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Vysus Group

# Getting ahead of accident scenarios using real-time predictions – The RASTEP method

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# Context

## Getting ahead of accident scenarios using real-time predictions – The RASTEP method

# Context

***"Prediction is difficult,***
***especially if it concerns the future."***

*Digital Globe - Earthquake and Tsunami damage – Fukushima Daiichi Nuclear Power Plant, Japan*

# Context

## “Normal” situation

Detailed and complex set of assessment criteria

Detailed and complex set of mathematical models

Comprehensive & extensive documentation

Large amounts of information and data available

Not time-critical

# Context

**Emergency situation**

***Approximately how much?***

***Approximately when?***

Need for quick decisions

Information and data may be limited, uncertain or delayed

# Context

*“The operational criteria for [emergency] classification shall include emergency action levels and other observable conditions (i.e. ‘observables’) and indicators of the conditions at the facility and/or on the site or off the site. The emergency classification system shall be established with the aim of allowing for the prompt initiation of an effective response in recognition of the uncertainty of the available information.”*

[IAEA Safety Standards, Preparedness and Response for a Nuclear or Radiological Emergency, GSR Part 7, 2015]

*“The decision to act needs to be made promptly. There is no time for meetings to determine what to do, and off-site decision makers cannot wait to see if a release actually occurs.”*

[IAEA Safety Standards, Actions to Protect the Public in an Emergency due to Severe Conditions at a Light Water Reactor, EPR-NPP PUBLIC PROTECTIVE ACTIONS, 2013]

*“During the response to the accident, ‘source term’ estimates from the ERSS could not be provided as an input to SPEEDI owing to the loss of on-site power. Decisions on evacuation and sheltering were taken on the basis of plant conditions (i.e. loss of core cooling), rather than on dose projections as had been planned.”*

[IAEA, The Fukushima Daiichi Accident, Technical Volume 3/5, 2015]

# Deterministic & Probabilistic Safety Assessment Prediction Capability

## Getting ahead of accident scenarios using real-time predictions – The RASTEP method

# Deterministic vs. Probabilistic Safety Assessment

**Deterministic safety assessment**

Define a set of *bounding* sequences (design basis) that the system *should withstand*.

Specify *acceptance criteria* to define the design limits for each bounding sequence.

Use *deterministic models* to verify that each bounding sequence stays within its limits.

The results also provide you with safety margins for the bounding sequences.

**Probabilistic safety assessment**

Since the design basis is finite, there are sequences that the system *will not withstand*.

Define an *overarching safety criterion* and *systematically search* for failing sequences.

Use *probabilistic models* to determine their frequency (likelihood).

The results also provide you with a risk profile.
(Which part of the system contributes more to the risk?)

# Level 2 Probabilistic Safety Assessment (Nuclear)

**Deterministic safety assessment**

A nuclear power plant has a design basis.

Define an acceptance criterion in terms of acceptable/unacceptable releases.

Use deterministic models to calculate the release category consequences (for typical or bounding sequences).

**Probabilistic safety assessment**

There are sequences which will lead to radioactive releases.

Define release categories as sets of similar accident sequences, and systematically search for failures that give rise to these sequences.

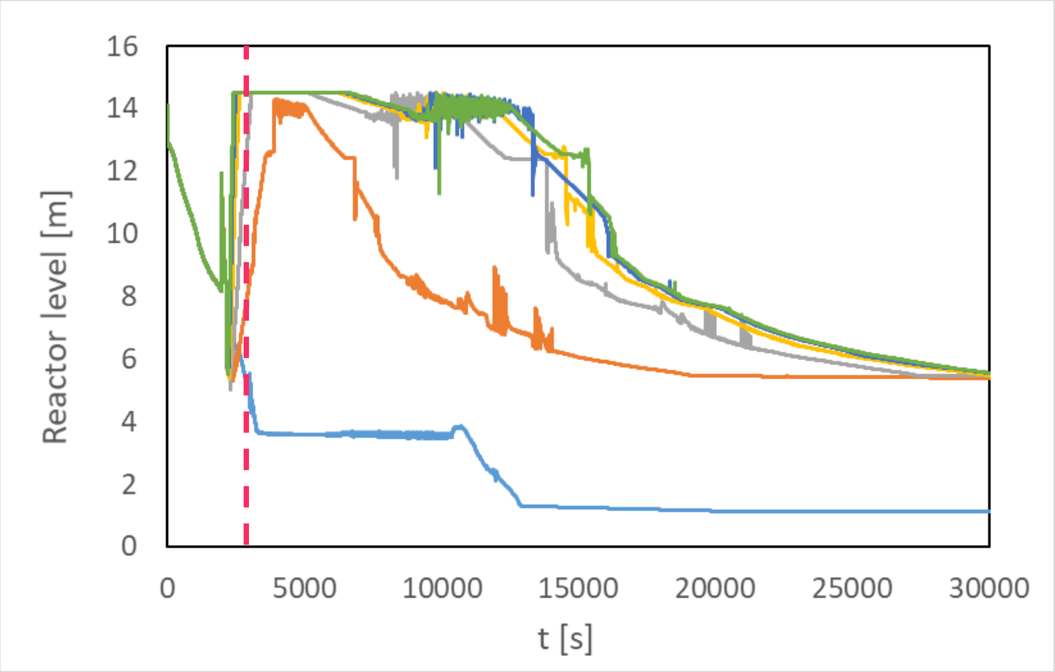
Use probabilistic models to determine the release category frequencies (likelihoods).

# Prediction Capability

## Deterministic safety assessment

| | Release category A | Observations | |
|---|---|---|---|
| **Initiator** | Initiating event X | Initiating event X | ☑ |
| **System failing** | System Y | System Y | ☑ |

If an ongoing accident is observed to belong to a specific release category, A,
the prediction is that the consequences will stay within the limits of that release category.



