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# NARSIS

New Approach to Reactor Safety ImprovementS

# Newsletter # 3

# Edito

## *Welcome!*

***Evelyne Foerster***
***NARSIS project coordinator***

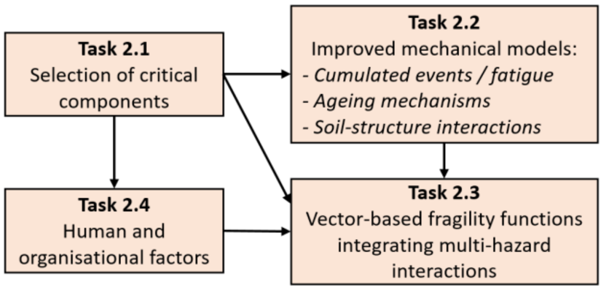
Dear reader
A warm welcome to the third issue of NARSIS Newsletter!

NARSIS coordinates the research efforts of eighteen partners encompassing leading universities, research institutes, technical support organizations (TSO), nuclear power producers and suppliers, reactor designers and operators from ten countries. The project aims at making significant scientific updates of some elements required for the Probabilistic Safety Assessment (PSA), focusing on external natural events such as earthquake, tsunami, flooding, high-speed winds etc.

Fragility Assessment is one of the main topics addressed by the project. Below you will find the summary of how this topic is covered in NARSIS.

*The reliability of the structures, systems and components (SCC) within a Nuclear Power Plant (NPP) constitutes a crucial step of the Probability Safety Assessment (PSA) approach. Therefore, their fragility must be quantified with respect to a wide range of external loadings induced by natural hazards, while accounting for various sources of aleatory or epistemic uncertainty. This probabilistic framework, at the interface between probabilistic hazard assessments (WP1) and system reliability analyses (WP3), is the object of the developments that are carried out within the Work Package in charge of the fragility assessment of main critical elements (WP2).*

*Almost at mid-point of the NARSIS project's timeline, the WP2 tasks (see Figure) are well under way and the first results have started to emerge:*




- *In Task 2.1, thanks to various metrics based on past seismic PSA or seismic margin assessment, the critical components that require detailed fragility analyses have been identified. They may be grouped into three categories, namely (i) I&C and switchgear cabinets/devices, (ii) reactor pressure vessel internals (esp. fuel assembly spacer grids) and (iii) distributed systems such as HVAC, piping or cable raceways.*
- *Task 2.2 has started to study the effect of cumulated seismic loadings, borrowing reliability methods from mechanical engineering (i.e., evaluation of fatigue effects through Stress-Strength Interference Analysis). Moreover, the structural model of a reactor building, for the study of soil-structure interactions, is currently being assembled.*
- *Task 2.3 has laid the first methodological grounds for the derivation of fragility functions using multiples intensity measures or multiple failure modes, in the case of single- or multi-hazard loadings. Two applications, related to the seismic fragility analysis of internal equipment and systems, have shown the benefit of considering multiple intensity measures, in terms of uncertainty quantification.*

- *Task 2.4 has led to the improvement of the SLIM (Successful Likelihood Index Model) approach, thanks to its coupling with a Bayesian Network (BN). The so-called BN-SLIM approach make use of the probability updating features of BN framework, in order to exploit new information to update the levels and weights of the performance shaping factors priorly identified by experts, thus updating the human error probabilities.*

*Despite these promising results, several challenges will still have to be overcome in the upcoming months. First of all, fragility analyses will have to shift from single seismic hazard to interactions between multiple hazards, provided that adequate hazard combinations are identified. It must also be ensured that the specific model developments carried out in Task 2.2 may be applied to the fragility analyses in Task 2.3, in order to quantity their impact on the final fragility functions. Finally, the integration of the outcomes of WP2 (i.e., the vector-based fragility models, and the method to incorporate human factors) with the Bayesian framework of WP3 will be key to understand the impact of these elaborate probabilistic models on the final output of the PSA.*

