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EST 1892

Application of Bayesian networks to hydrogen hazards in nuclear chemical plants

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Presentation structure

- Introduction
- Hydrogen generation mechanisms in nuclear chemical plants
- Hydrogen hazard management
- Bayesian methodology
- Case Study 1- Hydrogen hold-up and sudden release
- Case Study 2- Assessment of equipment reliability
- Conclusions

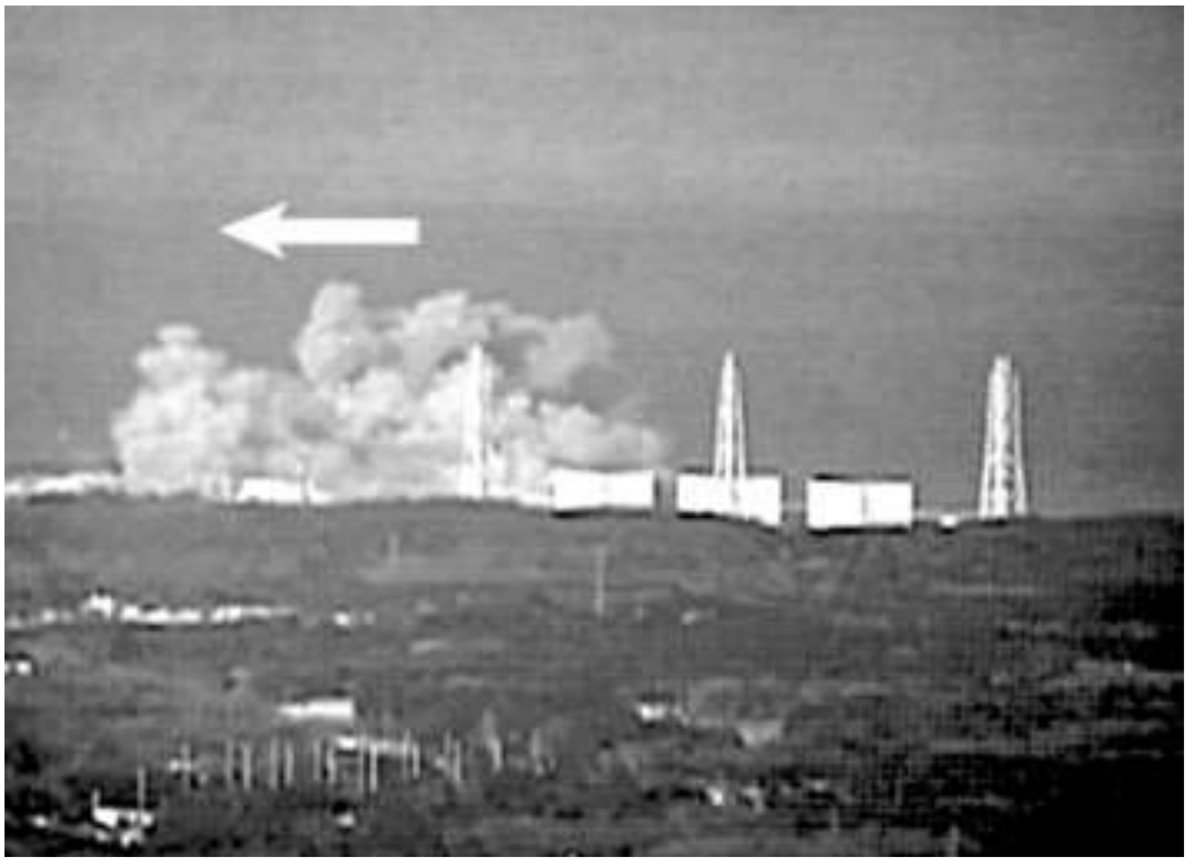
Introduction (1)

- Hydrogen generation in nuclear chemical plants presents a considerable challenge.
- Corrosion of metal fuel cladding waste and radiolysis are the main mechanisms.
- Consequences from hydrogen explosions can be significant.
- The Fukushima Daichaii event illustrates potential effects of hydrogen explosions (Figure 1).

Introduction (2)

- Duty Holder is legally required to demonstrate risk is ALARP.
- Demonstration of ALARP requires accurate risk analysis.
- Bayesian Belief Networks (BBNs) provide an improved means of risk quantification.
- Two case studies on application of BBNs to hydrogen safety are explored.