# Prediction Capability

## Probabilistic safety assessment

~~**RC1**~~
~~Sequence 1.1~~
~~Sequence 1.2~~
~~Sequence 1.3~~
…

**RC2**
Sequence 2.1
Sequence 2.2
Sequence 2.3
…

~~**RC3**~~
~~Sequence 3.1~~
~~Sequence 3.2~~
~~Sequence 3.3~~
…
…

**RCN**
Sequence N.1
Sequence N.2
Sequence N.3
…

With each new observation of an ongoing accident, the likelihoods of release categories that do not correspond with the set of observations will decrease.

As new information is gathered, the list will contain a decreasing number of release categories with increased likelihoods.

# RASTEP Overview

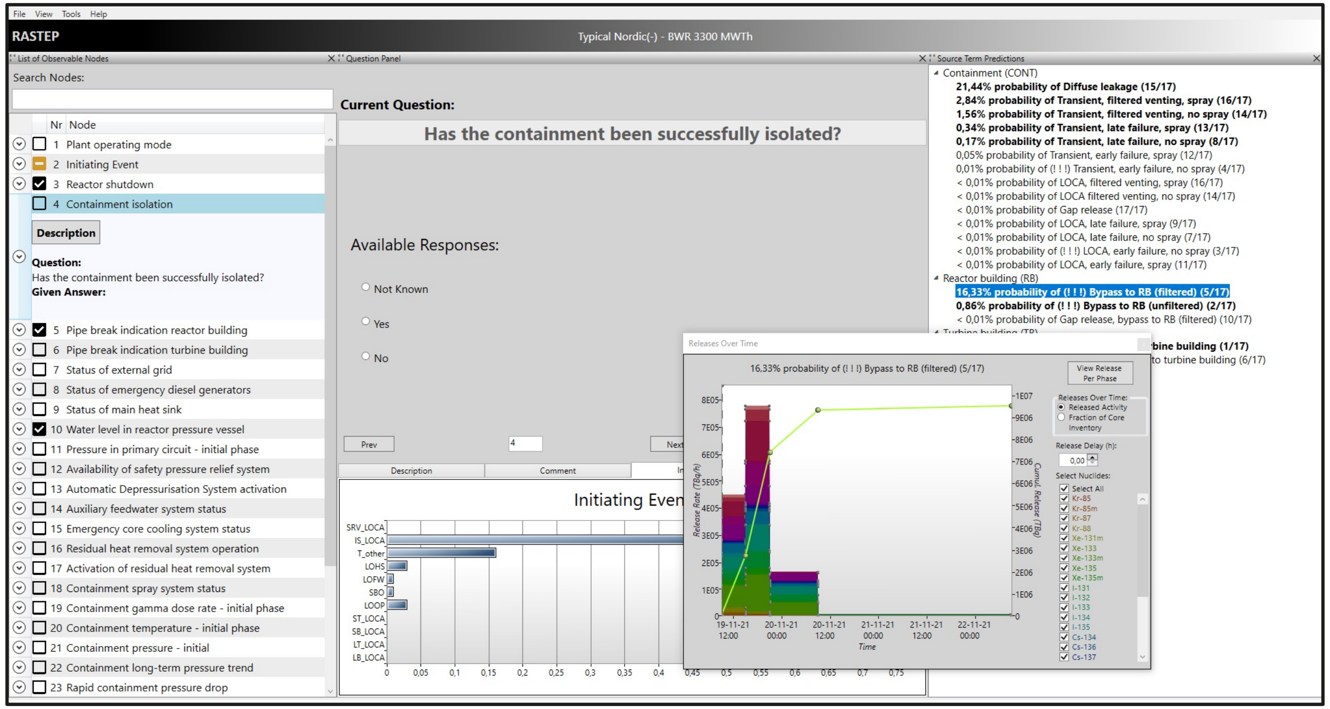
## Getting ahead of accident scenarios using real-time predictions – The RASTEP method

# Overview – History

2010: The Swedish Radiation Safety Authority (SSM) wanted a radioactive release estimation tool for use during the early stages of a severe accident, when little information would be available.

- The idea was to replace missing information with likelihoods.
- A suitable probabilistic model for taking new information into account is a so-called *Bayesian Belief Network.*

⟶ Vysus Group, previously LR Energy, initiated the development of RASTEP, funded by SSM.



| Nr | Node |
|---|---|
| ☐ 1 | Plant operating mode |
| ⊟ 2 | Initiating Event |
| ☑ 3 | Reactor shutdown |
| ☐ 4 | Containment isolation |
| ☑ 5 | Pipe break indication reactor building |
| ☐ 6 | Pipe break indication turbine building |
| ☐ 7 | Status of external grid |
| ☐ 8 | Status of emergency diesel generators |
| ☐ 9 | Status of main heat sink |
| ☑ 10 | Water level in reactor pressure vessel |
| ☐ 11 | Pressure in primary circuit - initial phase |
| ☐ 12 | Availability of safety pressure relief system |
| ☐ 13 | Automatic Depressurisation System activation |
| ☐ 14 | Auxiliary feedwater system status |
| ☐ 15 | Emergency core cooling system status |
| ☐ 16 | Residual heat removal system operation |
| ☐ 17 | Activation of residual heat removal system |
| ☐ 18 | Containment spray system status |
| ☐ 19 | Containment gamma dose rate - initial phase |
| ☐ 20 | Containment temperature - initial phase |
| ☐ 21 | Containment pressure - initial |
| ☐ 22 | Containment long-term pressure trend |
| ☐ 23 | Rapid containment pressure drop |

**Question:**
Has the containment been successfully isolated?
**Given Answer:**

**Current Question:**

Has the containment been successfully isolated?