The NARSIS project has now been running for a year and a half, and the first set of deliverables and milestones have been produced as part of the effort of the consortium. Datasets have been collected, methodologies tested, the state of the art has been researched, and various criteria and plans developed. The 3rd plenary meeting was held from the 19th to the 21th of March at the Delft University of Technology with over 40 members joining the 3 days of discussions, presentations, working groups and activities. Although it has been a busy period, the initial deliverables of the five work packages set the foundations for the integrated approach towards multi-hazard risk assessment and studies into the integration within PSA.

With this newsletter, we would like to broaden the circle and share the outcomes of our project with larger audience. Our objective is to attract wide support from and involvement of any stakeholder interested in cooperative development of the nuclear safety. This newsletter aims to function as an information tool for disseminating results and outcomes of our project but also to become a forum for discussion, reflection and dialogue. Our conceptual strategy is anticipative, reflecting our wish to involve more researchers, professionals and interested groups in the debate including through our web site www.narsis.eu

We will be happy to receive your comments and suggestions. Please feel free to communicate your feedback to Prof. Behrooz Bazargan Sabet (b.bazargan-sabet@brgm.fr) for inclusion in our forthcoming issues. We would also like you to help us disseminate this third newsletter to your network.

We look forward to hearing from you!

# WP summaries

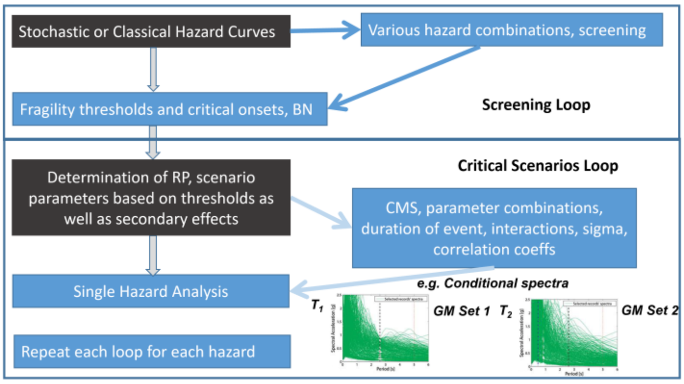
## WP1: Characterization of potential physical threats due to different external hazards and scenarios

***James Daniell***
***KIT***

The characterisation of external hazards in WP1 is in full swing, with many of the deliverables expected in the next 12 months. Most of the characterisation in this 12 month period since the first deliverable on the state-of-art in Nuclear external hazards characterisation for single and multiple hazards has been associated with the development of the methodologies and processes to do with the single hazards.

Much data was sourced in the first 12 months, relating to previous efforts on various European scale natural hazards analysis. The main hazard types included earthquake (ground shaking), flood (riverine), storm surge (coastal), tsunami, and extreme weather events (ranging from tornado, hail, lightning and convective storm; to longer period events like heatwave, drought and coldwaves).

Four deliverables associated with the four main hazards are being produced on the improvement of probabilistic hazard assessment (PHA) methodologies versus existing methods. For tsunami, various analyses are being undertaken between BRGM, KIT and CEA with existing methods used at each partner being benchmarked for some cases. The components of source uncertainty including stochastic slip distribution, path and wave modelling methods are examined, in addition to the various non-linear shallow water wave equation solutions, and inundation modelling frameworks. The variation associated with the DEM resolution, friction type, and seismic source has been examined as part of Schaefer (2018), in which it was seen that the seismic source has the greatest impact on model uncertainty when looking probabilistically.




*Example of a framework for a single hazard analysis*

Similarly for earthquake, flood and storm surge, various studies are being undertaken for theoretical conditions to constrain and investigate the uncertainty, as well as bring in relatively new concepts such as conditional mean spectra, flash flood finite volume modelling, climate change scenarios in line with RCPs.

