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Analysis of Emergency Planning Zones in Relation to Probabilistic Risk Assessment and Economic Optimization for International Reactor Innovative and Secure

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1. Introduction

Probabilistic Risk Assessment (PRA) tehniques applied to the definition of Emergency Planning Zone (EPZ) have not reached the same level of maturity when dealing with external events as PRA methodologies related only to internal events (Alzbutas et al., 2005). This is even of greater importance and relevance when PRA is used in the design phase of new reactors (IAEA-TECDOC-1511, 2006; IAEA-SSG-3, 2010; IAEA-SSG-4, 2010).

The design of the layout of a Nuclear Power Plant (NPP) within its identified site, with the arrangement of its structures, as well as the definition of the EPZ around the site can be used to maximise the plant safety related functions, thus further protecting nearby population and environment. In this regard, the design basis for NPP and site is deeply related to the effects of any postulated internal and external hazardous event and the possibilities of the reactor to cope with related accidents (i.e., to perform the plant safety related functions).

Among the objectives for advanced reactors there is the aim to establish such a higher safety level with improved design characteristics that would justify and enable revised emergency planning requirements. While providing at least the same level of protection to the public as the current regulations, ideally, but still not realistically, the total elimination of hazards' consequences would result in the EPZ coincidinge with the site boundary, thus, there would be no need for off-site evacuation planning, and the NPP would be perceived as any other industrial enterprise.

In this chapter, the International Reactor Innovative and Secure (IRIS) is adopted as a prime example of an advanced reactor with enhanced safety. The IRIS plant (Carelli, 2003, 2004, 2005) used a Safety-by-Design™ philosophy and such that its design features significantly reduced the probability and consequences of major hazardous events. In the Safety-by-Design™ approach, the PRA played a key role; therefore a Preliminary IRIS PRA had been developed along with the design, in an iterative fashion (Kling et al., 2005). This unprecedented application of the PRA techniques in the initial design phase of a reactor was also extended to the external event with the aim of reviewing the EPZ definition. To achieve this particular focus was dedicated to PRA and Balance Of Plant (BOP).

For the design and pre-licensing process of IRIS, the external events analysis included both qualitative evaluation and quantitative assessment. As a result of preliminary qualitative evaluation, the external events that had been chosen for more detailed quantitative assessment were as follows: high winds and tornadoes, aircraft crash and seismic activity (Alzbutas et al., 2005, Alzbutas & Maioli, 2008).

In general, the analysis of external events with related bounding site characteristics can also be used in order to optimize the potential future restrictions on plant siting and risk zoning. Due to this and Safety-by-Design™ approach, IRIS, apart from being a representative of innovative and advanced reactors, had the necessary prerequisite, (i.e., excellent safety), for attempting a redefinition of EPZ specification criteria, IRIS was therefore used as a test-bed.

The work presented in this chapter was performed within the scope of activities defined by the International Atomic Energy Agency (IAEA) Co-ordinated Research Project (CRP) on Small Reactors with no or infrequent on-site refuelling. Specifically, it was relevant to "Definition of the scope of requirements and broader specifications" with respect to its ultimate objective (revised evacuation requirements), and to "Identification of requirements and broader specifications for NPPs for selected representative regions" considering specific impact on countries with colder climate and increased interest for district heating co-generation.

The economic modelling and optimization presented in the second part of the chapter was concentrating on the evaluation of possibilities to construct a new energy source for Lithuania. The MESSAGE modelling tool was used for modelling and optimization of the future energy system development (IAEA MESSAGE, 2003). In this study, the introduced approach was applied focusing on Small and Medium nuclear Reactor (SMR), which was considered as one of the future options in Lithuania. As an example of SMR, the IRIS nuclear reactor was chosen in this analysis.

If IRIS with reduced EPZ could be built near the cities with a big heat demand is, it could be used not only for electricity generation, but also for heat supply for residential and industrial consumers. This would allow not only to reduce energy prices but also to decrease fossil fuel consumption and greenhouse gas emissions.

Finally, the analysis of uncertainty and sensitivity enabled to investigate how uncertain were results of this modelling and how they were sensitive to the uncertainty of model parameters (Alzbutas et al, 2001).

In summary, the study presented in this chapter consists of two main parts: the analysis of EPZ in relation to PRA with focus on external events, and the economic optimization of future energy system development scenarios with focus on sensitivity and uncertainty analysis in relation to initial model parameters. The study explicitly uses features of IRIS technology and a potentially reduced EPZ.

2. Approach used for IRIS

2.1 Safety-by-Design™ concept

The IRIS designers used the Safety-by-Design™ philosophy from its inception in 1999. Such a designing approach had been outlined in detail in previous works (Carelli, 2005), (Carelli, 2004); here it is suffice to remember that the key idea of the Safety-by-Design™ concept is to physically eliminate the possibility of occurrence or to reduce consequences of accidents, rather than focusing only on the mitigation phase.

The most evident implication of this design approach is the choice of an integral reactor configuration, where the integral reactor vessel (containing eight internal steam generators and reactor coolant pumps) and the internal control rod drive mechanism were introduced causing the consequential absence of large primary pipes. Such a configuration enabled to have either eliminated major design basis events such as Large Break LOCA (loss-of-coolant accident) or rod ejection and also to have significantly reduced the consequences of them.

This Safety-by-Design™ approach was used by the designers of IRIS to eliminate the possibility of occurrence of certain severe accidents caused by internal events and have been extended to the external events. The focus was on the balance of plant that had not been analyzed as extensively or explicitly as NPP accidents caused by internal events. However, since extreme external events, in general, have one of the largest contributions to the degradation of the defence in depth barriers, the external events, especially for new NPPs, represent a major challenge to the designer in order to determine siting parameters and to reduce the total risk.

2.2 External event analysis

The preliminary qualitative analysis and screening of external events considered for the IRIS PRA was, in general, based on the external events PRA methodology developed by the American Nuclear Society (ANSI/ANS-58.21, 2003) and on the PRA's of other NPPs (CESSAR-DC, 1997).

For the quantitative analyses, bounding site characteristics were used in order to minimize potential future restrictions on plant siting. The following four separate steps were performed in order to identify external events to be considered:

1. Initial identification of external events to be analysed in detail.
2. Grouping of events with similar plant effects and consequences.
3. Screening criteria establishment to determine which events are risk insignificant and can therefore be excluded from detailed quantitative analysis.
4. Each event evaluation against the screening criteria to determine if the event is risk-significant and thus requires further quantitative analysis.

