FAILURE ANALYSIS SIMULATION MODEL FOR THE NWMO’S APMRD-II

Contents

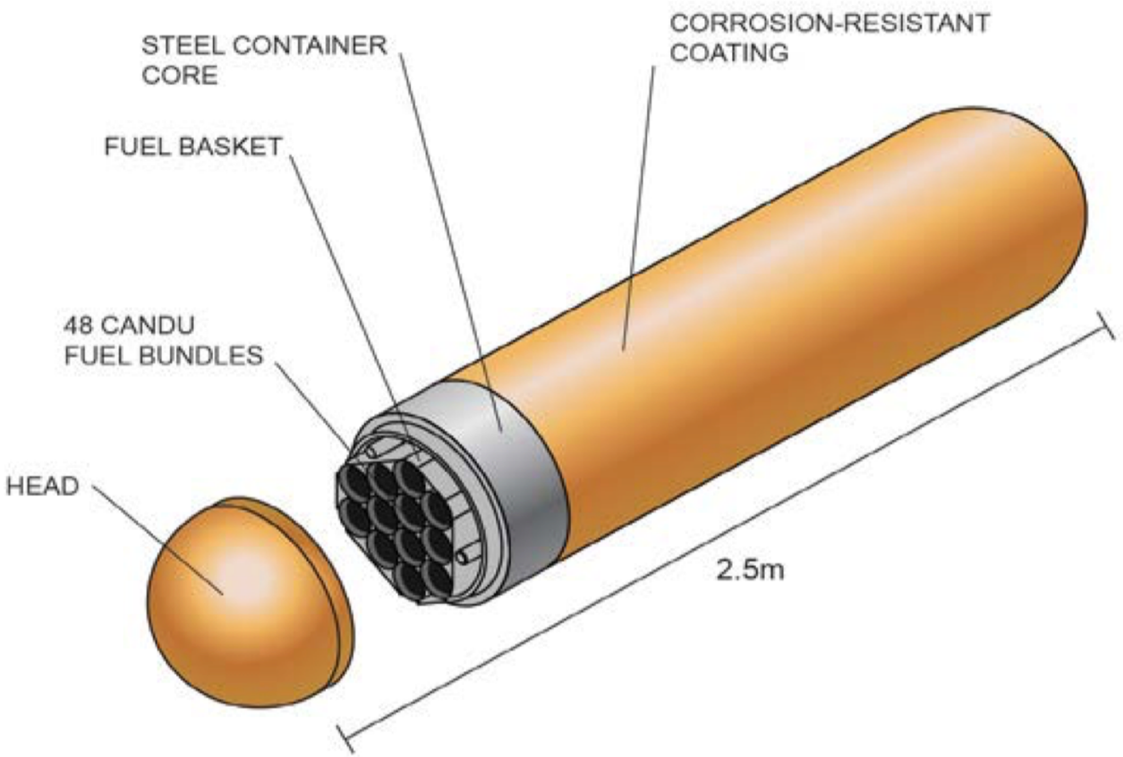
PROJECT DESCRIPTION

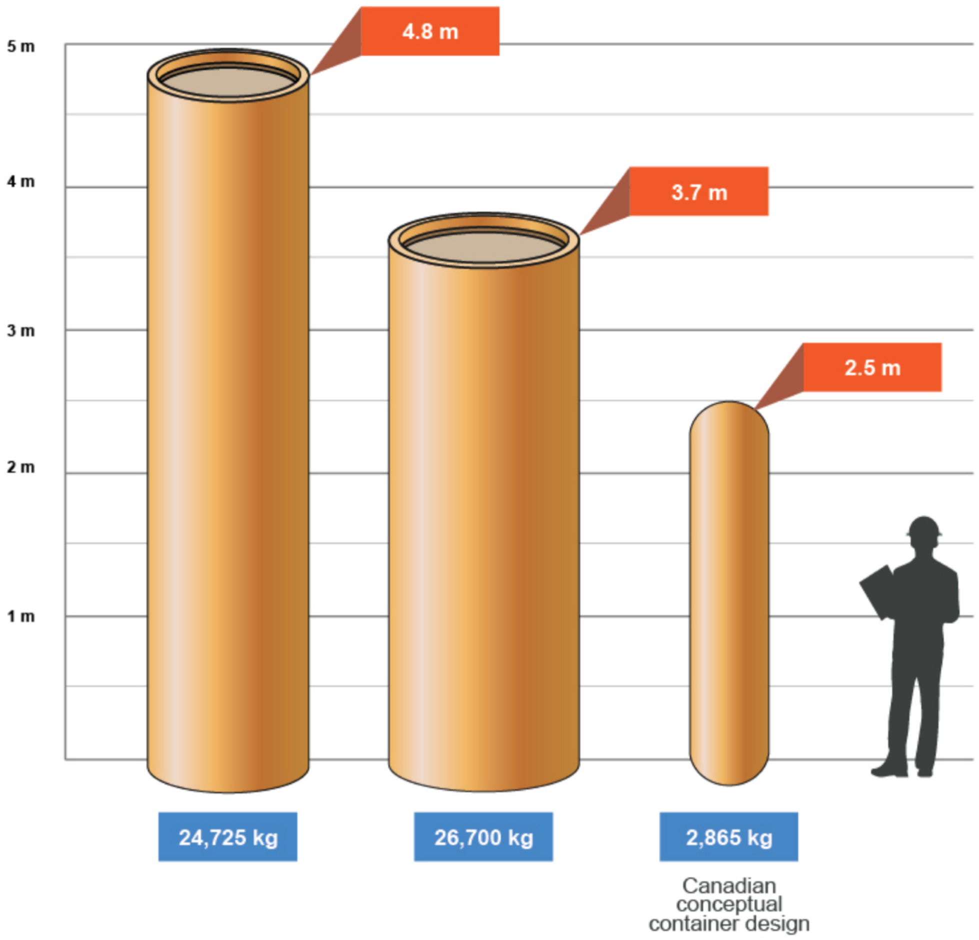
A hybrid strategy

Project Description

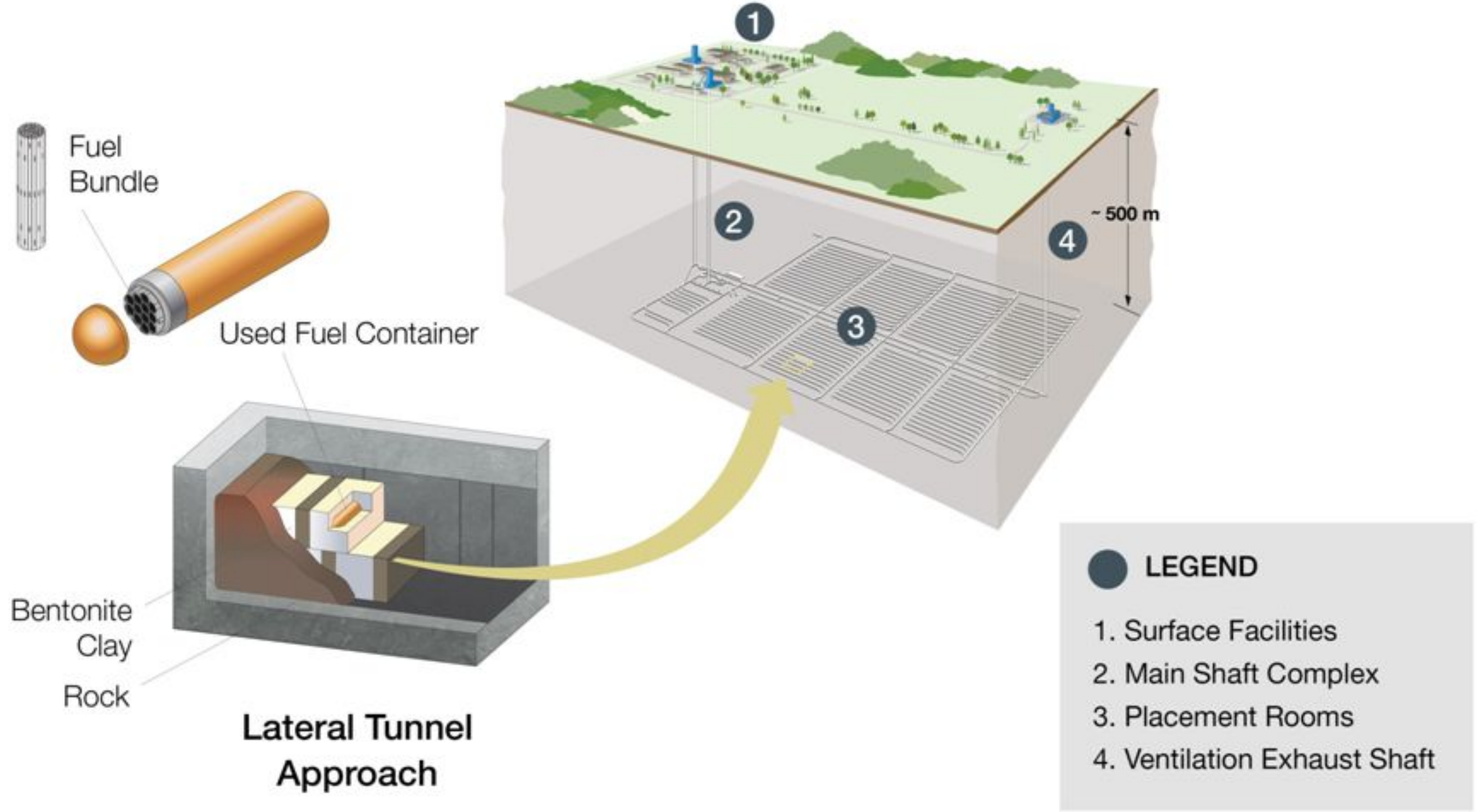
- Canada has a long history with nuclear power (first self-sustained Canadian nuclear reaction was achieved at Chalk River's ZEEP reactor in 1945). As of 2014, electricity is currently being produced by 19 CANDU reactors in Ontario and New Brunswick.
- Nuclear waste in Canada is a *fait accompli*: **how do we dispose of it safely?**
- The *Nuclear Waste Management Organization* (NWMO) has the mandate to provide recommendations to the Canadian Government for the long-term management of used nuclear fuel.
- In 2007, the NWMO recommended the establishment of *Adaptive Phased Management* (APM) as both a **social** and **technical** approach to permanently manage Canada's used nuclear fuel.
- Optimal strategy, given the current state of technology in Canada, is the construction of a **deep geological repository** to contain and isolate the fuel.

[images from NWMO]





Deep Geological Repository (DGR)



Project Description

- This structure as a whole cannot be tested in advance of use and essentially cannot be maintained once it is built. Furthermore, the environment and materials involved are themselves volatile and **their long term behaviour is difficult to predict.**
- Due diligence requires more than the simple assurance (and belief) that the structure will not fail – it also requires the provision of more quantitative information about the failure aspects of the structure.
- Those responsible for the structure need to be able to determine (and to help the stakeholders understand) what are the structure's **necessary and sufficient conditions for failure.**
- To produce these answers they need to be able to quantitatively examine what circumstances the structure might encounter, and under these circumstances, what the probability of failure is.

Project Description

- From an ideal testing point of view, the entire proposed structure would be built **many times over** to run trials relating to each of the foreseen circumstances.
- Data would then be gathered and analyzed to determine the failure tolerance of the structure. **Failure probabilities** would be calculated based on this data, along with an understanding of possible failure circumstances – the final structure might even be re-designed to take into account the results of the testing.
- This testing scenario is **simply not an option** in this case
  - the structure as a whole cannot be directly tested at all
  - not all failure circumstances (in particular those involving major geological forces and long time spans) can be recreated in a test environment.