As part of the Task 1.3 (*"Development of single and secondary effect hazard assessment methodologies and scenarios including uncertainty quantification and comparison"*) various hazard curves have been developed for each of the hazard types. Here, methodologies and source parameters have been examined Europewide. Decommissioned plant sites were examined as suitable locations but the hazard models were set up using the broad scale hazard models. For the toybox example in conjunction with WPs 2 and 3, a test case was made for an existing decommissioned site in order to play around with the methods needed to produce curves at any requested site in Europe.

For an example of earthquake:

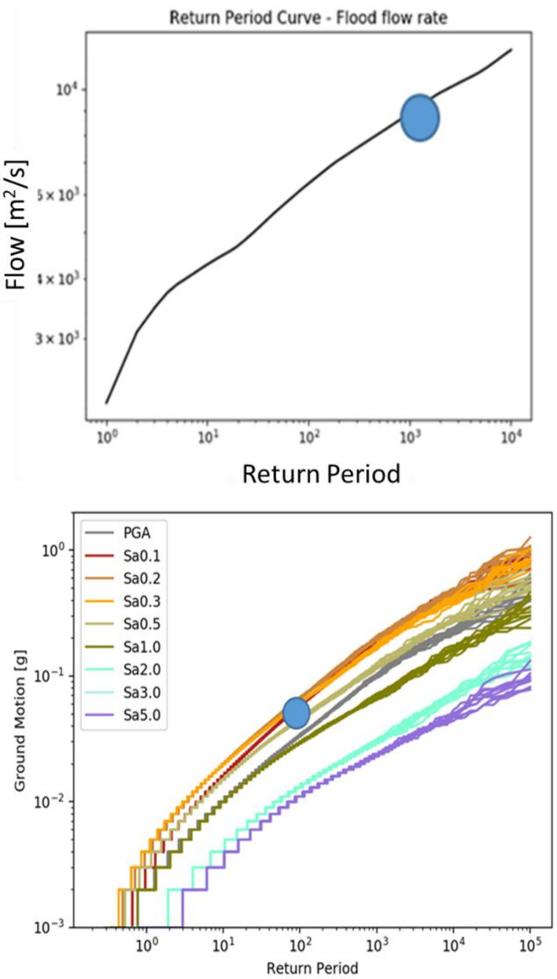
- Two types of modelling are needed for the scenario – probabilistic in order to create a first order (non-scenario based) result at the NPP (via bins); or stochastic event sets, as required.

- From here, the critical scenarios are then chosen based on thresholds within the fragility functions of damage onset etc.

- Then the scenario is constructed from this threshold based on CMS so that cascading effects such as earthquake-landslide + flooding at a later stage in the recovery process or any other such scenario could be given a return period.

- Duration of events and timing extremely important for the human factor, operating plans per scenario etc.

For the chosen site close to Trino Vercellese in Italy, earthquakes and floods were examined. For earthquake, hazard curves were developed for any site for earthquake using classical PSHA as well as event-based PSHA over a 10 * 100,000 year simulation. Vector-based hazard outputs were produced with 9 parameters on the earthquake side (0, 0.1, 0.2, 0.3, 0.5, 1, 2, 3, 5s Sa (spectral acceleration)); on the flood side (Q and h were produced – flow and height).




Example of a 1000 year flood (flow) and ground accelerations at various spectral periods for 100 years, in terms of the design hazard.

Methods for quantifying the uncertainty in the process are being examined as well as the best way to bring the modelling into the Bayesian network in WP3, via the fragility determined in WP2.

On the software side of WP1, steps have been taken towards the development of the package with components. The software is developed under the Electron Framework which works with javascript and html. It is open source, and multi-platform with web deployment possible. So far the feature list, the technological feasibility and some component parts have been developed, with initial delivery expected towards the end of 2019.