PRA Guides and PRAs of existing plants were used as the sources for list of external events development in order to ensure that all external events already recognized as possible threats for IRIS were taken into consideration. The resultant set of external events represented a consensus listing of external events. Then, the list was reviewed in order to group all the external events that are likely to have the same impact on the plant. During this grouping the specific screening criteria were also applied to determine, which events are risk-insignificant and could be excluded from quantitative analysis.

The criteria used for excluding external events from detailed quantitative analysis are:

1. The plant design encompasses events of greater severity than the event under consideration. Therefore, the potential for significant plant damage from the event is negligible.
2. The event cannot occur close enough to the plant to have an effect on the plant's operation.
3. The event has a significantly lower mean frequency of occurrence than other events with similar uncertainties and could not result in worse consequences than those events.
4. The event is included, explicitly or implicitly, in the occurrence frequency data for another event (internal or external).
5. The event is slow in developing, and it can be demonstrated that there is sufficient time to eliminate the source of the threat or to provide an adequate response.

As it is evident form screening criteria, some external events may not pose a significant threat of a severe accident, if they have a sufficiently low contribution to core damage frequency or plant risk. So, the final step in the qualitative analysis process was the evaluation of each external event against the screening criteria to determine if the event was risk-insignificant and could be excluded from further analysis. Thus, the external events identified as described above were screened out in order to select only the significant events for detailed risk quantification.

As a result of the qualitative analysis or screening criteria application , the identified external events that had beed needed further quantitative scoping evaluation to determine their impact on the core damage were as follows: aircraft crash, high winds or tornadoes and seismic activity.

This list of external events that require an additional analysis was consistent with previous PRAs and with what had been suggested for analysis and the individual plant examination of external events (NUREG-1407, 1991). In addition, a few so called area events such as internal flooding and internal fires were also considered for IRIS. Also an impact of aircraft crash, that had been modelled and quantitatively analysed previously (Alzbutas et al., 2003) was included in the IRIS PRA and presented as an example related to risk zoning (Alzbutas & Maioli, 2008).

2.3 IRIS designing features

The Safety-by-Design™ approach, used by the designers of IRIS to eliminate the possibility of occurrence of certain severe accidents caused by internal events, had been extended to the external events.

The normally operating IRIS systems and their non-safety, active backup systems were typically located within substantial structures that can withstand some degree of external event challenges. This equipment included the backup diesel generators. IRIS had non-safety related backup diesels for normally available active equipment that could bring the plant to cold shutdown conditions.

IRIS plant safety features, once actuated, relied on natural driving forces such as gravity and natural circulation flow for their continued function. These safety systems did not need diesel generators as they are designed to function without safety-grade support systems (e.g. AC power, component cooling water, or service water) for a period of 7 days.

All the IRIS safety related equipment, including the batteries that provide emergency power, and the passive habitability system, were also located within concrete structures. The reactor, containment, passive safety systems, fuel storage, power source, control room and backup control were all located within the reinforced concrete auxiliary building and were protected from on-site explosions.

Actually, IRIS had a very low profile, which was very important when considering aircraft crash, especially by terrorists. The IRIS containment was completely within the reinforced concrete auxiliary building and one-half of it (13 m) was actually underground. The external, surrounding building was only about 25 m high, thus offering a minimal target. The integral vessel configuration eliminated loop piping and external components, thus enabling compact containment (see Figure 1) and plant size.

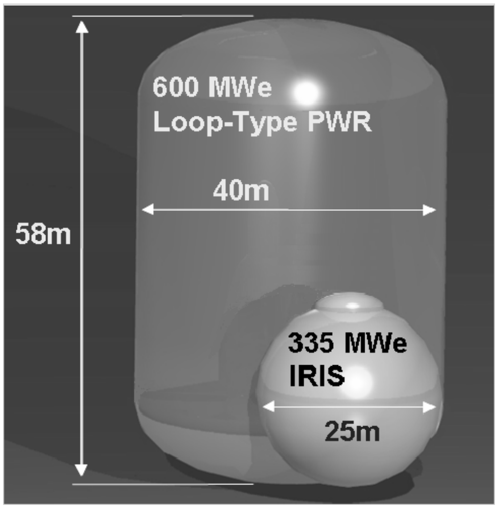

Fig. 1. IRIS Containment

The Refuelling Water Storage Tank (RWST) which is the plant's ultimate heat sink would be also protected from some external events by locating it inside the reinforced concrete auxiliary building structure. In addition, the IRIS RWST was designed to be replenished by alternative water sources such as fire trucks, therefore being completely independent by the plant power resources.

Because of these and other reasons, it was expected that the impact of external events at the site would be lower than that for current plants. In addition, typical design approaches, that could contribute to achieve such robustness in advanced NPPs design are:

- Capability to limit reactor power through inherent neutronic characteristics in the event of any failure of normal shut-down systems, and/or provision of a passive shut-down system not requiring any trip signal, power source, or operator action.
- Availability of a sufficiently large heat sink within the containment to indefinitely (or for a long grace period) remove core heat corresponding to above-mentioned events.
- Availability of very reliable passive heat transfer mechanisms for transfer of core heat to this heat sink.

It was observed that the implementation of innovative design measures needs to be supported (and encouraged) by a rational, technical and non-prescriptive basis to exclude any severe accident (core melt need not be presupposed to occur). The rational technical basis should be derived from realistic scenarios applicable for the plant design. Most of the innovative reactor designs aimed to eliminate the need for relocation or evacuation measures outside the plant site, through the use of enhanced safety features in design. Many of these designs also aimed to take advantage of these advanced safety characteristics to seek exemption from maintaining a large exclusion distance around the nuclear power plants.

3. EPZ in relation to PRA

3.1 PRA application for IRIS design

In the Safety-by-Design™ approach, the Probabilistic Risk Assessment plays obviously a key role, therefore a Preliminary IRIS PRA was initiated, and developed with the design, in an iterative way. This unprecedented application of the PRA techniques in the initial design phase of the reactor and the deep impact that this had in the development of the project was described in already published papers (Carelli, 2004, 2005).

Summarizing this, it is possible to note, that the success of the IRIS Safety-by-Design™ and PRA-guided design in the internal and external events assessments (Carelli, 2004) is due to the effective interactions between the IRIS Design team and the IRIS PRA team (see Figure 2). The main task of the PRA team was to identify high risk events and sequences.

The IRIS Design team provided information concerning the IRIS plant and site design. It updated IRIS component/system description and design data. PRA team identified assumptions concerning IRIS plant and site design requirements. The design team then reviewed assumptions concerning IRIS plant and site design requirements.

A preliminary evaluation of internal and external events was performed in the Preliminary IRIS PRA, to determine if there were any unforeseen vulnerabilities in the IRIS design that could be eliminated by design during the still evolving design phase of the reactor. The preliminary analysis of external events included both quantitative and qualitative analyses. For the quantitative analyses, bounding site characteristics were used in order to minimize potential future restrictions on plant siting.