Figure 1: Damage caused by the Fukushima Daiichai H_2 Explosions [1]



Hydrogen generation mechanisms in nuclear chemical plants (1)

- Corrosion of magnesium metal (Magnox) fuel cladding waste in storage vessels
- Magnesium hydroxide sludge formed as a bi-product of corrosion
- Hydrogen hold-up occurs within Magnox sludge waste
- Sudden release of hydrogen into vessel ullage space

Hydrogen generation mechanisms in nuclear chemical plants (2)

- Alpha, Beta Gamma radiation in radioactive liquors results in radiolysis.
- Water dissociates to form hydrogen and the hydroxyl radical:

$$H + e^- + H_2O \rightarrow H_2 + OH^-$$

- Radiolytic hydrogen generation rate is primarily affected by the 'G-value'.
- G- value is number of H_2 molecules evolved per 100eV of energy absorbed by the medium

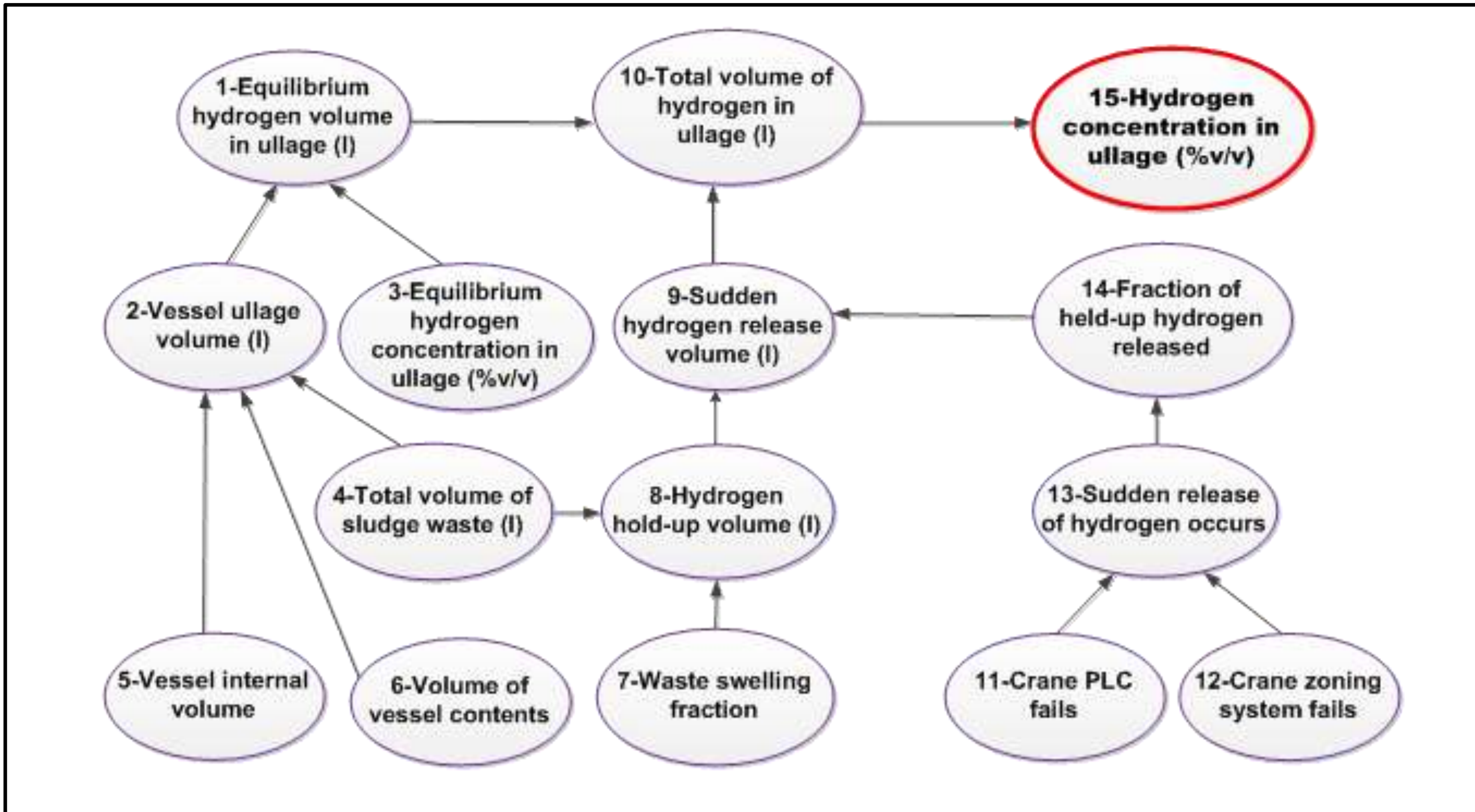
Chronic hydrogen hazard management (1)