Project Description

- **Alternative strategy:** combination of physical testing and modeling of the behaviour of the structure and environment.
- The larger structure is built up of many component parts, which themselves may be built up of many sub-components.
- Failure parameters of these (sub-)components may be tested, even if the structure as a whole cannot.
- Similarly, while the structure itself, and perhaps even in some cases the components themselves, cannot be tested repeatedly, there remains the option of creating **models of the structure and components** in question, and then using the behaviour of these models to **predict the behaviour of the components** and, in turn, of **the structure at large**.

Project Description

- In the absence of the ideal testing scenario, understanding and quantifying the failure of the system as a whole can be carried out by
  - understanding and quantifying the failure circumstances of the components of the system;
  - understanding the causal relationships between these components;
  - creating models of the system as a whole based on these relationships;
  - determining the failure circumstances and probabilities of the constructed structure-level models, and
  - transferring these findings over to the structure itself.
- This results in an estimate of the failure circumstances and probabilities of the actual engineered structure as a whole.

Project Description

- The end result is not just a simple **yes/no statement** (such as “No, the structure will not fail’”, for instance), but also:
  - a list of the possible failure circumstances;
  - an estimate of the failure probabilities for both the structure components and the structure itself, and
  - confidence measure indicating a level of confidence in the failure probabilities calculated for each failure circumstance.
- **General Objective:** estimate the failure probability of the *Mark II* canister and *engineered barrier system* immediately surrounding the canister, using a combination of statistical analysis, mathematical modeling, and simulations. The system under consideration is extensive; approach is tested on a **prototype causal chain** first.
- This is the demo that was presented to NWMO engineers and managers.

Predictive Modeling

Bird’s Eye View

Determine the **relevant system state** that you want to predict (e.g. breach in container)

Determine key objects and/or factors relevant to this state of interest

Gather data about key objects (e.g. probable behaviour under relevant scenarios)

Construct a model (e.g. mathematical models + computer simulations) that establishes proper **causal connections** between these objects, based on data.

Calculate behaviour of the model in scenarios of interest to generate predictions about the relevant system state in these scenarios

WHAT INFORMATION IS NEEDED?

An illustrated example

Simplified Version of the Modeling Steps for Creation of Model

Information → Causal Chains → Network

Our approach:

- Use information in existing documentation to answer relevant questions as best as possible
- **Get SMEs to answer particular questions (that have not been answered by existing documentation)**
- Use responses from questions to generate causal chain information
- Create network model based on causal chains

The process is illustrated using a demonstration model. The questions, answers, and probabilities that are presented are NOT meant to be realistic – they only serve to showcase the various types of nodes one may encounter in a causal model.

*These and following questions are adapted from questions from the book “Effective FMEAs”, written by Carl S. Carlson

Sample Questions*

Physical Description

System physical description:

- *What components exist in the system? (What components exist in your part of the system?)*
- *For a given component A:*
  - What is the intended physical structure or characteristics of component A?
  - What are some possible variations or variability in the physical structure of component A?
  - What are the materials used to construct component A?
  - How is component A constructed?
  - What is the physical relationship (if any) of component A to component B?
  - <u>How could component A interact with component B?</u>

Sample Questions
Component Function/Purpose

For a given component:

- *What are the primary functions of this item?*
- *What is the intended function of this component, in the context of the larger system?*
- *What is the item supposed to do, over the lifetime of the system?*
- *What is the standard of performance?*
- *What must the item not do?*

Sample Questions

Influencing Events, Processes – Component Level

For a given component:

- *What potentially occurring processes (in the past or ongoing, internal or external) could affect the state of the component?*
- *How would these ongoing process affect the state of the component?*
- *What specific factors of the process would affect the state of the component?*
- *What events could change the functionality of the component?*
- *What factors or events could cause the component to cease functioning as required?*

Sample Questions

Influencing Events, Processes – System Level

For the system as a whole:

- *What ongoing (external to system) processes or events could affect the state of the system?*
- *What specific factors of these external processes, factors or events would affect the state of the component*
- *How would these ongoing process affect the state of the various components in the system?*

Sample Questions

Causal Chains

Consider a causal chain of the form:

- *A could cause B, which could cause C, which could cause D*

What event, factor or component state (B) could cause the system, or components of the system to change state (C)?

To extend the causal chain:

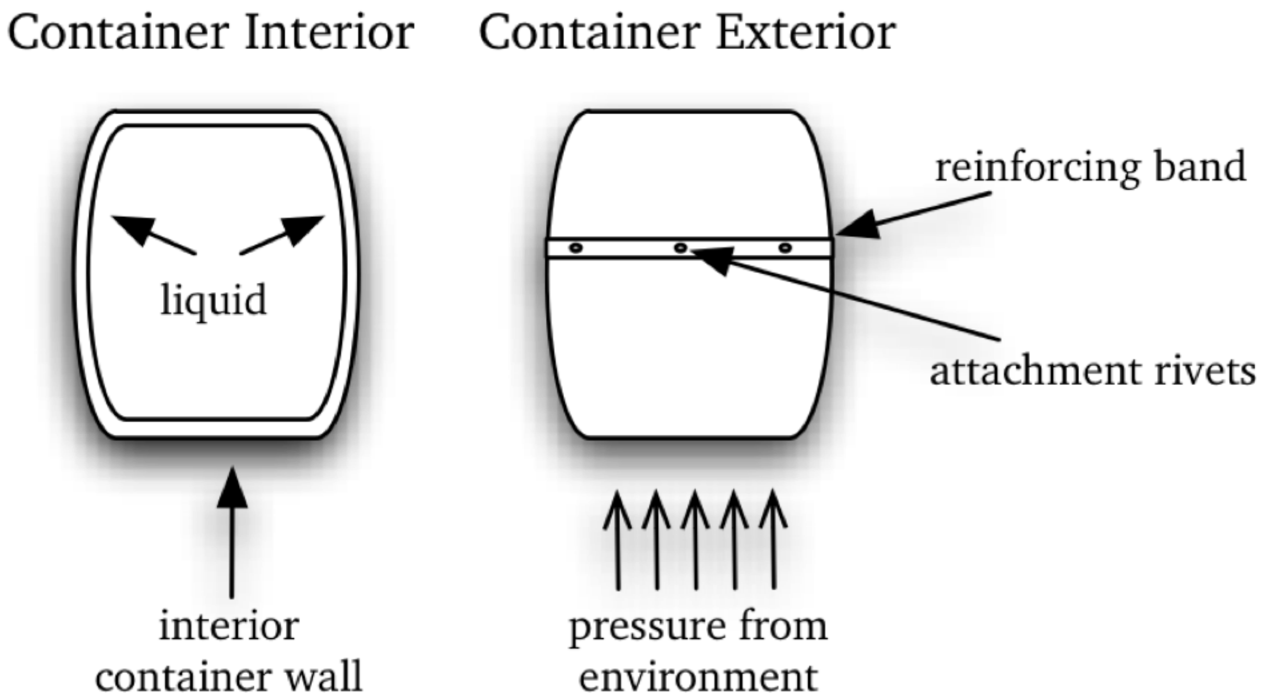
- *What could cause B? Could A cause B?*
- *What could C cause? Could C cause D?*