Referring to Figure 3, it can be seen that the initial PRA for internal events resulted in a Core Damage Frequency (CDF) of $2.0 \cdot 10^{-6}$. The PRA team then worked with the IRIS design team in order to implement design changes that improved plant reliability and to identify additional transient analyses that showed no core damage for various beyond design basis transients. The resulting CDF around $1.2 \cdot 10^{-8}$ was therefore obtained thanks to a combination of the Safety-by-Design™ features of the IRIS design, coupled with the insights provided by the PRA team regarding success criteria definition, common cause failures, system layout, support systems dependencies and human reliability assessment.

Being still in a design development/refinement phase, the PRA was kept constantly updated with the evolution of the design; moreover, all the assumptions required to have a reasonable complete PRA model capable of providing quantitative insights as well as qualitative considerations, were accurately tracked down and the uncertainties connected with such assumptions were assessed. These refinements of the Preliminary IRIS PRA yielded a predicted CDF from internal events around $2.0 \cdot 10^{-8}$.

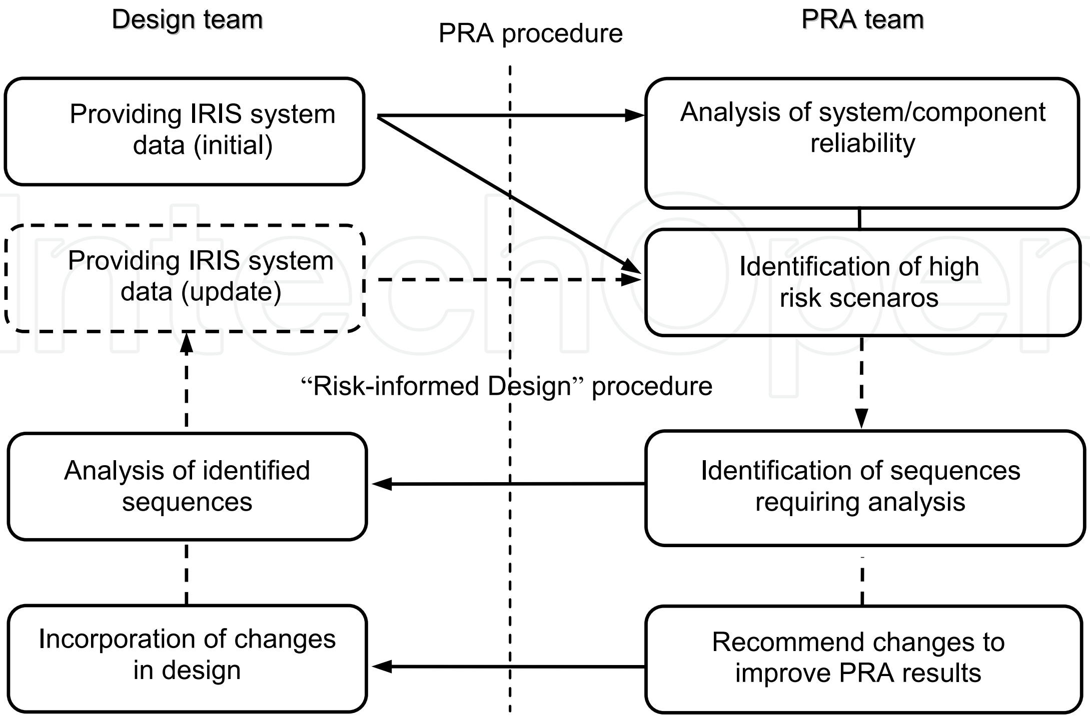

Fig. 2. IRIS Design and PRA Team Interactions

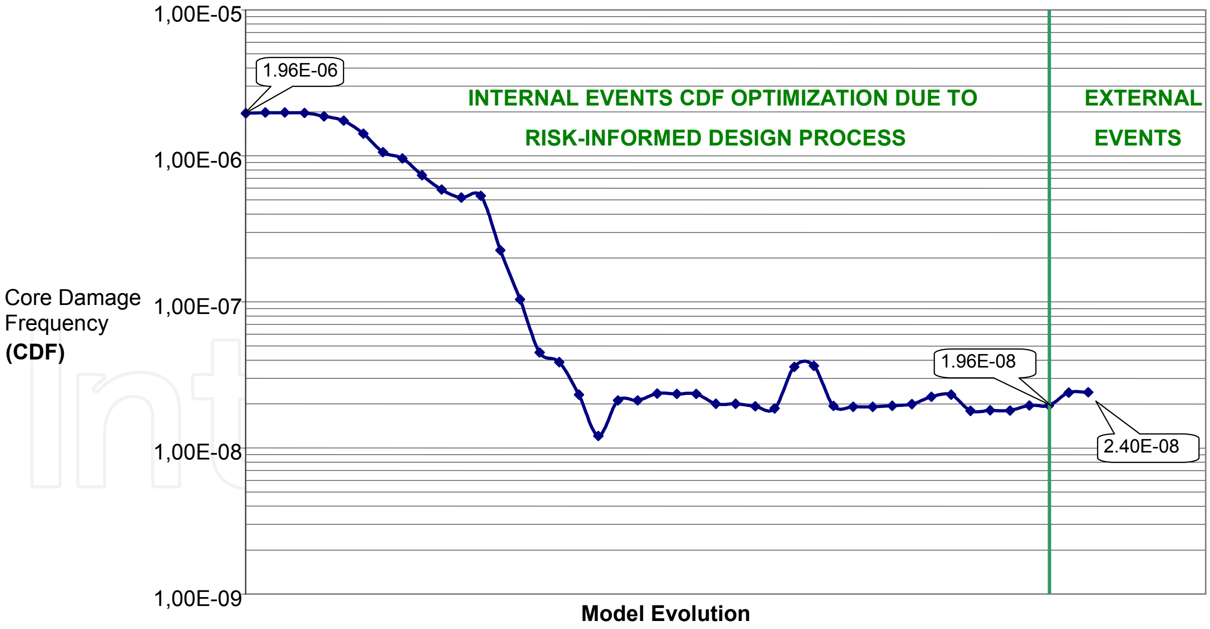

Fig. 3. IRIS Design CDF History

The same method was extended also to the external events. In comparison to events dominant in other plant PRA, the IRIS plant was expected to be significantly less vulnerable to some external events. In external events PRA, the focus was set on the plant BOP, that has not been analyzed as extensively or explicitly as accidents caused by internal events. In general, the IRIS plant arrangement structures were designed to minimize the potential for natural and manmade hazards external to the plant from affecting the plant safety related functions. The external events PRA insights were expected to help taking full advantage of the potential safety oriented features of the IRIS design and this implied probabilistic consideration of extreme winds, fires, flooding, aircraft crash, seismic activity, etc. In addition, it was shown that estimation of risk measures could be related to the site size and could be the input for the emergency zone planning.