- Waste storage vessel lids feature filtered outlets.
- Filtered vents designed to keep chronic H_2 concentration in ullage to <4%v/v.
- Control of vessel ullage volume is the key variable affecting H_2 concentration.
- Some hydrogen hold-up will occur in sludge waste forms.

Chronic hydrogen hazard management (2)

- Gas hold-up leads to waste expansion and reduction in ullage volume.
- Ullage volume is maximised to allow for waste expansion.
- Adverse waste disturbance could lead to a sudden release of H_2 in vessel ullage.
- Hazard management strategy is to reduce the risk of adverse disturbance of vessel.
- Figure 2 illustrates the key variables and effects.

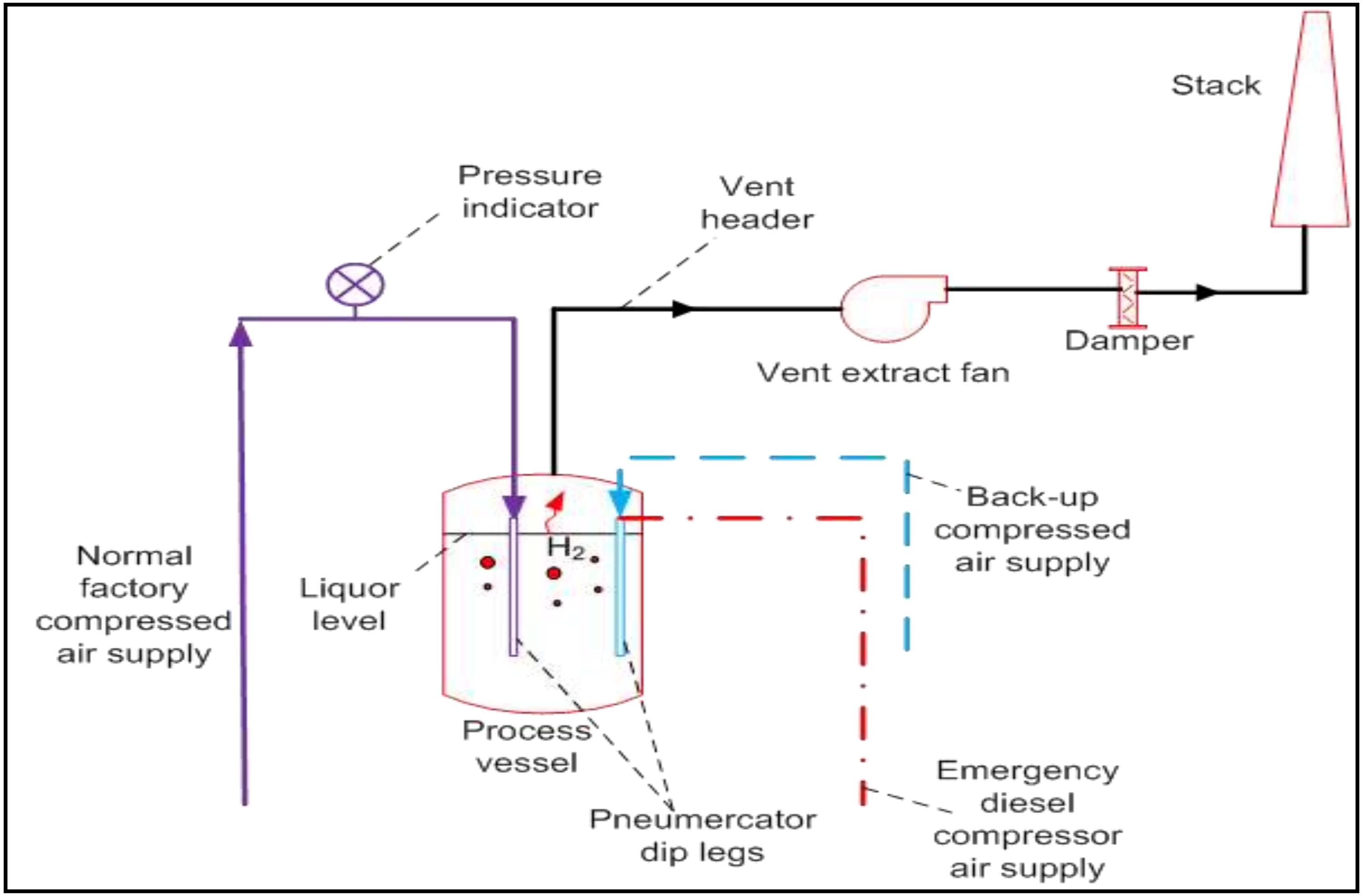
Figure 2: Key variables affecting H_2 hold-up and sudden release