TRANSLATING THE COLLECTED INFORMATION

An illustrated example

From Data to Model

Simple Illustration System



This is clearly a relatively trivial system which is abstractly described (**and so is not to be confused with an actual engineered barrier system model; the probabilities presented here have no link with the reality underpinning the APMRDII design or the DGR**)

Physical Description of Components

System Component	Information	Source
container wall	constructed of a ductile metal	design specifications
	initial wall thickness of 3 cm	design specification
	manufacturing process leads to some imperfections in the container walls	experimental failure data
	elastic deformation under stress	experimental data
	corrodes in presence of certain chemical compounds	experimental data
liquid	density of liquid is 1020 kg/m^3	physical materials data
reinforcing band	constructed from a semi-brittle compound	design specifications
	has a tensile strength of 2430 MPa	physical materials data
	brittle fractures under stress	physical materials data
rivets	constructed from semi-brittle metal	design specifications
bacteria	may be introduced into environment over time	experimental data
	produces a number of chemical compounds as part of its metabolic processes	experimental data
environment	exerts pressure on system during pressure events	physical simulation data

Table 1: Systems components and sources **(provided solely as an illustration of the methodology).**

Sample Function Information

Reinforcing Band

Component	Component Functionality Requirements
reinforcing band	– provides additional structure to the container wall – keeps the container wall from becoming distorted due to internal pressure – maintains an even distribution of pressure on the container so that it does not develop particular weak points over time, or points that are vulnerable to cracking or corrosion – must stay in direct contact with the container – must exert even pressure of a certain amount around the center of the container – must not crack – must not stretch over time – must not slip

Table 2: Required functionality of components **(provided solely as an illustration of the methodology)**.

Sample Influencing Factors

Container Wall and System

Component	Factors Influencing Component State
container wall	– over time the container may become corroded due to the presence of particular chemicals in the environment – presence of corrosion could cause thinning of container wall – if the thickness of the container is sufficiently reduced then external pressure could cause the container to deform – if the thickness of the container is completely reduced, a hole could be created in the container – presence of microbes could increase the presence of the chemicals that could cause corrosion of container walls – one set of equations describes corrosion rate of container wall in the presence of microbes, a different one in the absence of microbes – the size of the population of the microbes may potentially have an influence on corrosion rate of the container wall
container system	– presence of microbes in system – pressure exerted by the external environment

Table 3: Factors influencing state of components **(provided solely as an illustration of the methodology)**.

Sample Component Interactions

Components	Component Interaction
liquid, container wall	the liquid produces pressure on the container wall
bacteria, container wall	chemicals produced by bacteria corrode the outer wall of the container at certain rates
rivets, reinforcing band	rivets keep reinforcing band tightly attached to container
container wall, rivets	container wall keeps rivets in place and connected to reinforcing band
reinforcing band, container wall	reinforcing band enables container to withstand a certain amount of pressure without deforming
environment, container system	when pressure events occur env. exerts pressure on container system

Table 4: Component interactions **(provided solely as an illustration of the methodology)**.

