.5 Escalation vectors, threshold values and frequencies with respect to fragments projection

Two escalation vectors may be generated from mechanical explosions: the blast wave following the failure of the vessel, as stated above, and the fragments that may be generated in the vessel failure. Escalation may be caused by missile projection if a fragment impacts on a target vessel, causing a loss of containment. So two conditions must be verified: (1) the distance of the target vessel must be lower than the maximum projection distance and (2) the impact must be followed by a loss of containment at the target vessel.

Chapter 7 of the *Methods for the calculation of physical effects* "Yellow Book"*CPR 14E* [13] gives an overview of the existing methods for assessing the blast fragmentation effects of a vessel burst coupled with missile effects. The so called method for fragmentation effects determines the range of flying fragments, i.e. their maximum projection distances.

A model was developed by *G.Gubinelli , S.Zanelli and V.Cozzani* [11] for the assessment of fragment impact probability on a target vessel, following the collapse and fragmentation of a primary vessel due to mechanical explosions. The model provides the probability of impact of a fragment with defined shape, mass and initial velocity on a target equipment of a known shape situated at a given position with respect to the primary equipment.

The model developed by the authors permit the assessment of the probability $P_{\mathrm{d,F}}$ of the event sequence for a single fragment and is expressed as:

$$\boldsymbol{P}_{\mathbf{d,F}} = \boldsymbol{P}_{\mathbf{gen,F}} \text{ x } \boldsymbol{P}_{\mathbf{imp,F}} \text{ x } \boldsymbol{P}_{\mathbf{dam,F}} \tag{4}$$

where

- $P_{\mathrm{gen,F}}$ is the probability of the fragment F (with defined mass, shape and initial velocity) to be generated in the primary event;
- $P_{\mathrm{imp,F}}$ is the probability of impact between the fragment and a target;
- $P_{\mathrm{dam,F}}$ is the probability of target damage given the impact with the fragment.

The expected frequency of a domino event caused by various fragments impacting on a secondary target, *f*d, can be expressed as:

$$\boldsymbol{f}_{\mathbf{d}} = \boldsymbol{f}_{\mathbf{p}} \times \boldsymbol{P}_{\mathbf{d}} = \boldsymbol{f}_{\mathbf{p}} \times \sum_{\mathbf{F}} \boldsymbol{P}_{\mathbf{d,F}} \tag{5}$$

where *f*p is the expected frequency of the primary event.

A usual conservative hypothesis is to assume a unit value for the probabilities $P_{\mathrm{gen,F}}$ and $P_{\mathrm{dam,F}}$.
The *G.Gubinelli , S.Zanelli and V.Cozzani* [11] study focused on the estimation of the impact probability ($P_{\mathrm{imp,F}}$) of a fragment with defined shape, mass and initial velocity on a given target.

3.3 Case Study

To illustrate the methodology described in this paper, a tank storage site of a generic nuclear fuel cycle complex was analyzed. The activities related to the operation of fuel cycle facilities require addressing not only radiological hazards, but also other hazards associated with the processing chemicals used as raw materials.

The tank storage site was assumed to store hydrogen fluoride, ammonia, propane, methanol, carbon dioxide and hydrogen. Each tank is assumed to be at a distance of about 20m of each other, so that it is possible to occur an interaction between them in case of an accident.

By applying the method described in Section 3 it was found that the methanol tank could be discarded as a possible source of primary events. Twenty four dangerous events were selected to be analyzed in detail. Six of them were found to have frequencies higher than 10^{-7} events/year, so that they were considered as credible.

The escalation vectors related to these accidents were associated with thermal radiation, overpressure and missile generation and impact. The main secondary effects triggered by the top-events or primary events were found to be BLEVE and vapor cloud explosion. It was also found that, for the tanks layout analyzed, the escalation vector associated with missile impact, had a negligible contribution. The calculated frequencies were of the order of 10^{-10} to 10^{-16} events/year, so that they could be considered inconceivable.

Although the example chosen to illustrate the domino effect is not taken from a real facility, the results indicate that this effect should not be of great concern in fuel cycle installations, provided that some design variables are properly addressed. An obvious parameter is the minimum distance between the storage tanks, which plays an important role in minimizing the consequences of the escalation vectors.