Radiolytic hydrogen hazard management (1)

- Vessel ullage space purged with compressed air via pneumercators (Figure 3).
- Use ventilation extract fans as the driving force for hydrogen removal.
- For increased reliability, backup compressed air systems are introduced.
- Aim is to keep hydrogen concentration at 25% of the Lower Flammability Limit, i.e. 1%v/v.

Figure 3: Equipment for management of radiolytic H_2 in process vessels



Bayesian methodology (1)

- A statistical technique for modelling cause and effect relationships.
- Method relies on the concept of Bayes Theorem [**2**]:

$$P(A|B) = (P(A) \times P(B|A))/P(B)$$

- P(A) and P(B) are the probabilities of events A and B occurring.
- P(A) is probability of the hypothesis before any evidence is available.

Bayesian methodology (2)

- P(A|B) is a conditional probability of observing hypothesis A if B is true.
- P(B|A) is the probability of event B occurring if A is true.
- The equation in previous slide represents only two variables.
- Complex models with multiple variables require use of software , e.g. Netica [**3**].

Bayesian Network Process

- Bayesian software sets causal variables and effects in a graphical network (BBN).
- Each cause (Parent) is connected to the effect (Child) by an arc.
- Nodes can be Discrete or Continuous.
- Conditional Probability Tables (CPTs) are generated.
- CPTs can be based on expert judgement or mathematical functions.

Case Study 1: H_2 hold-up and sudden release - Objectives

1) Apply BBN technique to:

- Determine the key sensitivities affecting sudden release of hydrogen from sludgy waste forms.
- Assess the impact of sudden release on the vessel ullage H_2 concentration.

2) Use the results to determine the benefits of the BBN technique.