Causal Chain Sample

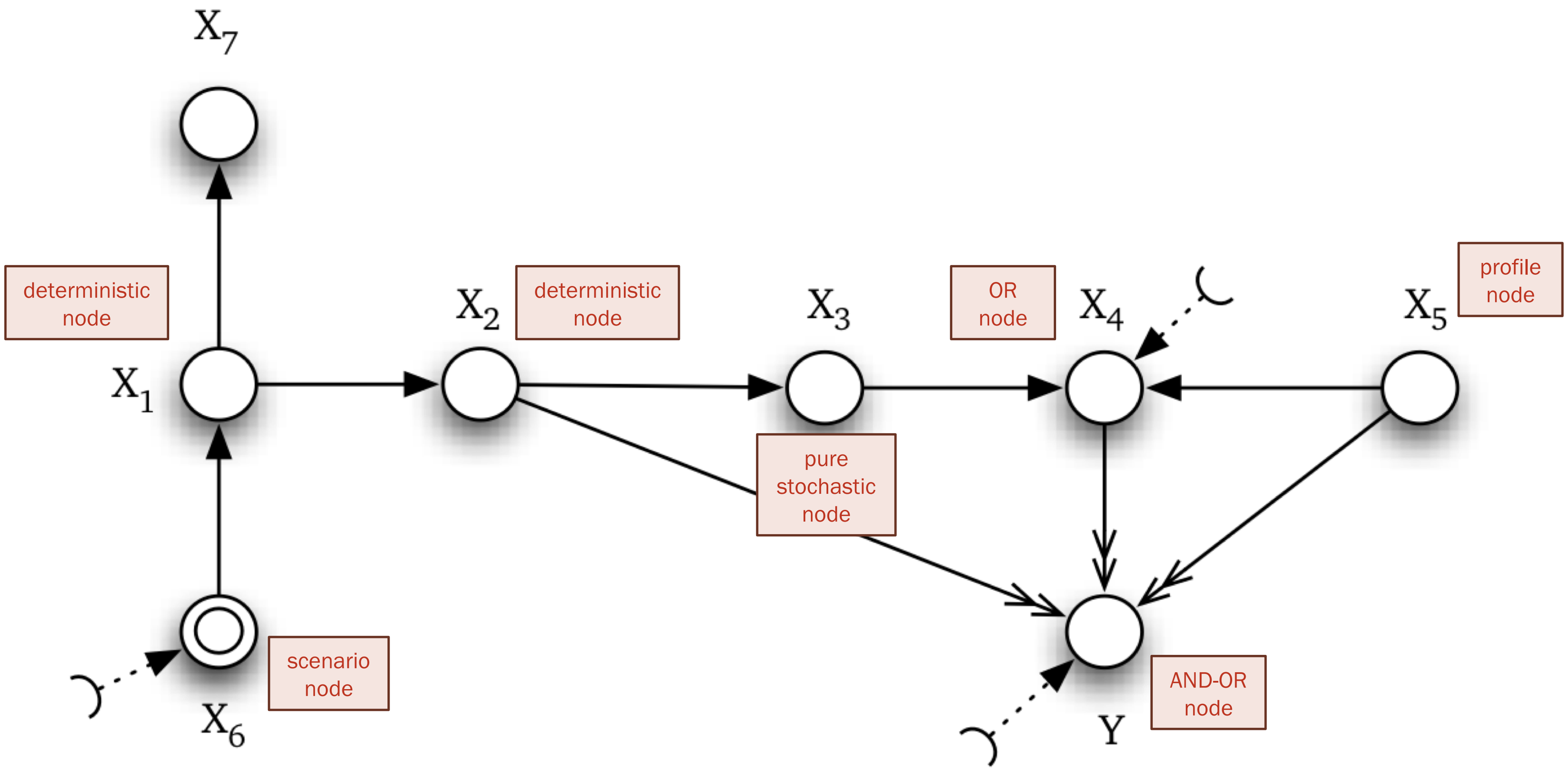
Extracted from Answers

Component States or Factors	Causal Chain
presence of microbes, container wall thickness	IF microbes are present, THEN the thickness of the wall will be reduced over time based on some equation (1)
no microbes, container wall thickness	IF microbes are not present, THEN the thickness of the wall be reduced over time based on some equation (2)
wall thickness, rivet failure	IF the thickness of the wall is reduced over time, THEN the rivets may fail with some probability π_1
rivet failure, retaining band failure (through slippage)	IF the rivets fail, THEN the band may slide off the container with some probability π_2
pressure increase, retaining band failure (through cracking)	IF the pressure increases past a certain threshold, THEN the band may crack with some probability π_3
retaining band failure, reduced wall thickness, pressure increase, container breach	IF the band fails AND the wall thickness is reduced AND the pressure increases past a certain threshold, THEN the container may be breached with some probability π_4

Table 5: Sample of some possible causal chains. **(provided solely as an illustration of the methodology)**.

Causal Network Model

Created From Causal Chains



Relevant System States Represented in Causal Network

Node Label	System State
X_1	Thickness of container wall is 2 mm at some point on the wall
X_2	Thickness of container wall is 1 mm at some point on the wall
X_3	At least one rivet fails
X_4	Reinforcing band fails
X_5	External pressure above a certain level imposed on container
X_6	Bacteria is introduced into the environment
X_7	Gap between container and fill created
Y	Container fails

Table 6: System states and events represented by nodes **(provided solely as an illustration of the methodology)**.

Simulation Framework

Simulation starts at $t = 0$, ends at $t = t_f$.

The state vector at time t is a stochastic function of the previous states:

$$\mathbf{Z}(t) = g(\mathbf{Z}(t-1), \ldots, \mathbf{Z}(0); \text{various parameters}),$$

where $\mathbf{Z}(t) = (X_1(t), X_2(t), X_3(t), X_4(t), X_5(t), X_6(t), X_7(t), Y(t))$, and $\mathbf{Z}(0) = \mathbf{0}$.

X_6 – Microbe Simulation
(Scenario Node)

Inputs

- $\rho_1(s)$: probability of microbial occurrence at some point before $t = t_f$
- $f_1(t), f_2(t), \ldots$: various scenarios for the distribution of onset, conditional on occurrence (such as: increasing pdf, decreasing pdf, uniform pdf, etc).

Output

$$X_6(t) = \begin{cases} 1 & \text{if microbes are present at time } t \\ 0 & \text{else} \end{cases} = \begin{cases} 1 & \text{if } t > t_1 \\ 0 & \text{else} \end{cases}$$

Procedure

1. With probability $\rho_1(t_f)$, microbes will appear at some point before $t = t_f$.
2. If microbes appear at some point, select time of onset $t_1 \sim f_j(t)$ using the inverse transform sampling method, for scenario j.
3. If microbes do not appear, set $t_1 = \infty$.