Available Responses:

○ Not Known
○ Yes
○ No

Containment (CONT)
**21,44% probability of Diffuse leakage (15/17)**
**2,84% probability of Transient, filtered venting, spray (16/17)**
**1,56% probability of Transient, filtered venting, no spray (14/17)**
**0,34% probability of Transient, late failure, spray (13/17)**
**0,17% probability of Transient, late failure, no spray (8/17)**
0,05% probability of Transient, early failure, spray (12/17)
0,01% probability of (! ! !) Transient, early failure, no spray (4/17)
< 0,01% probability of LOCA, filtered venting, spray (16/17)
< 0,01% probability of LOCA filtered venting, no spray (14/17)
< 0,01% probability of Gap release (17/17)
< 0,01% probability of LOCA, late failure, spray (9/17)
< 0,01% probability of LOCA, late failure, no spray (7/17)
< 0,01% probability of (! ! !) LOCA, early failure, no spray (3/17)
< 0,01% probability of LOCA, early failure, spray (11/17)
Reactor building (RB)
**16,33% probability of (! ! !) Bypass to RB (filtered) (5/17)**
**0,86% probability of (! ! !) Bypass to RB (unfiltered) (2/17)**
< 0,01% probability of Gap release, bypass to RB (filtered) (10/17)

16,33% probability of (! ! !) Bypass to RB (filtered) (5/17)

*The RASTEP graphical user interface, version 1.4, released 2021.*

Strål
säkerhets
myndigheten
**Swedish Radiation Safety Authority**

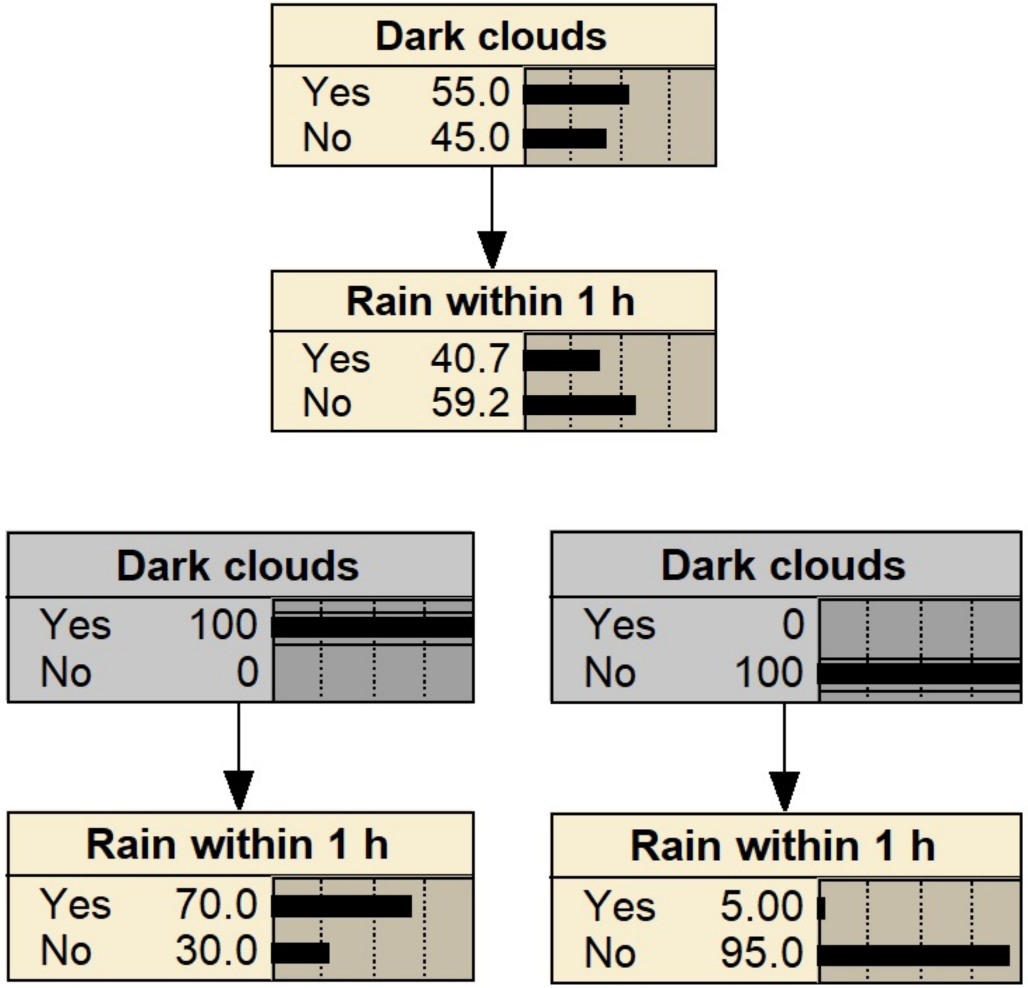
# Overview – Bayesian Belief Networks (BBN)

Bayesian Belief Networks are based on the concept of conditional probability as expressed in Bayes theorem.

The theorem implies that prior belief on an event (hypothesis) can be updated given additional evidence (observations).

$$P(State|Information) = \frac{P(Information|State) \cdot P(State)}{P(Information)}$$

Each node in a BBN contains the conditional probabilities of observing its’ states, given observations of its’ input nodes.