Due to the limited space available, detailed results are not shown in the present paper. The interested reader will find details in the study "*Um estudo sobre o efeito dominó em instalações do ciclo do combustível nuclea*r" [14]. This study proposes a complete systematic procedure for the quantitative assessment of the risk caused by domino effect in the nuclear fuel cycle chemical plants. This work is based on recent advances in the modeling of fire and explosion damage to process equipment due to the different escalation vectors and the studies of damage propagation models developed by *Valerio Cozzani* [8, 9, 10, 11, 12]*, Ernesto Salzano* [8, 9, 12]*, Severino Zanelli* [10, 11 *Gianfilippo Gubinelli* [10, 11, 12], *Giacomo Antonioni* [10] and *Gigliola Spadoni* [10] in the framework of the quantitative assessment of domino effects. The top-events and escalation vectors were identified, their consequences estimated and credible domino scenarios selected on the basis of their frequencies.

4. CONCLUSIONS

As a suggestion the study recommends the development of a computer-automated methodology which could be used in support to enable one to predict (1) whether domino effects are likely to occur in a given plant, (2) if they do occur what would be the likely accident scenarios, and (3) the likely impacts of these accident scenarios**.**

REFERENCES

1. The Council of the European Union. "Council Directive 96/82/EC on the control of major-accident hazards involving dangerous substances", *Official Journal of the European Communities*, LO10/97, 1996.
2. J. Gledhill; I. Lines, "Development of methods to assess the significance of domino effects from major hazard sites**",** (*HSE Report WSA/RSU8000/105*). (1998).
3. D.F. Bagster; R.M. Pitblado, "The estimation of domino incident frequencies – an approach", *Process Safety Environment,***Vol. 69B, 196, (1991).**
4. S. Contini, S. Boy; M. Atkinson,; N. Labath; M. Banca; J.P Nordvik, "Domino effect evaluation of major industrial installations: a computer aided methodological approach", *Proceedings of the European Seminar on Domino Effects.*, (1996).
5. The European Commission Community, "Research_ARAMIS User Guide", http://aramis.jrc.it/ (2004).
6. V. Cozzani, E. Salzano, "The quantitative assessment of domino effects caused by overpressure. Part I. Probit models", Journal of Hazardous Materials **A107** pp. 67 – 80 (2003).
7. F.I Khan, S.A Abbasi, "DOMIFFECT (DOMIno eFFECT): user-friendly software for domino effect analysis", *Environmental Modelling & Software,* **Vol.13**, pp. 163 - 177 (1998).
8. V. Cozzani, E. Salzano, "Threshold values for domino effects caused by blast wave interaction with process equipment", *Journal of Loss Prevention in the Process Industries*, **Vol.17**, pp. 437 - 447 (2004).
9. V. Cozzani, E. Salzano, "The quantitative assessment of domino effects caused by overpressure. Part I. Probit models", *Journal of Hazardous Materials*, **A107,** pp. 67 - 80 (2004).
10. V. Cozzani, G. Gubinelli, G. Antonioni, G. Spadoni, S. Zanelli, "The assessment of risk caused by domino effect in quantitative area risk analysis", *Journal of Hazardous Materials*, **A127,** pp. 14 - 30 (2005).
11. G. Gubinellia, S. Zanelli, V. Cozzani, "A simplified model for the assessment of the impact probability of fragments," *Journal of Hazardous Materials*, **A116**, pp. 175 – 187 (2004).
12. V. Cozzani, G. Gubinelli, E. Salzano, "Escalation thresholds in the assessment of domino accidental events," *Journal of Hazardous Materials*, **A129**, pp. 1– 21 (2006).
13. C.J.H. Van den Bosch (ed); R.A.P.M. Weterings (ed). *Methods for the calculation of physical effects "Yellow Book". TNO CPR 14E (Part2), third edition*, Sdu Uitgevers, The Hague, Nederland (1997).
14. J.C. Bozzolan, "Um Estudo sobre o Efeito Dominó em Instalações do Ciclo do Combustível Nuclear", Dissertação (Mestrado) – Instituto de Pesquisas Energéticas e Nucleares, São Paulo Brasil, (2006).