X_1, X_2 – Container Wall Coating
(“Deterministic” Nodes)

Inputs

- $q_1(0)$: initial thickness of container wall coating
- β_1: rate at which the coating deteriorates
- γ_1: rate increase when microbes are present
- τ_1, τ_2: thresholds $\in [0,1]$

Output

$$X_1(t) = \begin{cases} 1 & \text{if } q_1(t) < \tau_1 q_1(0) \\ 0 & \text{else} \end{cases} \quad \text{and} \quad X_2(t) = \begin{cases} 1 & \text{if } q_1(t) < \tau_2 q_1(0) \\ 0 & \text{else} \end{cases}$$

X_1, X_2 – Container Wall Coating
("Deterministic" Nodes)

Procedure

1. Let $q_1(t)$ be the actual container wall thickness at time t.
2. The rate on which this quantity decreases depends on the presence or absence of microbes, according to

$$q_1(t) = \begin{cases} q_1(t-1) - \beta_1 + \varepsilon_1 & \text{if } X_6(t-1) = 0 \text{ (no microbes)} \\ q_1(t-1) - \gamma_1\beta_1 + \varepsilon_2 & \text{if } X_6(t-1) = 1 \text{ (microbes)} \end{cases}$$

where $\varepsilon_1, \varepsilon_2$ are physically appropriate error terms.

X_3 – Rivets
("Pure Stochastic" Node)

Inputs

- $X_2(t-1)$: state of thickness of container wall coating at time $t-1$
- $q_1(t-1)$: actual thickness of container wall coating at time $t-1$
- probability of rivet failure given state of thickness of container wall coating at time $t-1$, with non-zero coating thickness (see graph for example):

$$p_1(t) = P(X_3(t) = 1 | X_2(t-1) = 1; q_1(t-1) \neq 0) := P(X_3 | X_2; q_1 \neq 0)$$

- probability of rivet failure given state of thickness of container wall coating at time $t-1$, with zero thickness (see graph for example):

$$p_2(t) = P(X_3(t) = 1 | X_2(t-1) = 1; q_1(t-1) = 0) := P(X_3 | X_2; 0)$$

X_3 – Rivets
("Pure Stochastic" Node)

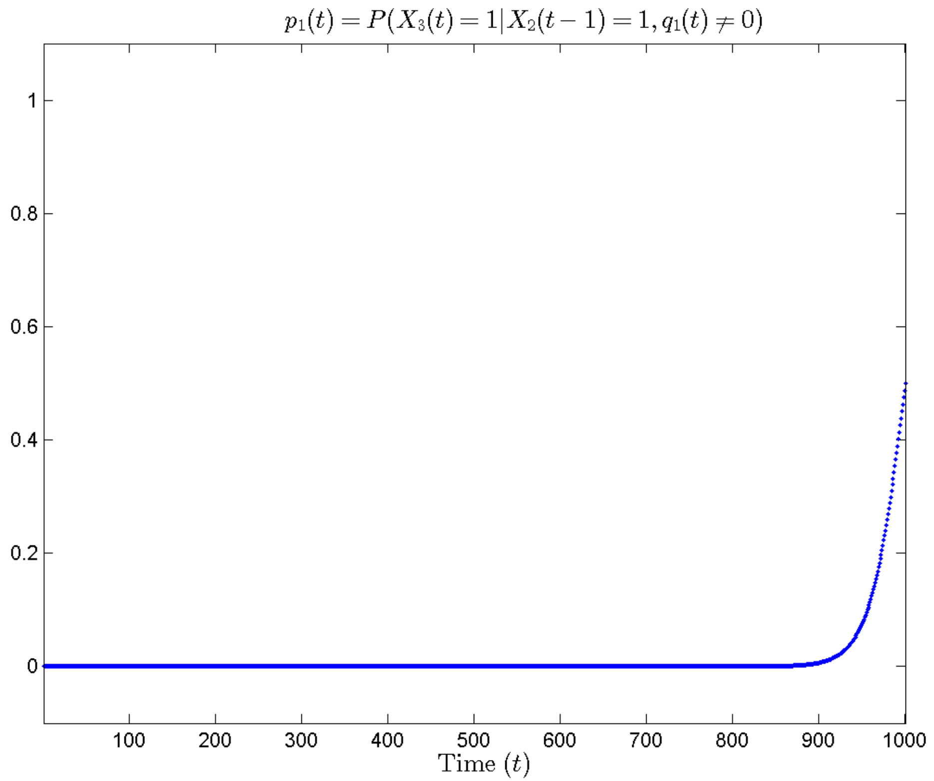
Output

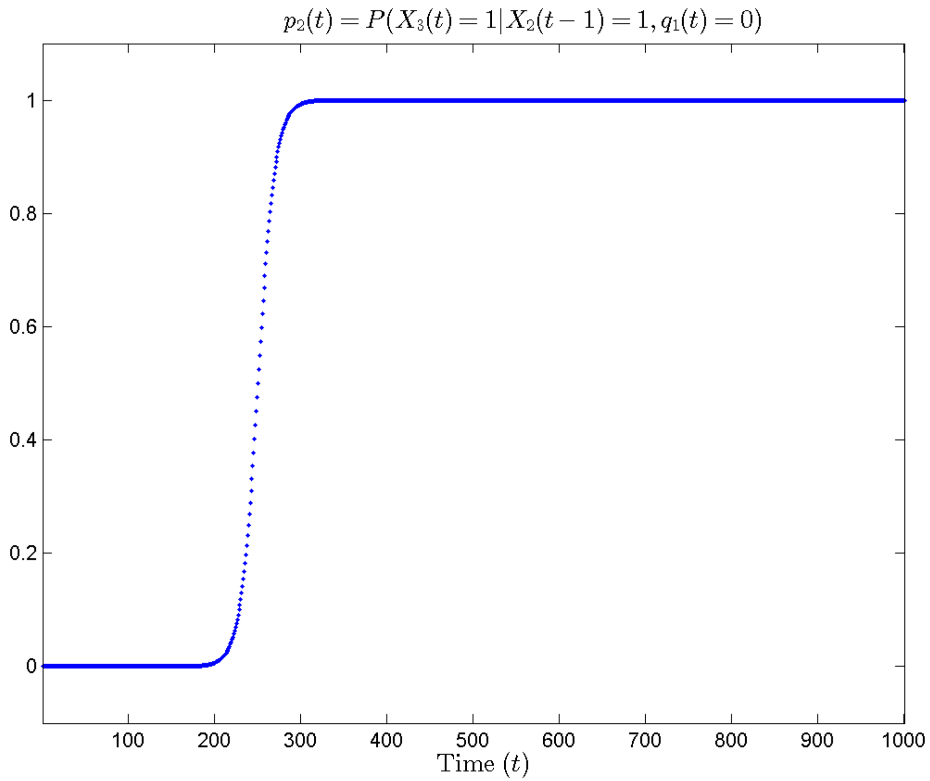
$$X_3(t) = \begin{cases} 1 & \text{if at least one rivet fails at time } t \\ 0 & \text{else} \end{cases}$$