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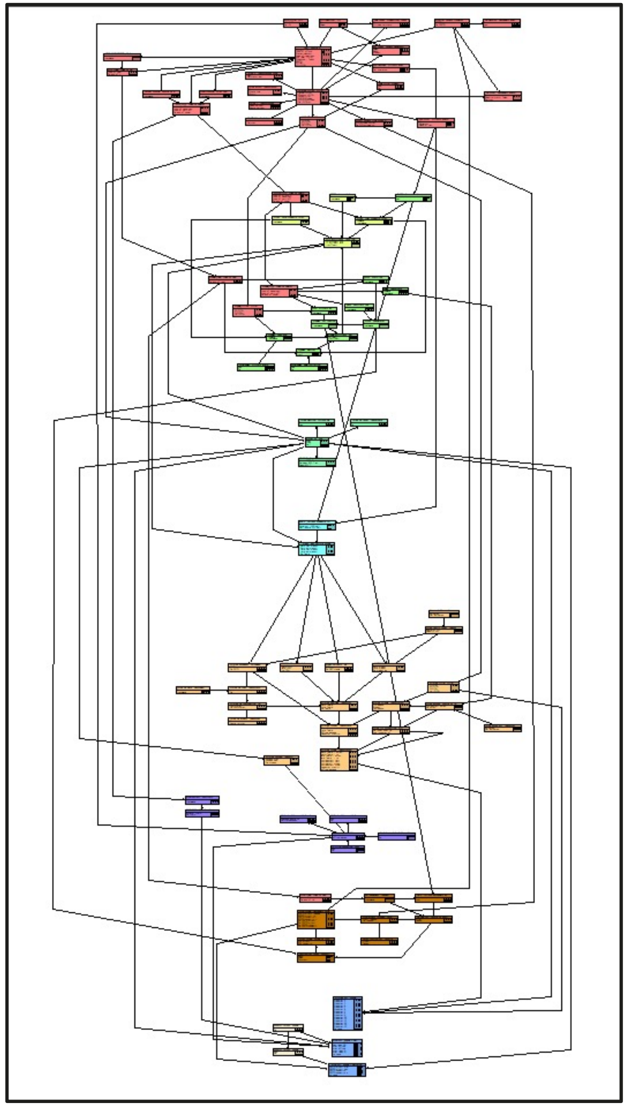
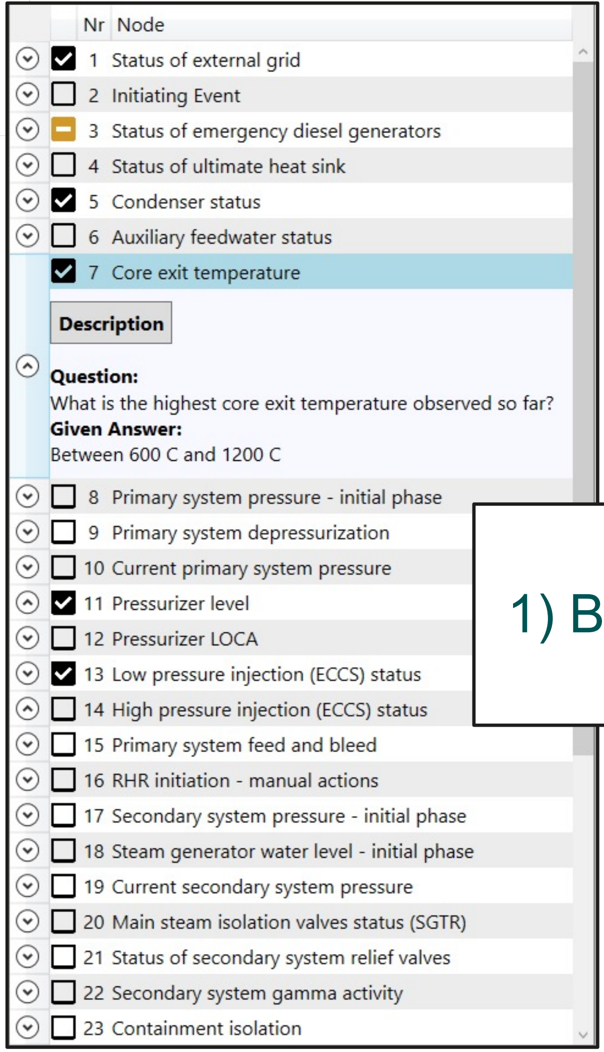