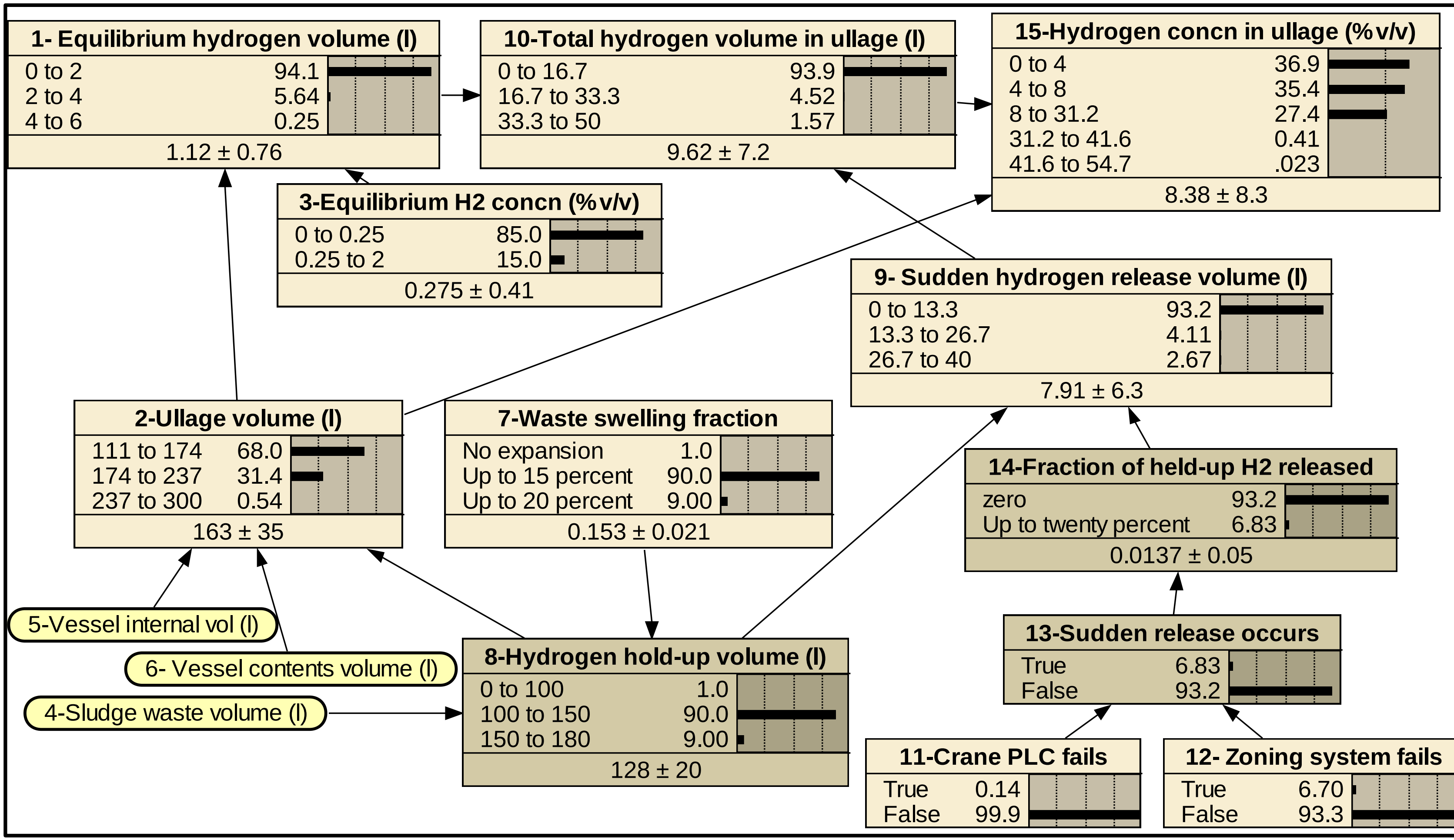
Case Study 1: H_2 hold-up and sudden release- BBN analysis

The following data was input into the BBN:

- 99% probability of waste expansion fraction being in the range 15-20 %v/v.
- 85% probability of a low corrosion hydrogen generation rate of 0.1 l/hr.
- 85% probability of the equilibrium hydrogen concentration being in the range 0 to 0.25%v/v.

BBN (Figure 4) constructed by replicating Figure 2 and using above input data.