Procedure

1. If $X_2(t-1) = 0$, there is no probability of rivet failure.
2. If $X_3(t-1) = 1$ (rivet(s) have already failed), then $X_3(t) = 1$.
3. Otherwise, rivets fail with probability $p_1(t)$ if $q_1(t-1) \neq 0$, and with probability $p_2(t)$ if $q_1(t) = 0$.

X_3 – Rivets
("Pure Stochastic" Node)





X_5 – Internal Pressure
(Profile Node)

Inputs

- $h_1(t)$: external pressure profile (assumed to be known)
- τ_3: threshold

Output

$$X_5(t) = \begin{cases} 1 & \text{if pressure exceed the threshold} \\ 0 & \text{else} \end{cases} = \begin{cases} 1 & \text{if } h_1(t) > \tau_3 \\ 0 & \text{else} \end{cases}$$

Procedure

1. State changes based on observed data (see graph).

X_4 – Retaining Band
(OR Node)

Inputs

- $X_3(t-1)$: state of rivet failure at time $t-1$
- $X_5(t-1)$: state of pressure on system at time $t-1$
- $X_4(t-1)$: state of band at time $t-1$
- probability of band failure from internal processes (see graph for example):

$$p_3(t) = P(X_4(t) = 1 | X_4(t-1) = 0) := P(X_4 | \overline{X}_4)$$

- probability of band failure from slippage given failure of at least one rivet failure at time $t-1$ (see graph for example):

$$p_4(t) = P(X_4(t) = 1 | X_3(t-1) = 1) := P(X_4 | X_3)$$

- probability of band failure from cracking given high external pressure at time $t-1$ (see graph for example):

$$p_5(t) = P(X_4(t) = 1 | X_5(t-1) = 1) := P(X_4 | X_5)$$

X_4 – Retaining Band
(OR Node)

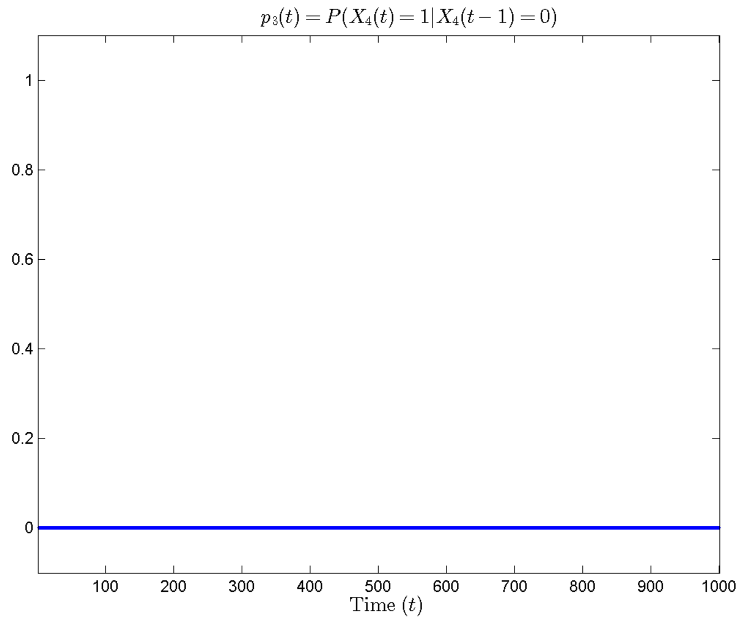
Output

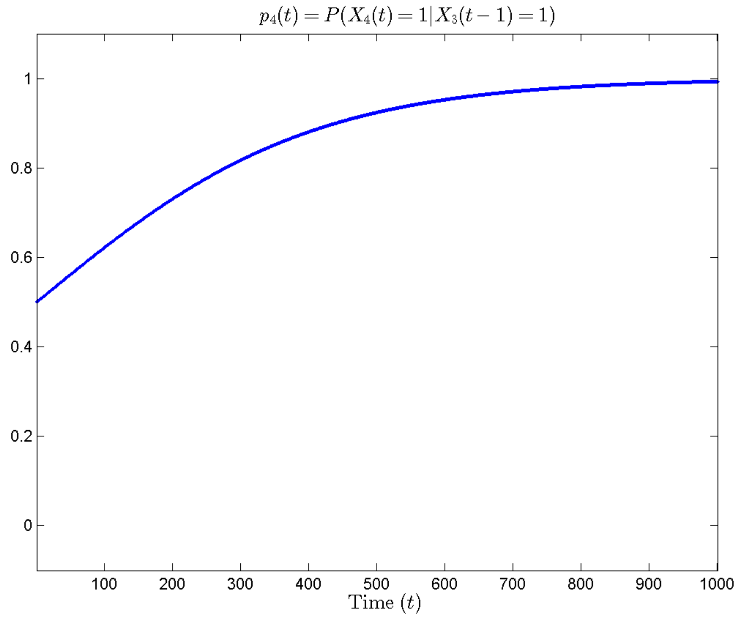
$$X_4(t) = \begin{cases} 1 & \text{if band fails due to either slippage or cracking at time } t \\ 0 & \text{else} \end{cases}$$