5 main components are present:

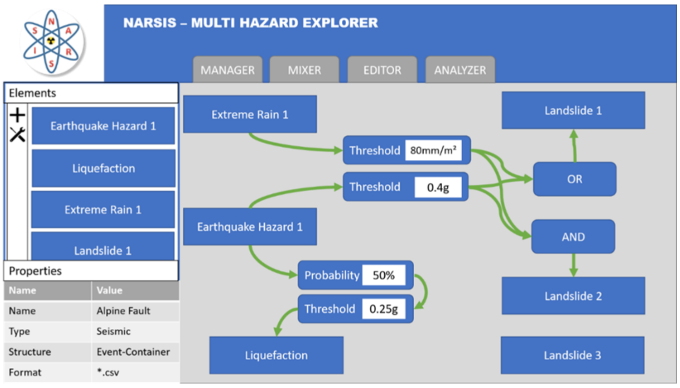
1. IMPORT - Import of hazard curves and event specs via meta format (*.xml); Meta format defines data type & structure (needed for mixing and event outputs)

2. MANAGER - Managing different event logics, pre-built & custom

3. MIXER - Visual Scripting System to build event logics

4. EDITOR - Manual calibration of hazard curves

5. EXPORT - Exporting graphics for analysis and related event-logics



# WP summaries

## WP2: Fragility assessment of main NPPs critical elements

**Pierre Gehl**
**BRGM**

The first part of the Year 2019 has seen the completion of two deliverable reports within Task 2.3 and 2.4, respectively on the development of multi-hazard fragility functions and on the integration of human factors in reliability analyses.

In Task 2.3 (*"Development of methods to derive vector-valued fragility functions in a multi-hazard approach"*), a first deliverable report (D2.6) has been devoted to methodological developments for the derivation of vector-based fragility functions. In particular, an emphasis is put on the treatment of uncertainties and their propagation up to the representation of the fragility functions. For instance, in the case of seismic fragility functions, the benefits of using vector-based intensity measures (or "vector-IMs") are discussed from the point-of-view of the reduction of aleatory uncertainty (i.e., record-to-record variability). Two simplified case studies are detailed as examples, i.e. the seismic fragility of a PWR main steam line and the seismic fragility of a fuel assembly grid. For both these applications, the uncertainties induced by scalar-IM fragility curves or vector-IM fragility functions are compared and discussed. Globally, a reduction in the dispersion is observed, although some care should be taken when interpreting vector-IM fragility functions that are based on strongly correlated variables (i.e., ground-motion parameters).

So far, seismic fragility analyses have received the most attention in the Work Package, although the focus is now shifting towards other natural hazards and the combination of multiple hazard loadings on the exposed components. To this end, a harmonized framework for the treatment of various cases of multi-cases may be able to describe most of the configurations that are encountered, when dealing with external hazard events:

1. *Standard single-IM case*, with a simple relationship between the IM and the component's response.
2. *Vector-IM fragility function*, usually with a correlation between the IMs.
3. *System fragility function*, resulting from the assembly of single component damage events (i.e., combination of failure modes). The correlation between the occurrences of the failure modes, given the IMs, should be taken into account.
4. *Multi-hazard fragility function*, where a multi-variate distribution function represents the damage probability due to the interaction of co-occurring loadings.
5. *Damage-state-dependent fragility functions* where a first hazard loading may degrade the resistance of the SSC or alter the conditions for when a subsequent hazard loading is applied (i.e., sequence of events). The hazards may be correlated (i.e., same source event, or one hazard event triggering another) or independent (i.e., occurrence within the same time window).

While cases #1 to #3 have been demonstrated and applied to some examples, one of the remaining challenges of the Task will reside in the identification of relevant hazard combinations for the implementation of cases #4 and #5.