3.2 Risk zoning practices

In fact, in the context of some severe external events, the assumption of continued availability of infrastructure required to administer emergency measures (for example roads and bridges) may not be valid. Under such situation, it is more effective to enhance the quality of the other levels of defence in depth. There is therefore, a need to define the scope of off-site emergency planning activities for advanced reactors, consistent with the ability of these reactor designs to meet enhanced safety objectives.

In some cases, such as the presence of a nearby airport, the consideration of the hazards may change risk zoning or eliminate a site from further consideration for an NPP, but most external hazards are either screened out from the necessity of being considered further or are taken into account in plant designing and siting. Risk zoning and siting is a matter for:

- The uncertainties of risk measures and influence to the public perception;
- Economic consideration (where power is needed, the availability of existing grid);
- Social and political factors;
- Topography affecting the dispersion of radio-nuclides through the atmosphere, rivers and ground-water;
- Political and safety consideration;
- Demographic characteristics;
- Hazards (natural and manmade).

Some IAEA Member States only address the risk to an individual member of the public, others have requirements to consider the potential aggregated effects to the population as a whole – societal risk.

Usually, off-site emergency measures are still seen as part of the Defence in Depth approach, which is mainly understood in deterministic sense, but to take full advantage of new reactor designs it should be moved towards a more probabilistic approach based on risk assessment with sensitivity and uncertainty analysis. The full benefit of innovative and evolutionary NPP requires the ability to licence without the need of an off-site Emergency Planning Zone.

In general, the desirability or possibility of reducing emergency response plans for accidents depends not only on the reactor type but also on a number of complex and intertwined factors including technical, societal, economical and cultural. The subject cannot be coupled directly and solely to the requirements for the external events but requires a separate consideration. Under the same subject also the risk-informed decision making related to the design basis accidents and severe accidents may be considered with the intent of moving away from somehow postulated risk zones and towards clearly calculated risk zones. Without such a change, related procedures and criteria, the issue of the emergency response plans cannot be resolved. In particular, in order to deal with external events and apply the risk-informed approach for plant design and siting, it is desirable to couple the PRA with analysis techniques of civil engineering.

3.3 Enhanced licensing framework

The ultimate objective for advanced NPPs is to establish an enhanced approach to licensing, reflecting improved safety characteristics of advanced reactors, that is expected to justify and enable revised (reduced or eliminated) emergency planning requirements, while providing at least the same level to protection to the public as the current regulations. Ideally, the emergency planning zone would coincide with (or be contained within) the site boundary, thus, there would be no need for off-site evacuation planning, and the NPP would become, relative to the general population, the same type of facility as any other industrial enterprise.

In order to contribute toward achieving this ultimate objective by addressing some of the relevant issues there is a need to consider the following research tasks:

- Critically evaluate current regulations to identify what changes are necessary to enable advanced licensing.
- Identify criteria based on technical, quantifiable parameters that may be used in support of the objective.
- Identify approach, based on a combination of deterministic modelling, probabilistic analysis, and risk management, which will enable assessment of advanced plants based on their key design operational and safety characteristics with respect to adequate emergency planning requirements.
- Prepare site-specific representative data (e.g., meteorological).
- Perform probabilistic analyses needed to support the proposed approach.
- Perform deterministic / dose evaluation analyses needed to support the proposed approach.
- Perform a detailed evaluation of the representative reactor utilizing the combined proposed approach.
- Identify, discuss and quantify the benefits attainable through the implementation of this objective, i.e., licensing with reduced emergency planning requirements.

In order to perform these tasks with the ultimate goal of developing a technology-independent approach, the design of IRIS was used as a testbed. IRIS was representative of innovative reactors, but because it was a LWR, its possible sequences and its behaviour under accident conditions was much better understood and predicted than that of some more distant new technologies. Moreover, it had the necessary prerequisite, excellent safety, due to its Safety-by-Design™ approach.

The related work was within the scope of activities defined within the International Atomic Energy Agency (IAEA) Co-ordinated Research Project (CRP) on Small Reactors with no or infrequent on-site refuelling. Specifically, it was relevant to “Definition of the scope of requirements and broader specifications” with respect to its ultimate objective (revised evacuation requirements) and to “Identification of requirements and broader specifications for NPPs for selected representative regions” considering specific impact on countries with colder climate and high interest for district heating co-generation.

It was expected that these results would contribute to ultimately defining a generic, country-independent approach and would support development of justification for reduced emergency planning through PRA analyses.

In addition, a study of the economic impact of revised licensing requirements on district heating was initiated. Thus the task was to perform economic study to evaluate positive economic effect on the nuclear district heating co-generation option, due to revised siting requirements with reduced emergency planning, which would allow placement of NPPs closer to population centres and allow them to be attractive option in heat energy supply market.

Finally, as part of this IAEA CRP a general methodology for revising the need for relocation and evacuation measures unique for NPPs for Innovative SMRs was developed and issued as IAEA publication (IAEA-TECDOC-1487, 2006).

Regarding further elaboration of the methodology it was suggested that external events and reasonable combinations of the external and internal events need to be included in the initial step of the methodology (accident sequence re-categorization), as for advanced reactors with the enforced inherent and safety by design features it might be that the impacts of external events would dominate the risk of severe accidents with possible radioactivity release. Work in this direction had already been started and was continued further, see (Alzbutas & Maioli, 2008) and (IAEA-TECDOC-1652, 2010).

3.4 Reduction of emergency planning zones

The developed approach for reduction of emergency planning zones (EPZ) was summarized in related IAEA document (IAEA-TECDOC-1652, 2010). It is applicable and recommended for all types of SMRs without on-site refuelling. The spatial extents of regulatory-mandated EPZ have historically been set according to conservative approaches for calculating bounding individual dose rates subsequent to a postulated accident sequence. The zones are not small – ranging up to 10 kilometers or even miles in radius. Moreover, regulations often require the reactor owner to provide for emplacement of infrastructure such as roads and bridges throughout the EPZ to facilitate public evacuation – as well as to periodic training and equipment supply to first responders. Current practice has been developed over many years specifically for the historical and current situation of large water-cooled reactor installations generating electricity for a regional grid.