Figure 4: BBN analysis for case study 1- H_2 hold-up and sudden release



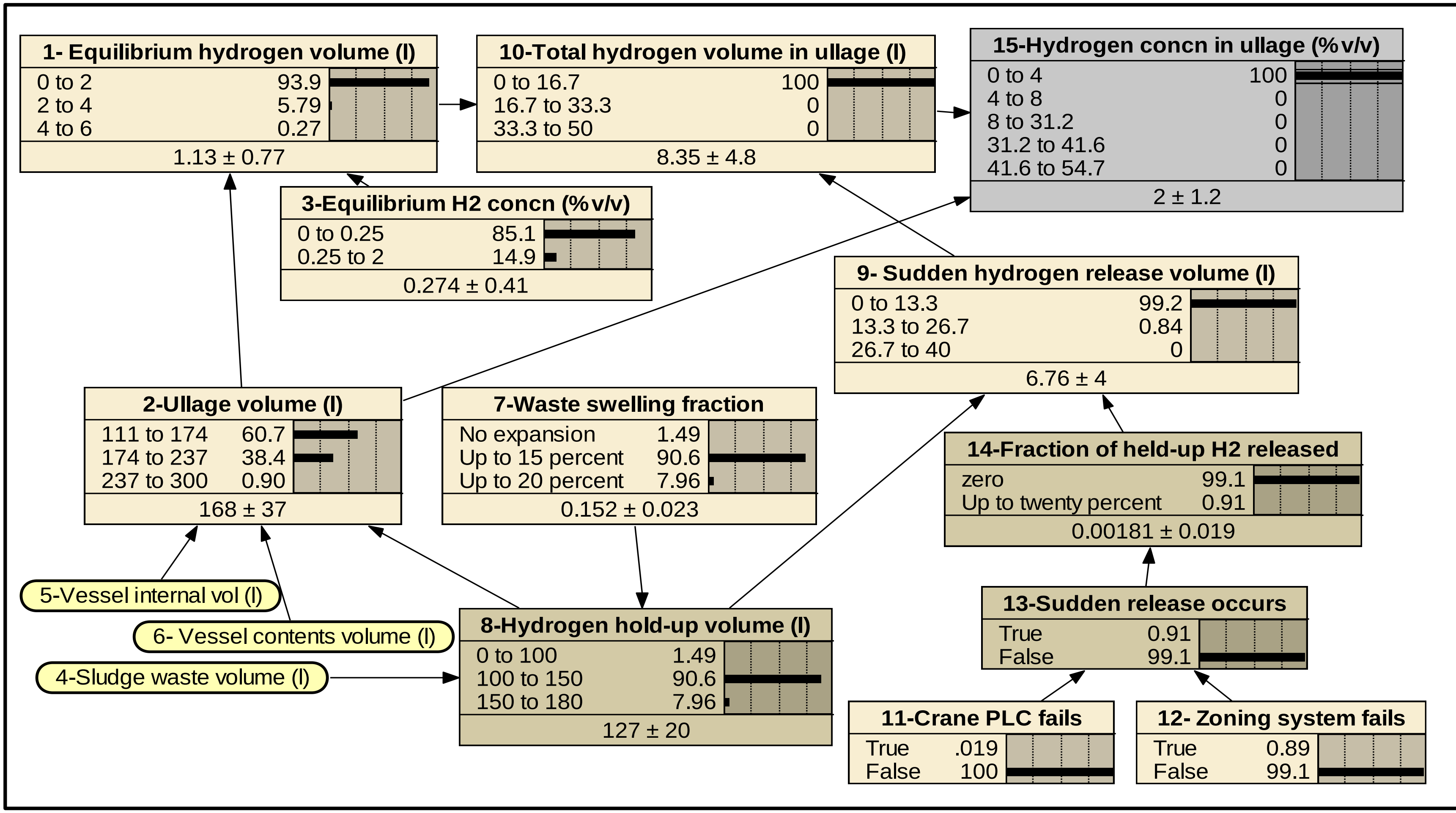
Case Study 1: H_2 hold-up and sudden release- BBN results

- The probability of hydrogen hold-up volume being in the range 100-150 litres is 90%.
- Adverse waste disturbance leads to sudden release of hydrogen gas.
- The probability of sudden hydrogen release volume being in the range 0 to 13.3 litres is 93.2%.
- The probability of ullage hydrogen concentration being in the range 0-4%v/v is 36.9%.

Case Study 1: H_2 hold-up and sudden release- Updating of BBN

- BBN updating capability enables a ‘reverse analysis’ to predict key sensitivities.
- The probability of ullage hydrogen concentration, Node 15, in the 0-4%v/v range is updated to 100% (Figure 5).
- Main sensitivities are crane PLC and vessel transfer zoning system failures.
- Both failures lead to adverse waste disturbance.