On the other hand, Task 2.4 (*"Development of methods to incorporate human factors within a multi-hazard approach"*) has reached its conclusion through the completion of deliverable report D2.8. The developed approach, referred to as BN-SLIM, is based on an existing methodology (i.e., SLIM which stands for Successful Likelihood Index Model), which has been extended to a BN. It is shown that BN-SLIM is able to identify the upper and lower bounds of the error probability while the result of SLIM alone is in the form of a single value incapable of reflecting the possible judgment inconsistency. Moreover, the probability updating feature of BN-SLIM makes it possible to use new information to update the levels and weights of the performance shaping factors priorly identified by experts, thus updating the human error probabilities. The outcomes of this task will be used as input to Task 3.2.1 of the NARSIS project (i.e., risk sub-networks for social/organizational aspects).

Finally, the latest results of this Work Package will be presented at upcoming international conferences:

- Presentation on the performance of the BN-SLIM approach, by TU Delft, at the ESREL2019 conference;
- Presentation on the decomposition of aleatory and epistemic uncertainty sources when deriving seismic fragility functions, by BRGM and IRSN, at the COMPDYN2019 conference.

# WP summaries

## WP3: Integration and safety analysis

***Phil Vardon***
***TU Delft***

In the previous phase of Work Package 3 activities, various risk assessment methods were examined and two approaches - the Bayesian network (BN) and the "Extended Best Estimate plus Uncertainty" (E-BEPU) – were selected for further development within the project. In this phase, the Bayesian network methodology was adapted for implementation in the context of NPP risk. A generalized procedure was developed to perform multi-risk assessment via a Bayesian network framework. This iterative procedure allows for taking advantage of the inference capabilities of the Bayesian network. A 'toy' Bayesian network was created to model dependencies between random variables (including SSCs and external hazard factors). A simplified, yet realistic, example of a station blackout event, caused by earthquake or flooding events was considered to demonstrate the use of the methodology. Multiple hazard intensity measures based on preliminary results from WP1 were used. Corresponding vector-based fragility was included based on WP2 results. The network was used for both causative and diagnostic inference within the assumed sequence of events leading to station blackout. The procedure and preliminary results were submitted as an abstract and poster for the FISA 2019 and EURADWASTE '19 Conference.

This toy BN example will further be extended to larger test cases representing realistic NPP risk scenarios.

A geotechnical sub-network modelling the reliability of a flood defence dike was developed. The network was built using several continuous random variables representing dike soil properties, dike geometry and reliability and consequence measures. The network was used for measuring the impact of geotechnical testing on the uncertainty of dike reliability. The workings of this sub-network will be presented at the 7th International Symposium on Geotechnical Safety and Risk, ISGSR 2019. This sub-network will further be integrated into a larger BN to evaluate the effect of geotechnical uncertainty on the risk of adverse events in the NPP (e.g. station blackout). The sub-network will also be used to test BN parameter learning approaches and the non-parametric Bayesian approach for modelling continuous BNs. Other sub-networks involving human aspects and time aspects (dynamic BNs) are under development.

The BN approach is also being tested as an integrative tool for uncertainty propagation, sensitivity analysis, what-if scenario study and probability updating. A methodology was developed for quantifying aleatory and epistemic uncertainty for discrete BNs. The method will be tested for a realistic, NPP-related risk scenario – for e.g. the toy BN developed for the station blackout scenario.

# WP summaries

## WP4: Applying and comparing various safety assessment approaches on a virtual reactor

*Giuseppe Rastiello*
*CEA*

During the first 18 months, the main task consisted in defining a simplified theoretical Nuclear Power Plant (NPP) representative of the European fleet, to be used for validation and comparison of existing and new methods for PSA (Deliverable D4.1 - "Definition of a simplified theoretical NPP representative of the European fleet").

This theoretical NPP can now be used for conducting reactor safety analyses (in Task 4.3), considering different scenarios (WP3) and external physical threats (WP1) and their consequences regarding the fragility of system components. This referential model can also be used (in Task 4.2) for applying reduced modeling strategies (e.g., meta-models) to the evaluation of the impact of external hazards (earthquakes, tsunamis, flooding) form a probabilistic viewpoint as the development of meta-modeling strategies (Task 4.2) is now completed.