Alternately, SMRs without on-site refuelling are being designed for local grids and some are even designed for cogeneration missions wherein the reactor must of necessity be placed very near the cogeneration application due to short heat transport distances. EPZ defined for large reactors on a one-size-fits-all basis can place a severe economic disadvantage on SMRs without on-site refuelling. For this reason, the IAEA CRP has conducted a review of the basis for the current regulations and has proposed a risk-informed methodology which could justify a reduced emergency planning zone extent on the basis of a smaller source term and a reduced probability of release for advanced SMRs, accounting for their passive safety and other risk reduction features. The methodology is not limited to small reactors without on-site refuelling, but is unique to many NPPs with innovative SMRs and larger reactors.

Within this methodology the information gathered from the PRA (both internal and external events) may be used to provide a basis for the redefinition of the EPZ defining criteria. The proposed approach consists of coupling the PRA results with deterministic dose evaluations associated to each relevant PRA sequence considered, and thus achieving a technically sound bases for the definition of a plant specific EPZ. In this approach the two basic components of risk (i.e. probability of occurrence and consequences of a given accident) are therefore explicitly combined. The EPZ radius then is defined as the distance from the plant such that the probability of exceeding the dose limit triggering the actuation of emergency procedure is equal to a specified threshold value. To identify this threshold value, detailed analysis of existing installations should be performed to infer the risk associated with the current EPZ definition.

The study conducted in the CRP included a sample application of the developed methodology for the IRIS-like SMR design under conditions of a particular site. This application indicated a potential for remarkable reduction of EPZ radius without increase in the public risk. However, to achieve this practically the proposed methodology first needs to be embraced by regulatory authorities. More details of the methodology and its trial application are provided in related IAEA document (IAEA-TECDOC-1652, 2010).

It must be noticed that the use of existing regulations and installations as the basis for this redefinition will not in any way impact the high degree of conservativism inherent in current regulations. Moreover, the remapping process makes this methodology partially independent from the uncertainties still affecting probabilistic techniques. Notwithstanding these considerations, it is still expected that applying this methodology to advanced plant designs with improved safety features will allow significant reductions in the emergency planning requirements, and specifically the size of the EPZ. In particular, in the case of IRIS it was expected that taking full credit of the Safety-by-Design™ approach of the IRIS reactor will allow a dramatic reduction in the EPZ requirement, while still maintaining a level of protection to the public fully consistent with existing regulations.

4. Case study for EPZ and economic optimization

The series of various studies were carried out in order to answer the question what energy sources should replace the lost nuclear electricity capacities (IAEA-TECDOC-1408, 2004; IAEA-TECDOC-1541, 2007). Currently all Baltic region countries cooperating and seeking to solve energy supply and energy security problems and planning to construct new nuclear reactors in Lithuania at existing NPP site. The last Ignalina Unit 2 RBMK-1500 was closed in the end of 2009 and Lithuania is considering both nuclear and fossil options for its replacement. In order to expand the research of the Lithuanian energy future another option to the analysis is also added: small and medium type nuclear reactor in the new site close to the cities with large heat demand. In general, it could be considered for small countries as alternative for the big nuclear units due to limitation imposed by the grid size and available financial resources.

The results of various studies concerning the future structure of power plants in Lithuanian energy system have showed that looking from the economical point of view the best options to replace Ignalina NPP are new nuclear unit or new combined cycle condensing units together with the existing and new units of Combined Heat and Power plants (CHP) (IAEA-TECDOC-1408, 2004; Norvaisa, 2005). Due to climate conditions in Lithuania, district heating presents a notable fraction of energy consumption in winter months, and infrastructure for its use is already in place in population centers in Lithuania. District heating is widely used in Lithuania (46% of total heat consumption), and the cities of Vilnius and Kaunas comprise the two largest consumers of district heat supply (see Table 1). So, in the future new cogeneration units are likely to be the best alternative for electricity and heat generation in Lithuania.

District heat (DH) supply:				Fuel structure:		
Total DH supply	GWh	9300		Natural gas	%	74
DH supply in Vilnius	GWh	3000		Renewables	%	19
DH supply in Kaunas	GWh	1600		Oil	%	5.5
Losses in DH	%	16		other	%	1.5

Table 1. Lithuanian district heating (DH) sector in 2009

Among the nuclear alternatives the 330 MW(e) IRIS-like reactor was used for the conceptual investigation, as it could be operated in either the electricity only or the co-generation mode. Thus, a case study was conducted to determine the best way to provide the electricity and district heat in Lithuania up to year 2025 and to assess the tactical implications that a reduced-radius emergency planning zone might have on least cost planning with the IRIS-like reactor operating in the electricity only versus the electricity/district heat (co-generation) mode (Norvaiša & Alzbutas, 2009).

The length of any newly required hot water/steam pipelines into the cities of Vilnius and Kaunas will depend on the radius of the emergency planning zone emplaced around the IRIS-like reactor site; these pipelines represent a cost due to construction and a cost due to heat losses. Both costs increase with the pipeline length and, thereby, affect the viability of the co-generation mode. The case study was conducted parametrically for pipeline lengths of 0.5, 5, 15, and 30 km.

4.1 Modelling of Lithuanian energy system

The IAEA's energy planning tool, MESSAGE, was used to model several alternate scenarios for Lithuania for a time horizon until 2025. The MESSAGE is an optimization model which from the set of existing and possible new technologies selects the optimal, in terms of selection criterion, mix of technologies capable to cover given country demand for various energy forms during the whole study period (IAEA MESSAGE, 2003). Table 2 lists the scenario options that were considered.

Figure 4 shows the base case, where the Ignalina NPP comes off line in 2009, and electricity and heat production is provided by the new fossil plants – some of which operate in electricity mode and some in co-generation mode. No nuclear plant is deployed in the base case. Figure 5 compares the total cost of this base case to the costs of the several options where IRIS-like NPP is deployed; clearly IRIS is a preferred option, no matter what configuration of its deployment.

At Lithuania's largest cities of Vilnius and Kaunas, the heat distribution pipelines already run through the neighbourhoods emanating from a massive heating plant sited at the outer edge of the city. Figures 6 and 7 show the evolution of electricity and district heat delivery by IRIS-like reactors operating in the cogeneration mode under the condition that the IRIS-like reactors can be sited at the city's edge within 0.5 km of the distribution header of the district piping network. This option is labelled 'IRIS cogeneration' in Figure 5 and is the overall lowest cost option. The optimization shows that by 2025, three IRIS-like reactors would have been deployed and would be supplying 44% of Lithuania's electricity (Figure 6) and 31% of Lithuania's district heat (Figure 7) centred in the cities of Vilnius and Kaunas.