# Overview – Solution

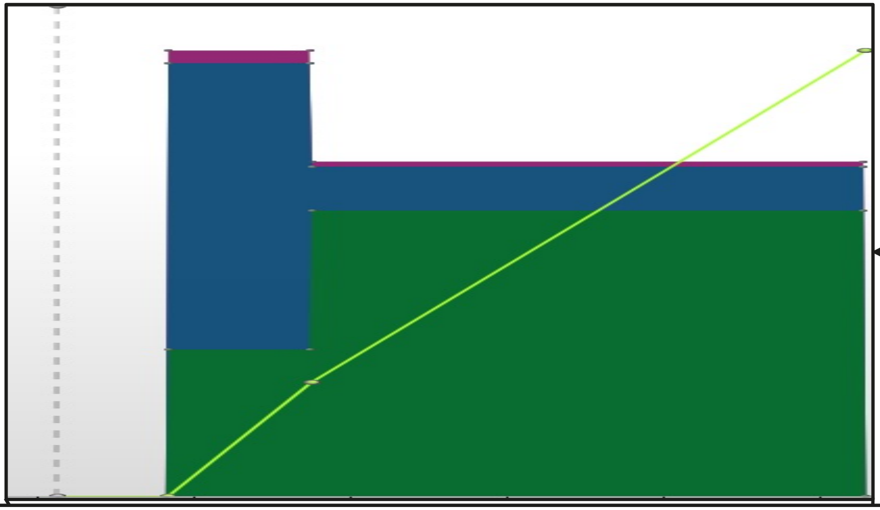


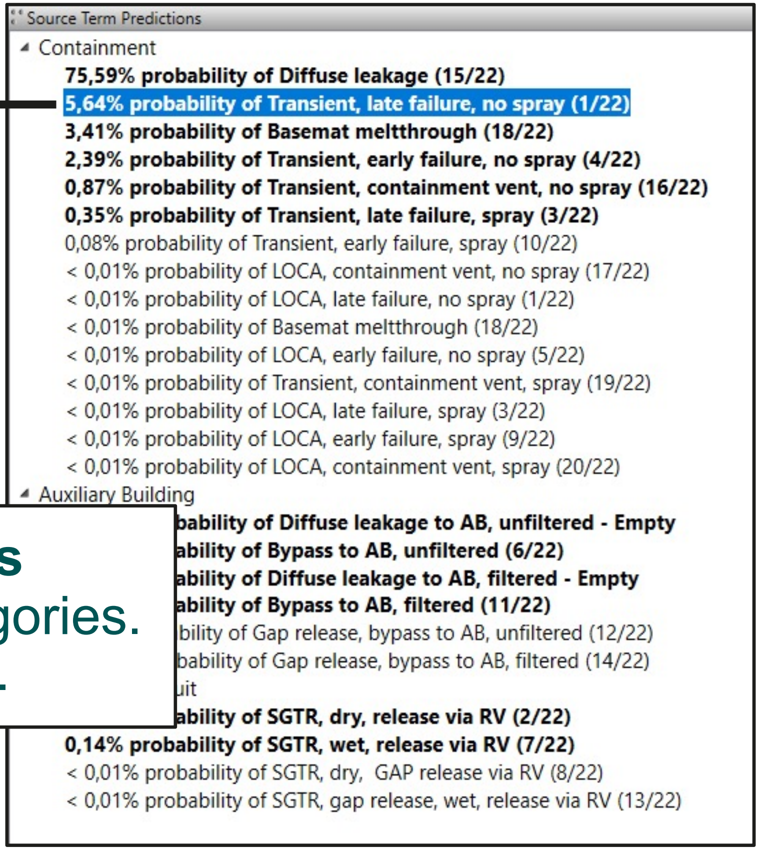
Nr Node

☑ 1 Status of external grid
☐ 2 Initiating Event
⊟ 3 Status of emergency diesel generators
☐ 4 Status of ultimate heat sink
☑ 5 Condenser status
☐ 6 Auxiliary feedwater status
☑ 7 Core exit temperature

**Question:**
What is the highest core exit temperature observed so far?
**Given Answer:**
Between 600 C and 1200 C

☐ 8 Primary system pressure - initial phase
☐ 9 Primary system depressurization
☐ 10 Current primary system pressure
☑ 11 Pressurizer level
☐ 12 Pressurizer LOCA
☑ 13 Low pressure injection (ECCS) status
☐ 14 High pressure injection (ECCS) status
☐ 15 Primary system feed and bleed
☐ 16 RHR initiation - manual actions
☐ 17 Secondary system pressure - initial phase
☐ 18 Steam generator water level - initial phase
☐ 19 Current secondary system pressure
☐ 20 Main steam isolation valves status (SGTR)
☐ 21 Status of secondary system relief valves
☐ 22 Secondary system gamma activity
☐ 23 Containment isolation





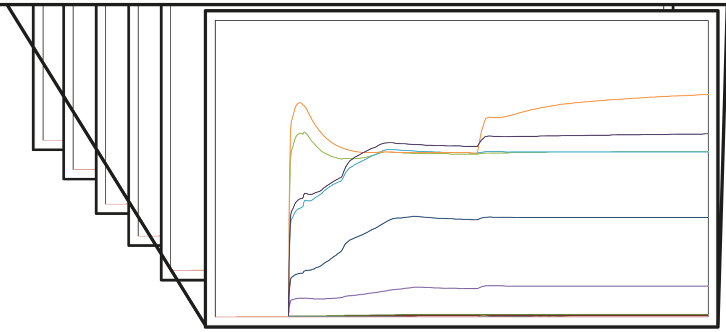
Source Term Predictions

Containment
- **75,59% probability of Diffuse leakage (15/22)**
- **5,64% probability of Transient, late failure, no spray (1/22)**
- **3,41% probability of Basemat meltthrough (18/22)**
- **2,39% probability of Transient, early failure, no spray (4/22)**
- **0,87% probability of Transient, containment vent, no spray (16/22)**
- **0,35% probability of Transient, late failure, spray (3/22)**
- 0,08% probability of Transient, early failure, spray (10/22)
- < 0,01% probability of LOCA, containment vent, no spray (17/22)
- < 0,01% probability of LOCA, late failure, no spray (1/22)
- < 0,01% probability of Basemat meltthrough (18/22)
- < 0,01% probability of LOCA, early failure, no spray (5/22)
- < 0,01% probability of Transient, containment vent, spray (19/22)
- < 0,01% probability of LOCA, late failure, spray (3/22)
- < 0,01% probability of LOCA, early failure, spray (9/22)
- < 0,01% probability of LOCA, containment vent, spray (20/22)

Auxiliary Building
- **bability of Diffuse leakage to AB, unfiltered - Empty**
- **ability of Bypass to AB, unfiltered (6/22)**
- **ability of Diffuse leakage to AB, filtered - Empty**
- **ability of Bypass to AB, filtered (11/22)**
- bility of Gap release, bypass to AB, unfiltered (12/22)
- bability of Gap release, bypass to AB, filtered (14/22)

uit
- **ability of SGTR, dry, release via RV (2/22)**
- **0,14% probability of SGTR, wet, release via RV (7/22)**
- < 0,01% probability of SGTR, dry, GAP release via RV (8/22)
- < 0,01% probability of SGTR, gap release, wet, release via RV (13/22)

**Uncertainty is represented in two ways**
1) By assigning likelihoods to all release categories.
2) By averaging simulations into phases.