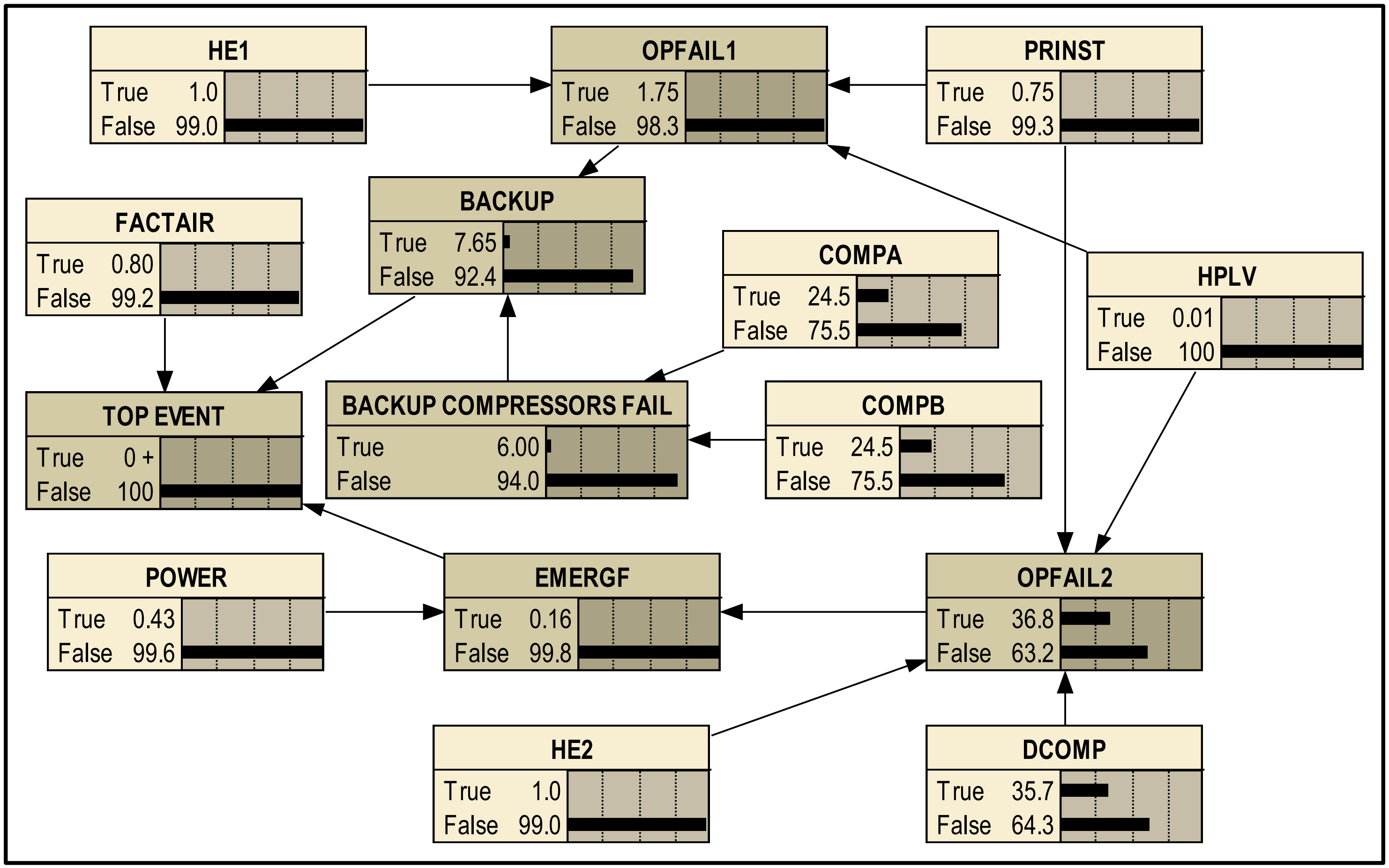
Figure 5: Updated BBN for case study 1- H_2 hold-up and sudden release



Case study 2: Reliability of purge air supply for radiolytic H_2 management

- Variables are represented by purge air equipment (Figure 3) and associated failure modes.
- Key failure modes included, normal air supply, back-up air compressors, site power supply and emergency diesel generator.
- Each variable modelled as a Discrete Node with a failure being in True or False state.
- Based on the Prior failure probabilities of the primary nodes, the BBN is given in Figure 6.