No.	Scenario name	Description
1	No IRIS-like NPP	Base scenario: construction of IRIS-like NPP is not allowed
2	Co-generation with IRIS-like reactor	Construction of IRIS-like NPP (with co-generation option) is allowed in Vilnius and Kaunas cities. No additional heat supply network must be constructed. (0.5 km pipeline)
3	'IRIS EPZ' - IRIS-like NPP with larger emergency planning zone	Construction of IRIS-like NPP (with co-generation option) is allowed in Vilnius and Kaunas cities. The EPZ is parametrically assumed to be 5-30 km. Construction of IRIS-like units only for electricity production is also allowed in other locations.
4	IRIS-like NPP for electricity only	Construction of IRIS-like units used only for electricity generation is allowed (no co-generation option).

Table 2. Description of scenarios

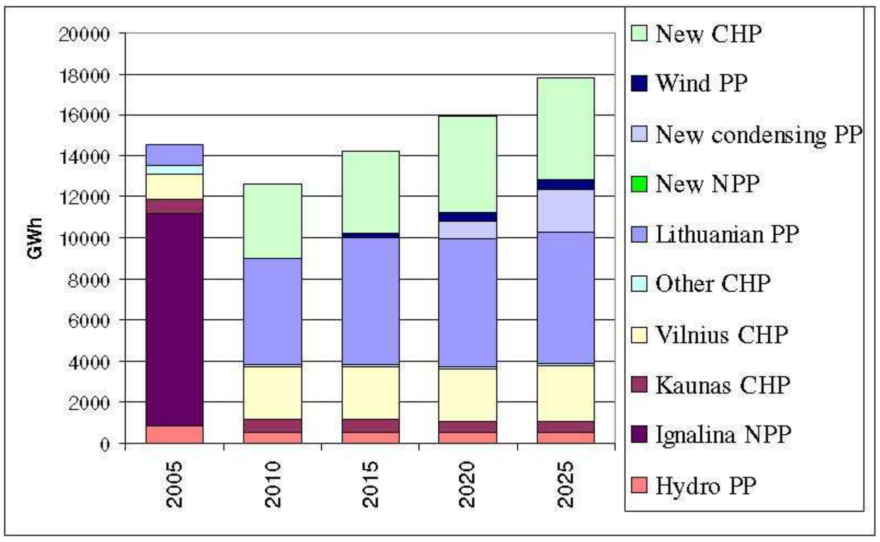

Fig. 4. Dynamics of electricity production in the case of 'No IRIS-like NPP' scenario (CHP – combined heat and power plant, PP – power plant)

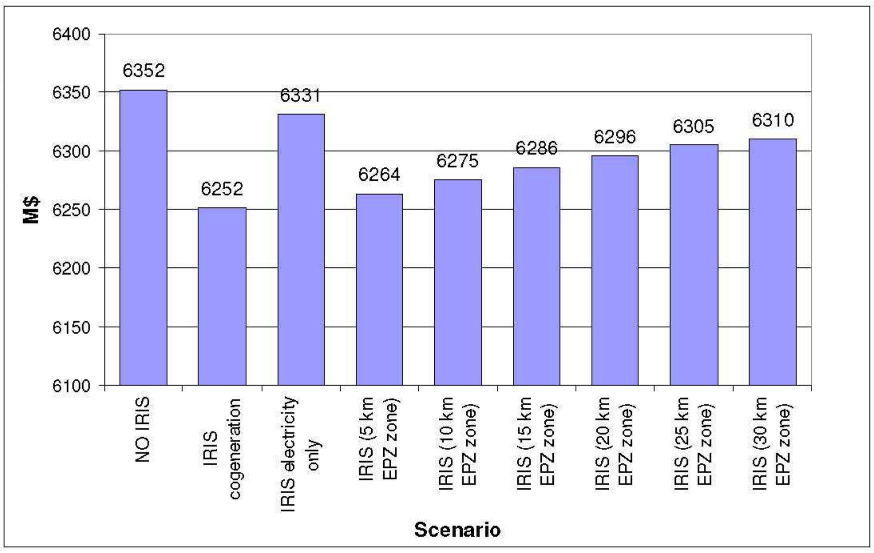

Fig. 5. Discounted total cost of energy system operation and development until 2025

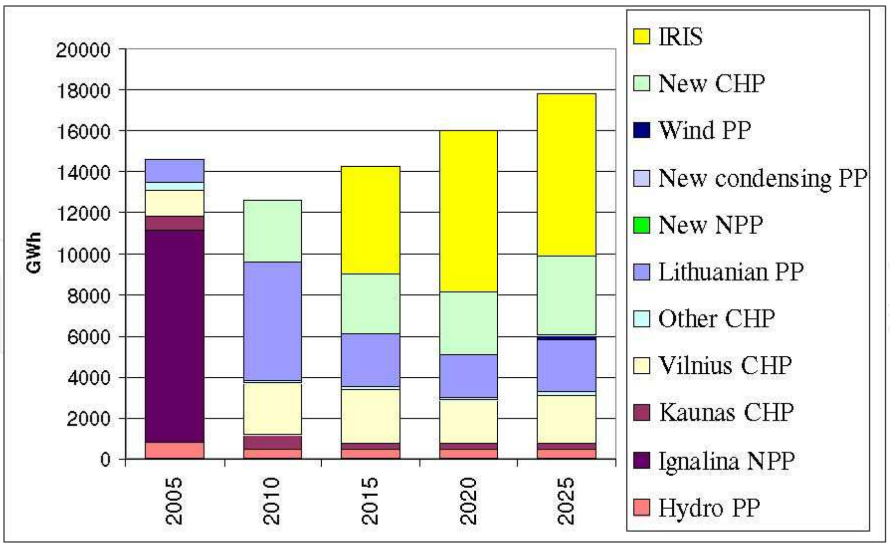

Fig. 6. Dynamics of electricity production in the case of 'IRIS cogeneration' scenario