# Overview – Solution

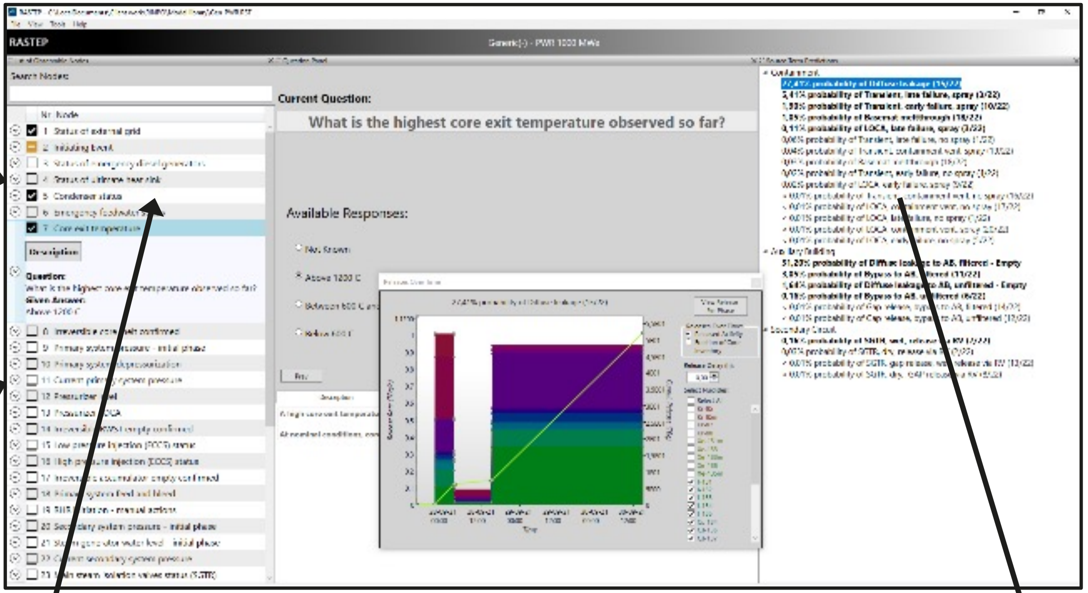
*Model building*

Probabilistic/ statistic model

BBN Model

Deterministic model

Database



Current Question:

What is the highest core exit temperature observed so far?

Available Responses:

○ Not Known

● Above 1200 C

Question:
What is the highest core exit temperature observed so far?
Given Answer:
Above 1200 C

Observations

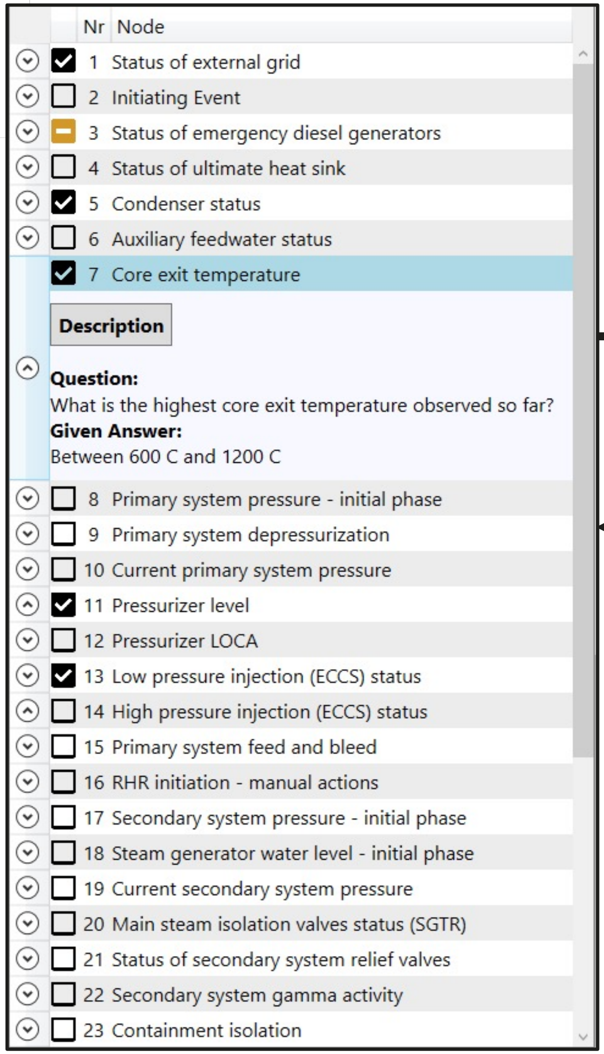
Data for use in decision-making

*Model use*

# Related R&D, outlook and summary

## Getting ahead of accident scenarios using real-time predictions – The RASTEP method

# R&D – Cross-Verification and Information Loss



Nr Node

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- ☑ 7 Core exit temperature

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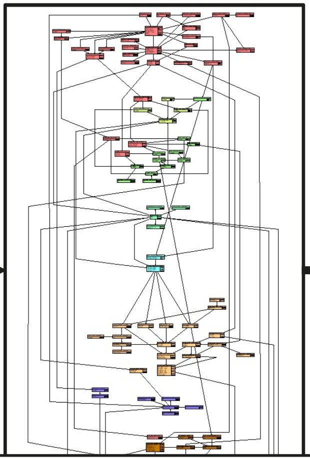