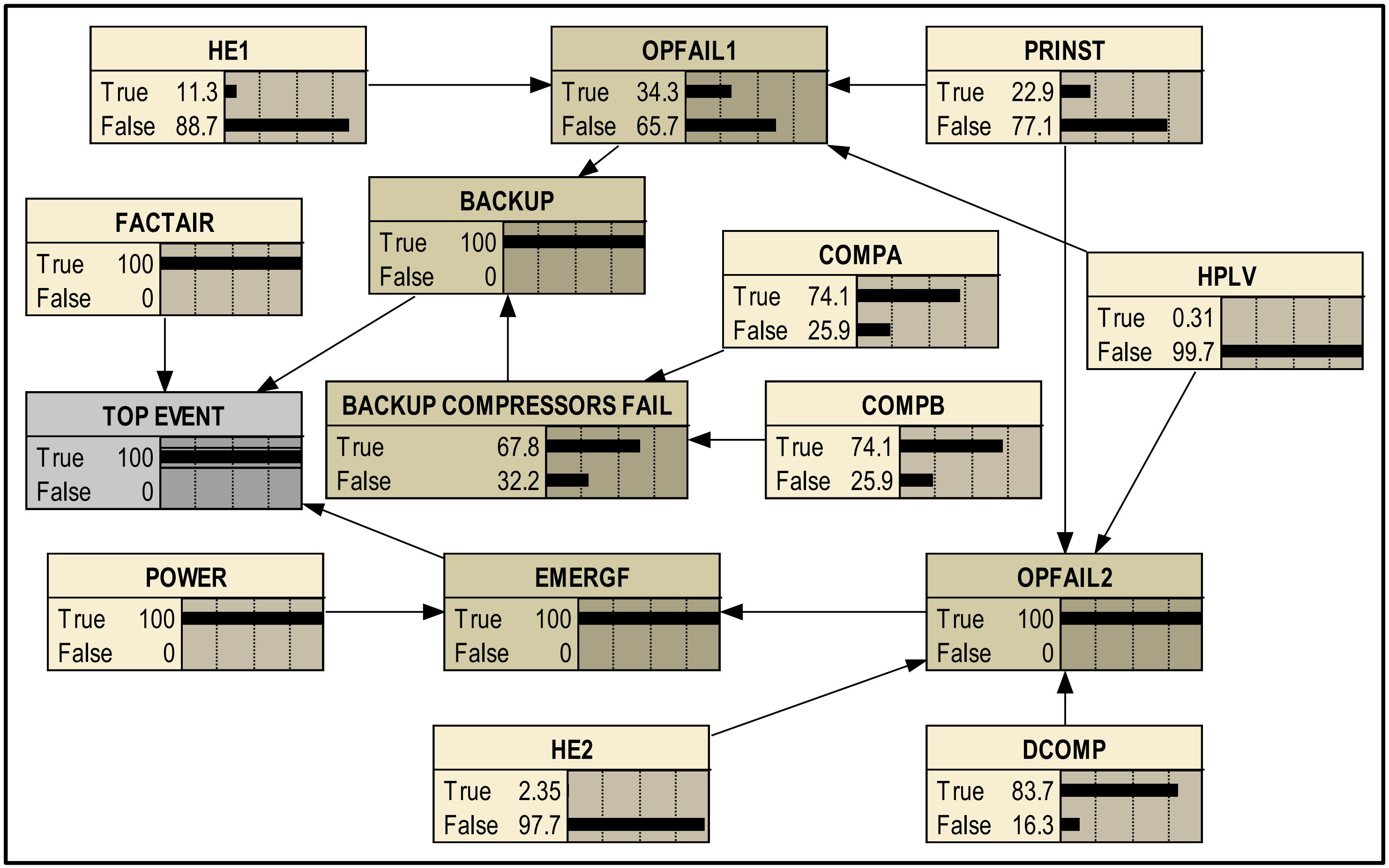
Figure 6: BBN for case study 2-unavailability of the purge air system



Case study 2: Reliability of purge air supply for radiolytic H_2 management

- The results show that the unavailability of the purge air system is low, i.e. $1x10^{-6}$ (Top Event probability shown as ‘0+’).
- Back- up compressor and emergency diesel compressor system failures are accountable for the Top Event probability of $1x10^{-6}$.
- Factory air and power supply failures present the key sensitivities for Top Event to occur indefinitely (Figure 7).

Figure 7: Updated BBN for case study 2- unavailability of the purge air system



Conclusions

- Hydrogen generation in nuclear chemical plants is a complex process.
- The H_2 explosion scenarios are affected by multiple dependent variables.
- Bayesian networks are demonstrated to provide an improved means of modelling dependency and uncertainty.
- The Bayesian updating feature has enabled a reverse analysis, hence sensitivity prediction.

References

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[3] Netica, Norsys, Available at www.norsys.com.