EDF has proposed a methodology (Wang et al., 2018) based on Artificial Neural Networks (ANN) for the construction of metamodels to build the relations between seismic IMs and Engineering Demand Parameters (EDPs) of the structures, to accelerate the fragility analysis. Fragility curves can then be evaluated point-by-point using direct Monte Carlo simulations, by assuming a lognormal model and by applying linear regression techniques. The methodology allows for vector-valued fragility curves. First applications concerned the estimation of the probability of failure of an electrical cabinet in a reactor building of the Kashiwazaki-Kariwa NPP (Japan). Applications to the NARSIS theoretical NPP will start in the coming months.

CEA methodology based on Support Vector Machines (SVMs) (Sainct et al., 2019) coupled with an Active Learning algorithm. In this methodology, SVMs are adopted to achieve a binary classification of structural responses relative to a limit threshold of exceedance. Since the SVM output is not binary but a real-valued score, a probabilistic interpretation of this real-valued score is introduced to estimate fragility curves very efficiently.

Finally, BRGM has proposed a method to construct metamodels for earthquake-induced tsunamis hazard assessments accounting for uncertainties on the scenario parameters, namely: the location of the epicenter, the size of the rupturing fault, the slip displacements. The selected technique is the kriging approach (e.g., Roustant et al., 2012), which enables to learn in a nonparametric manner the statistical link between the scenario parameters and the indicator of tsunami hazard, namely the maximum sea surface elevation (SSE) at the coast.

In parallel with these theoretical and methodological developments, analytical models (severe accident, thermal-hydraulics, PSA) of the referential NPP were developed in Task 4.3. The aim was to prepare models useful in nuclear safety research, and which can be used to test novel methods developed in other WPs. In particular, analytical models (severe accident, thermal-hydraulics, PSA) of the referential NPP are now available.

The severe accident model was developed using the MELCOR 2.2 computer code, whereas the thermal-hydraulics model was developed by WUT & NCBJ, using the RELAP5 system code. Finally, concerning the PSA model of the referential plant, the migration of the model from the RiskSpectrum code (model delivered by Framatome in August 2018) to the Saphire code has also been completed.

# WP summaries

## WP5: Supporting Tool for Severe Accident Management

***Luka Štrubelj***
***Gen Energija***

This WP5 is composed of four tasks. The first one, Task 5.1 "Characterization of the referential NPP", was completed in August 2018 and was described in the last issue of the newsletter (#2).

The Task 5.2 ("Characterization of EOP/EDMG/SAMG") was completed in the autumn 2018 with a report (Deliverable D5.2). The purpose of this report has been to describe procedures and guidelines (EOP "Emergency Operating Procedure"/EDMG "Extreme Damage Management Guidelines"/SAMG "Severe Accident Management Guidelines") applicable to the referential NPP and to support the development of the SAMG decision making/support tool. The general information about procedures and guidelines of the referential NPP has been provided and the entrance to EOP described. Furthermore, this report describes the transition from EOP to SAMG and discusses the transition of responsibilities from the main control room (MCR) and the technical support center (TSC). It also describes the SAMGs guidelines applicable to selected sequences necessary for developing the SAMG decision making tool. Most important technical support actions in SAMG are: injection into SG (Steam Generators), depressurization of RCS (Reactor Coolant System), injection into the RCS and control of containment conditions. This description includes purpose, entry conditions, negative impacts mitigation actions and long term concerns.

The purpose of injection into the SG are to protect the SG tubes from creep rupture, to scrub fission products entering the SG via tube leakage and to provide heat sing for the RCS. The entry into this action is based on low SG water level. The negative impacts are: thermal shock of SG, fission release from leaking SG tubes, creep rupture of SG tubes, degraded heat transfer, component corrosion.