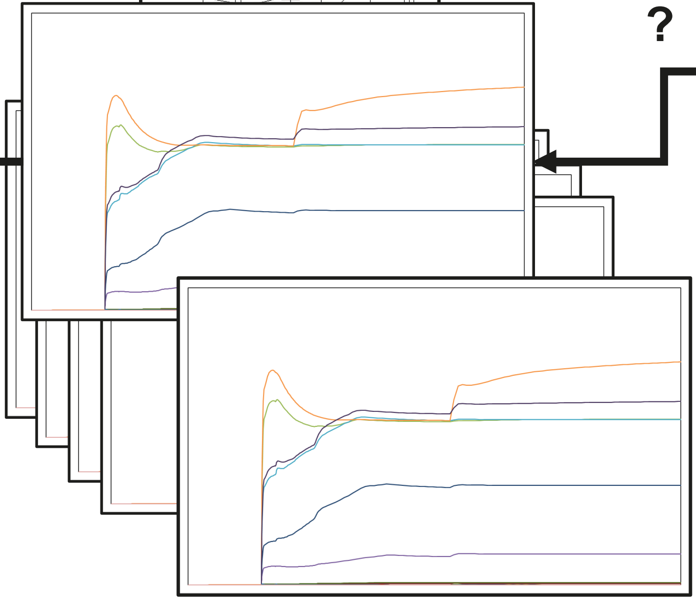

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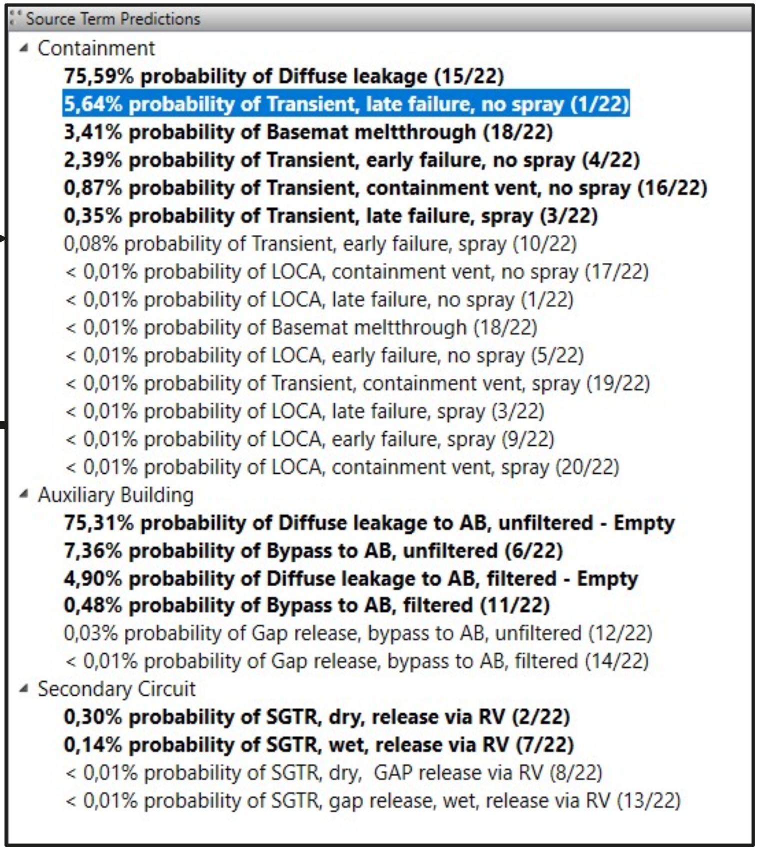

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  - < 0,01% probability of LOCA, early failure, spray (9/22)
  - < 0,01% probability of LOCA, containment vent, spray (20/22)
- Auxiliary Building
  - **75,31% probability of Diffuse leakage to AB, unfiltered - Empty**
  - **7,36% probability of Bypass to AB, unfiltered (6/22)**
  - **4,90% probability of Diffuse leakage to AB, filtered - Empty**
  - **0,48% probability of Bypass to AB, filtered (11/22)**
  - 0,03% probability of Gap release, bypass to AB, unfiltered (12/22)
  - < 0,01% probability of Gap release, bypass to AB, filtered (14/22)
- Secondary Circuit
  - **0,30% probability of SGTR, dry, release via RV (2/22)**
  - **0,14% probability of SGTR, wet, release via RV (7/22)**
  - < 0,01% probability of SGTR, dry,  GAP release via RV (8/22)
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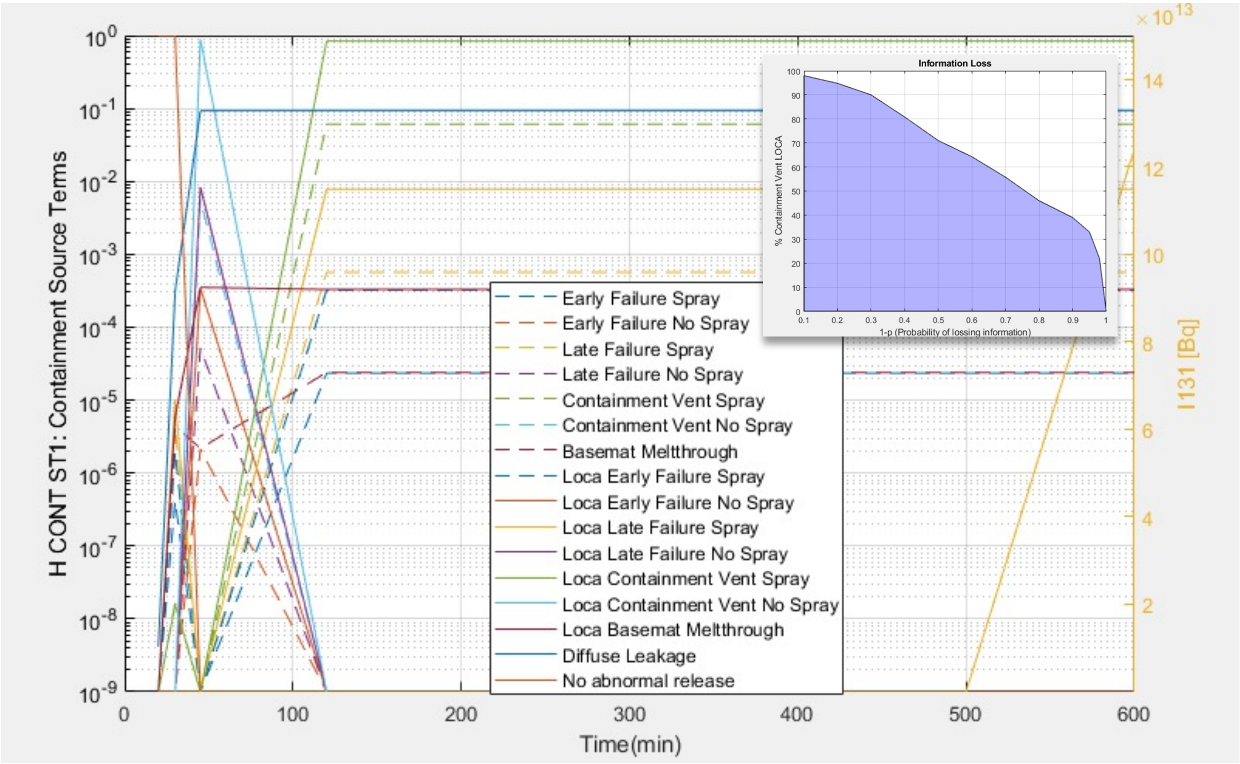
# R&D – Cross-Verification and Information Loss

MSc Thesis project with student from Royal Institute of Technology & Université de Paris.