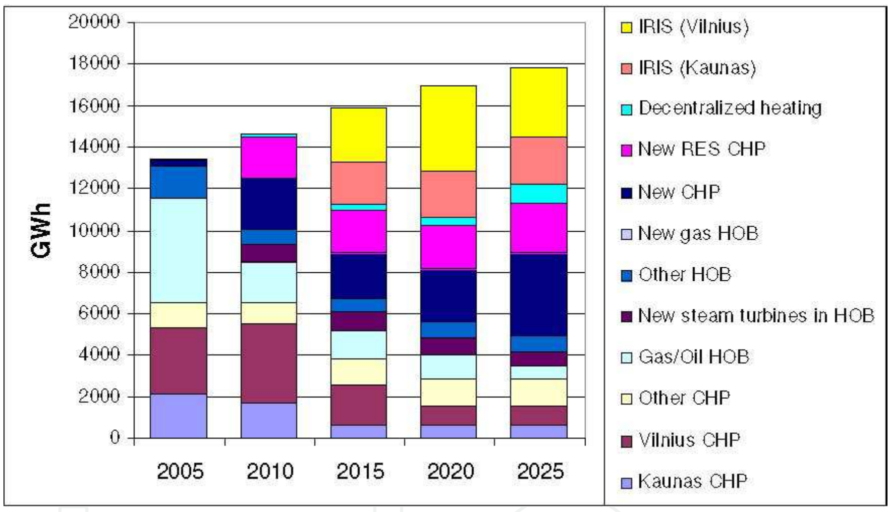

Fig. 7. Heat production by technologies in Lithuania for 'IRIS cogeneration' scenario (HOB – heat only boilers, RES – renewable energy sources)

4.2 Uncertainty and sensitivity analysis

Usually, the calculation results of such analysis depend on initial parameters and modelling techniques. In any case, having quite uncertain parameters, the influence of the main initial parameters to the main results may be investigated performing uncertainty and sensitivity analysis. In particular case, the analysis focuses on how the calculation results could change, when the initial parameters describing IRIS-like technology in MESSAGE model are changed. In addition, the most important parameters for the precision of calculation results were also indentified.

The main parameters and their possible values (describing the IRIS-like technology in the model) for different scenarios are presented in Table 3.

Par. No.	Parameter	Distribution type	Reference value	Min	Max
1	IRIS Investments, $/kW	Uniform	1410	1410	2000
2	IRIS fixed O&M costs, $/kW	Uniform	44.8	44.8	67.2
3	Discount rate, %	Uniform	5	5	10
4	IRIS starting year	Discrete	2015	2010	2025
5	Heat pipeline length, km	Discrete	0	0	30
6	Nuclear fuel cost, $/kWyr	Uniform	11.3	11.3	15

Table 3. Uncertain parameters and data for scenario generation

The reference values of some parameters presented in this table are taken from (Alzbutas & Maioli, 2008). The possible variations of these parameters are based on calculation assumptions. For instance, in the calculations it was assumed that the EPZ could change from 0 to 30 kilometers. In the model this is represented by the length of additional heat supply pipe in order to connect IRIS-like NPP with cogeneration option to the existing district heating network. In addition, the number of IRIS units in the MESSAGE model is adapting depending on specific conditions in the modelled energy system.

The distribution of total discounted costs of the energy system operation and development in the time period analyzed (the main result) are presented in the Figure 8.

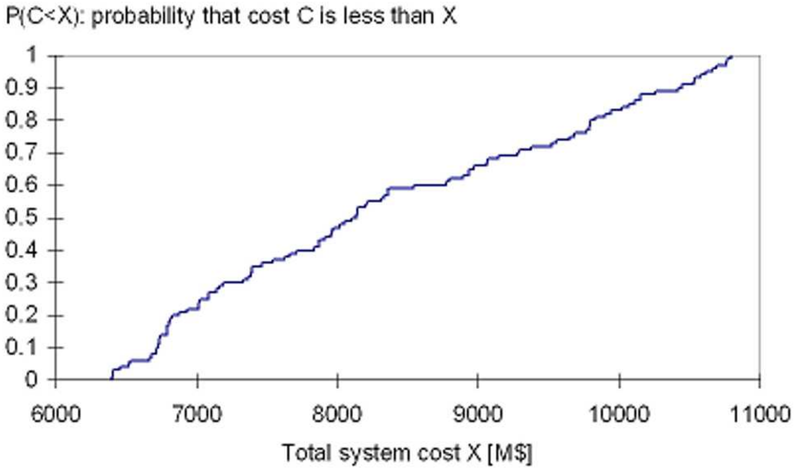

Fig. 8. Uncertainty of modelling result: empirical distribution function of total system cost

Following the uncertainty analysis the sensitivity measure PCC (see Fig. 9) describes how the initial conditions and model parameters (see Table 3) influence the result. From the sensitivity analysis we can see that the 3rd parameter (discount rate) has the largest (negative) influence on the total system costs (main modelling result). When this parameter increases, the considered model result decreases most significantly. Alternatively, the increase of nuclear fuel price (the increase of 6th parameter) in the considered range has the lowest influence.

In general, a high discount rate gives more weight or importance to present expenditures than to future ones, while a low discount rate reduces these differences and thus favours technologies that have high investment cost but low operation costs (for example NPPs).

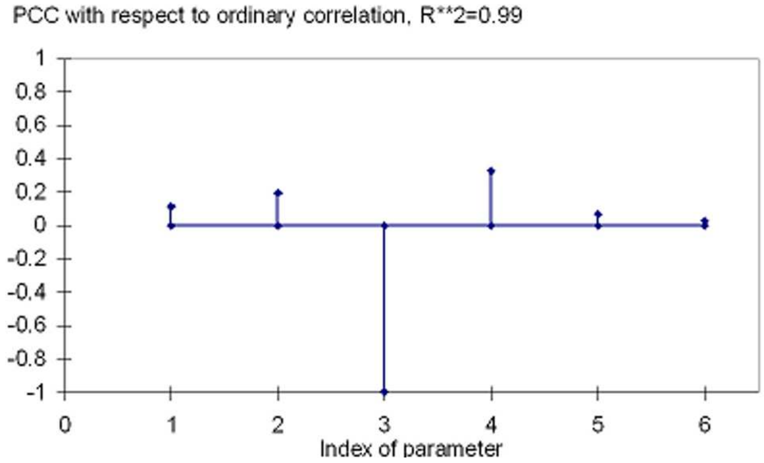

Fig. 9. Sensitivity measure and determination coefficient (R**2) for total system cost

In this case study, the sensitivity measure, which is a product of the statistical analysis, shows which sources of uncertainty are contributing most to the uncertainty in the predicted energy system performance (see Fig. 9). But it is possible that sensitivity measure, in this case a Partial Correlation Coefficient (PCC), explains too small a fraction of the variability of the model output values, for instance, if coefficient of determination is less than 0.5. However, for analyzed case the coefficient of determination is 0.99. Thus, in this case the sensitivity measure PCC in a very good way express the relation in variability and analyst can easily determine which model parameters should be controlled better in order to decrease unfavourable changes of results. Alternatively, the analyst can determine which parameters could be less precise without substantially affecting results.