The purpose of the RCS depressurization are to prevent a high pressure melt ejection, to prevent the creep rupture of the SG tubes when there are dry to allow RCS makeup from low pressure injection sources, to maximize RCS makeup from any centrifugal pump injection source, to prevent RHR (Residual Heat Removal) system overpressure if still aligned for service. The entry to this action is based on high RCS pressure. There can be several negative impacts: containment severe challenge from overpressure, SG fission product releases, loss of SG inventory, and containment fission product releases.

The purpose of injection into the RCS are: to remove stored energy from the core when it has been uncovered, to provide an ongoing decay heat removal mechanism, to prevent or delay vessel failure, to provide a water cover to scrub fission products released from the core debris, and to provide water to cool fuel in the refueling cavity. The entry condition is based on high core temperature and high containment radiation. The negative impacts are: creep rupture of SG tubes, containment flooding and overpressure, auxiliary building un-habitability, RCP seal degradation, component corrosion, and fission product releases. The negative impacts could also be: insufficient RCS injection source, containment overpressure challenge, and containment flooding.

The purpose of controlling containment conditions are: to prevent a challenge to containment integrity, to prevent a challenge to containment penetration seals, to minimize the challenge on containment equipment and instrumentation, to reduce the airborne fission product concentrations, and to mitigate fission product leakage from containment. The entry condition is based on high containment pressure. Finally, the Deliverable D5.2 describes the basic principles of EDMGs.

Selected severe accident sequences (postulated initiating events resulted with significant core degradation) can be generally grouped into 2 major sequences, based on RCS pressure at which reactor pressure vessel (RPV) fails and dynamic effect on containment structures: high pressure sequence towards low pressure sequence. Both are briefly described in D5.2, however the more extensive description will be done in the next Task T5.3 and documented in deliverable D5.3.

In Task 5.4, the supporting SAMG decision making tool for demonstration purposes will be developed. The concept of the tool is under development and several discussions has been already conducted I order to exchange between the decision making tool developers and the nuclear safety experts. In the meantime, the model of the reactor core, reactor coolant system and containment is ongoing. The results of severe accident safety analyses, parts of probabilistic safety analyse and expert judgement will be a guidance and input for decision support tool.

# EVENTS

## PATRAM 2019 - Packaging and Transportation of Radioactive Materials Symposium

*04 Aug 2019 - 09 Aug 2019 • New Orleans, LA, United States*

**Event website:**

http://www.patram.org/

## NURETH-18 — 18th International Topical Meeting on Nuclear Reactor Thermal Hydraulics

*18 Aug 2019 - 22 Aug 2019 • Portland, OR, United States*

**Event website:**

http://www.ans.org/meetings/m_285

## NARSIS workshop training on Probabilistic Safety Assessment for Nuclear Facilities

*2 Sept -5 Sept 2019 • Institute of Heat Engineering, Warsaw University of Technology, Warsaw, Poland*

**Event website:**

http://nuclear.itc.pw.edu.pl/narsis-workshop/

## 24th World Energy Congress

*09 Sep 2019 - 12 Sep 2019 • Abu Dhabi, United Arab Emirates*

**Event website:**

https://www.wec24.org/

## ISFNT-14 - International Symposium on Fusion Nuclear Technology

*22 Sep 2019 - 27 Sep 2019 • Budapest, Hungary*

**Event website:**

http://isfnt-14.org/

## International Conference on Climate Change and the Role of Nuclear Power

*07 Oct 2019 - 11 Oct 2019 • Vienna, Austria*

**Event website:**

https://www.iaea.org/atoms4climate

## NAWG-16 - 16th Workshop of the Natural Analogue Working Group

*15 Oct 2019 - 18 Oct 2019 • Yamagata, Japan*

**Event website:**

http://www.natural-analogues.com/nawg-news-and-events/226-nawg-16-latest

# Partners

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