Verify BBN model by introducing new information to the model as observables change states in the simulation.

We can measure:

- Time to correct prediction
- Time between correct prediction and time of major release.
- Sensitivity to missing information.



*Example of time evolution of RASTEP scenario likelihoods, with increasing amounts of information provided to the Bayesian Belief Network.*

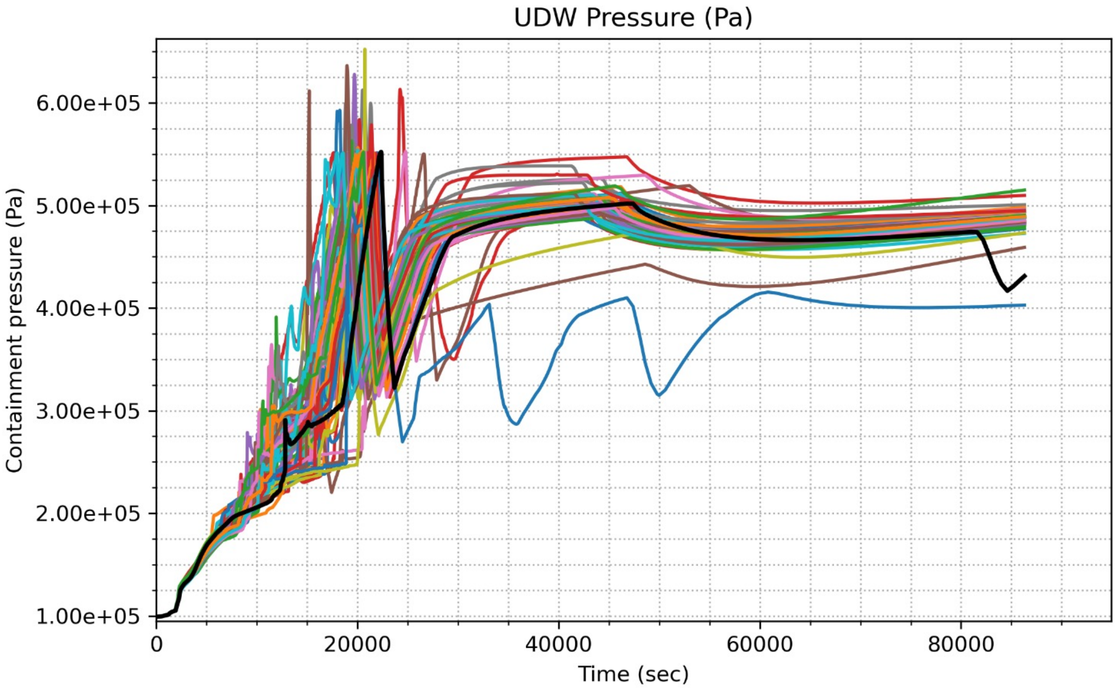
# R&D – Deterministic Model Uncertainty

## NKS STATUS

Assessment of the radioactive releases related to nuclear severe accident scenarios is typically performed with so-called integral plant response codes. These assessments are subject to uncertainty in the accident scenarios (aleatory) and in modeling of phenomena (epistemic).

The main goal of the project, coordinated by Vysus Group, is to generate a body of knowledge regarding this uncertainty, as well as to provide valuable insights into the effect of different types of uncertainty, to be used in safety assessment and emergency planning.

***Project partners***



*Simulation of pressure development from the MELCOR code, with uncertainty in deterministic model parameters.*

VTT

KTH VETENSKAP OCH KONST

Strål säkerhets myndigheten
Swedish Radiation Safety Authority

DSA Norwegian Radiation and Nuclear Safety Authority

# Outlook – New Applications

NKS CRESCENT project: “Credible release scenarios for nuclear-powered vessels operating in Nordic waters”

- For an accident in a commercial nuclear power plant, the challenge is to identify the sequence type in a complex but well-known plant.
- For an accident in naval nuclear power plant, the challenge is to make reasonable assumptions on releases and uncertainties for a less complex but unknown plant.

Vysus Group is performing a feasibility study of using RASTEP for this purpose.

*Image: Tove Holmøy, Tegneglede*

# Outlook – New Applications

**Some examples**

*Application ideas, similar to the nuclear emergency response case*

- Accident release scenarios for chemical or petro-chemical systems
- Dynamic emergency response exercise feedback

*Other known application examples*

- Medical diagnosis
- Managing risk of runway excursions in aviation safety
- Prior-launch final checks in aerospace industry
- Identification of concern factors related to the spread of an infectious disease

# Summary

RASTEP (RApid Source TErm Prediction) is a software tool and method for accident scenario identification and consequence prediction, using Bayesian Belief Networks and observations of plant conditions to support decision-making in situations with scarce or uncertain information.

Vysus Group has developed the tool, the methodology and various plant models over >10 years in cooperation with clients and project partners:

Strål
säkerhets
myndigheten
Swedish Radiation Safety Authority

FASTNET

DSA
Norwegian
Radiation and Nuclear
Safety Authority

中核武汉核电运行技术股份有限公司
China Nuclear Power Operation Technology Corporation,LTD.
核动力运行研究所
Research Institute Of Nuclear Power Operation
中核集团
CNNC

Further reading

https://www.vysusgroup.com/services/nuclear-facility-emergency-preparedness-rastep-rapid-source-term-prediction

https://www.vysusgroup.com/whitepapers/the-rastep-methodology-aiding-decision-making-for-accidents-at-nuclear-power-plants-and-wider-markets

December 1 , 2021

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Find out more about the RASTEP method on our website

# Thank you