5. Conclusions

1. While innovative design solutions are possible in an early design stage to cope with extreme internal events, the need for integrating external events considerations on a probabilistic basis at a relatively early design stage is going to be another challenge for effective and balanced use of PSA as a support of the design phase.
2. Further progress of PSA application and EPZ definition could be achieved via discussion with national regulatory authorities in those IAEA Member States that are considering performance-based and risk-informed licensing approaches for future NPPs.
3. Construction of SMR units is very attractive option (looking from economical point of view) for the future electricity and heat generation. The option with SMR cogeneration mode may cause the lowest total discounted cost among the scenarios analyzed.
4. In the case, when IRIS cogeneration unit should be installed away from existing district heating networks (due to EPZ), the attractiveness of this unit is decreasing gradually with distance, because of investment cost and heat losses in addition district heating pipelines.
5. The sensitivity analysis may be essential as it shows how particular parameter is important to the modelling results and where the accuracy of primary data could be increased (in order to decrease the uncertainty of the results). Alternatively, the analyst can determine which parameters could be less precise without substantially affecting results.
6. In our case, the discount rate has the highest influence on the total system costs, while the increase of nuclear fuel price in the considered range has the lowest influence to the total system costs.

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7. References

Alzbutas R., Maioli A. (2008). Risk zoning in relation to risk of external events (application to IRIS design). *International journal of risk assessment and management.* ISSN 1466-8297. Vol. 8, No. 1/2, p. 104-122.

Alzbutas, R., Augutis, J., Krikštolaitis, R., Ušpuras, E. (2003). Uncertainty and Sensitivity Analysis in Aircraft Crash Modelling, ISSN 1642-9311, *Proceedings of The 3-rd Safety and Reliability International Conference (KONBiN'03)*, V2, pp. 267–274, Gdynia, Poland.

Alzbutas, R., Augutis, J., Maioli, A., Finnicum, D.J., Carelli, M.D., Petrovic, B., Kling, C.L., Kumagai, Y. (2005). External Events Analysis and Probabilistic Risk Assessment Application for IRIS Plant Design, *Proceedings of the 13th International Conference on Nuclear Engineering (ICONE-13)*, Beijing, China, Atomic Energy Press, CD: 8 p.

Alzbutas, R., Augutis, J., Urbonas, R. (2001). Risk and sensitivity analysis in relation to external events, ISBN 961-6207-17-2, *Proceedings of International Conference on Nuclear Energy in Central Europe 2001*, Portorož, CD308: 14 p.

ANSI/ANS-58.21 (2003). *External-Events PRA Methodology*, American Nuclear Society, March 3.

Carelli, M.D. (2003). IRIS: A global approach to nuclear power renaissance. *Nuclear News*, 46, No. 10, pp. 32-42.

Carelli, M.D., et al. (2004). The Design and Safety Features of the IRIS Reactor. *Nuclear Engineering and Design*, 230, pp. 151-167.

Carelli, M.D., et al. (2005). IRIS reactor design overview and status update. Proceedings of the American Nuclear Society-international congress on advances in Nuclear Power Plants (ICAPP'05). Vol. 5, pp. 451-459.

CESSAR-DC (1997). Combustion Engineering Standard Safety Report – Design Certification for System 80+ Design, *Combustion Engineering*, Inc. Volume 20.

IAEA MESSAGE. (2003). *Model for Energy Supply Strategy Alternatives and their General Environmental Impact*. Vienna, Austria: International Atomic Energy Agency.

IAEA-SSG-3. (2010). *Development and application of level 1 probabilistic safety assessment for Nuclear Power Plants*. IAEA safety standards series No. SSG-3. Austria: International Atomic Energy Agency. 195 p. ISBN 978-92-0-114509-3.

IAEA-SSG-4. (2010). *Development and application of level 2 probabilistic safety assessment for Nuclear Power Plants.* IAEA safety standards series No. SSG-4. Vienna, Austria: International Energy Atomic Agency. 82 p. ISBN 978-92-0-102210-3.

IAEA-TECDOC-1408. (2004). *Energy supply options for Lithuania: a detailed multi-sector integrated energy demand, supply and environmental analysis*. Vienna, Austria: International Atomic Energy Agency, 171 p. ISBN 92-0-110004–3, ISSN 1011–4289.

IAEA-TECDOC-1487. (2006). *Advanced nuclear power plant design options to cope with external events*. Vienna, Austria: International Atomic Energy Agency. 221 p. ISBN 92-0-100506-7.

IAEA-TECDOC-1511. (2006). *Determining the quality of probabilistic safety assessment (PSA) for applications in nuclear power plants*. Vienna, Austria: International Atomic Energy Agency. 172 p. ISBN 92-0-108706-3, ISSN 1011-4289.

IAEA-TECDOC-1541. (2007). *Analyses of Energy Supply Options and Security of Energy Supply in the Baltic States*, Vienna, Austria: International Atomic Energy Agency, 323 p. ISBN 92–0–101107–5, ISSN 1011-4289.

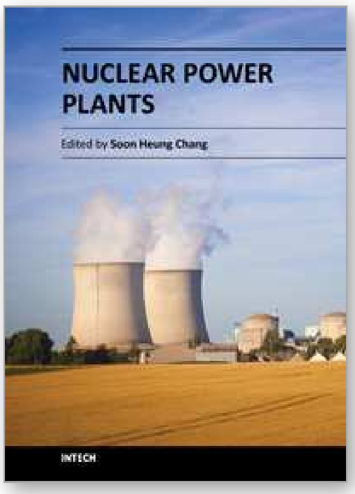
IAEA-TECDOC-1652. (2010). *Small reactors without on-site refuelling: neutronic characteristics, emergency planning and development scenarios*, Vienna: International Atomic Energy Agency. 94 p. ISBN 978-92-0-106810-1.

Kling, C.L., Carelli, M.D., Finnicum, D., Alzbutas, R., Maioli, A., Barra, M., Ghisu, M., Leva, C., Kumagai, Y. (2005). PRA improves IRIS plant safety-by-design. *Proceedings of the American Nuclear Society-international congress on advances in Nuclear Power Plants (ICAPP'05)*. Vol. 5, pp. 3011-3019.

Norvaiša, E. (2005). *Modeling and analysis of sustainable development of Lithuanian power and heat supply sectors* [summary of dissertation]. Kaunas University of Technology. Lithuanian Energy Institute.

Norvaiša, E., Alzbutas, R. (2009). Economic and sensitivity analysis of non-large nuclear reactors with cogeneration option in Lithuania, *Energy, policies and technologies for sustainable economies: 10th IAEE European conference*, Vienna, Austria, International Association for Energy Economics, Cleveland OH. ISSN 1559-792X, p. 1-19.

NUREG-1407 (1991). *Procedural and Submittal Guidance for the Individual Plant Examination of the Externals Events (IPEEE) for Severe Accidents Vulnerabilities*, NRC.



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