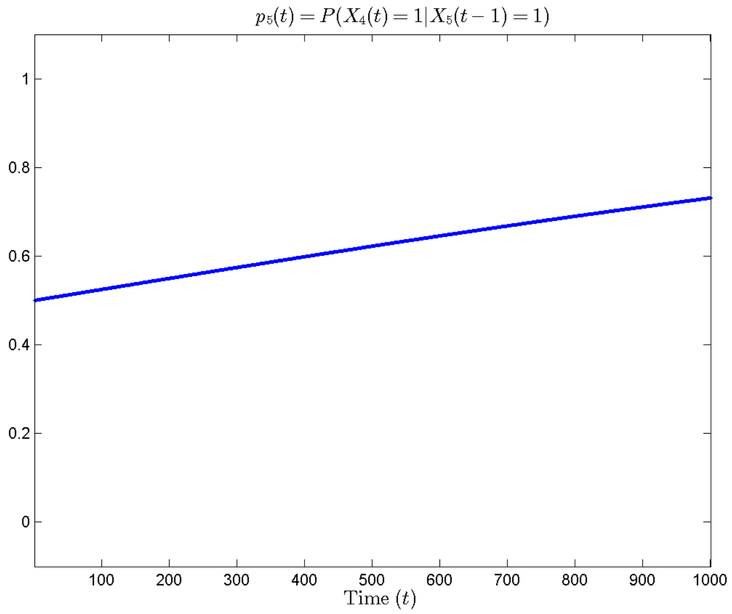
Procedure

1. If $X_4(t-1) = 0$, the band will fail due to internal processes with probability $p_3(t)$.
2. Otherwise, if $X_3(t-1) = 1$ (rivet(s) have already failed), the band will fail due to slippage with probability $p_4(t)$.
3. Otherwise, if $X_5(t-1) = 1$ (high external pressure), the band will fail due to cracking with probability $p_5(t)$.

X_4 – Retaining Band
(OR Node)







X_7 – Fill Gap

The fill gap node was found to have no influence on the failure probability and was thus not included in the implemented model.

Y – Container Breach

(AND-OR Node)

Inputs

- $X_2(t-1)$: state of wall thickness at time $t-1$
- $X_4(t-1)$: state of band at time $t-1$
- $X_5(t-1)$: state of pressure on system at time $t-1$
- $(t-1)$: state of container breach at time $t-1$
- probability of container breach from internal processes (see graph for example):

$$p_6(t) = P(Y(t) = 1 | Y(t-1) = 0) = P(Y|\overline{Y})$$

- probability of container breach given states at time $t-1$ (see graph for example):

$$p_7(t) = P(Y(t) = 1 | X_2(t-1) = 1, X_4(t-1) = 1, X_5(t-1) = 1) = P(Y | X_2 X_4 X_5)$$

Y – Container Breach

(AND-OR Node)

Output

$$Y(t) = \begin{cases} 1 & \text{if container breaches at time } t \\ 0 & \text{else} \end{cases}$$

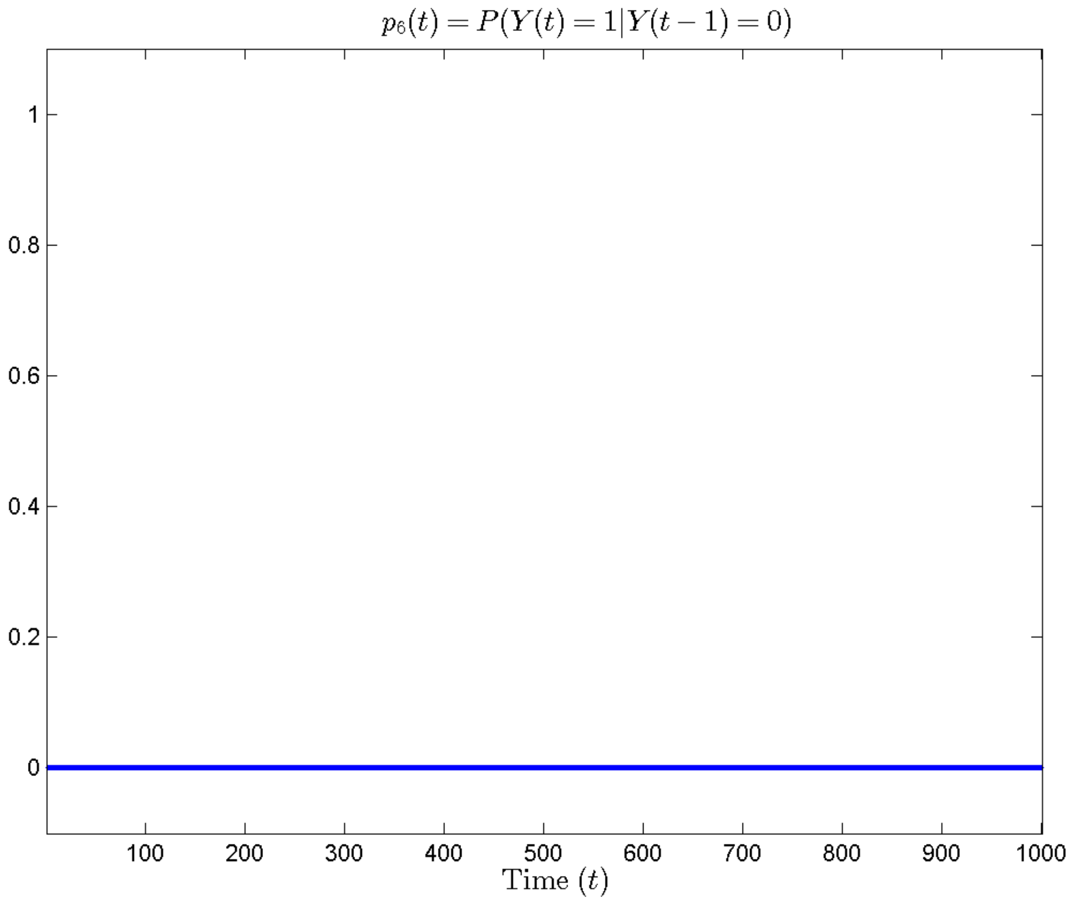
Procedure

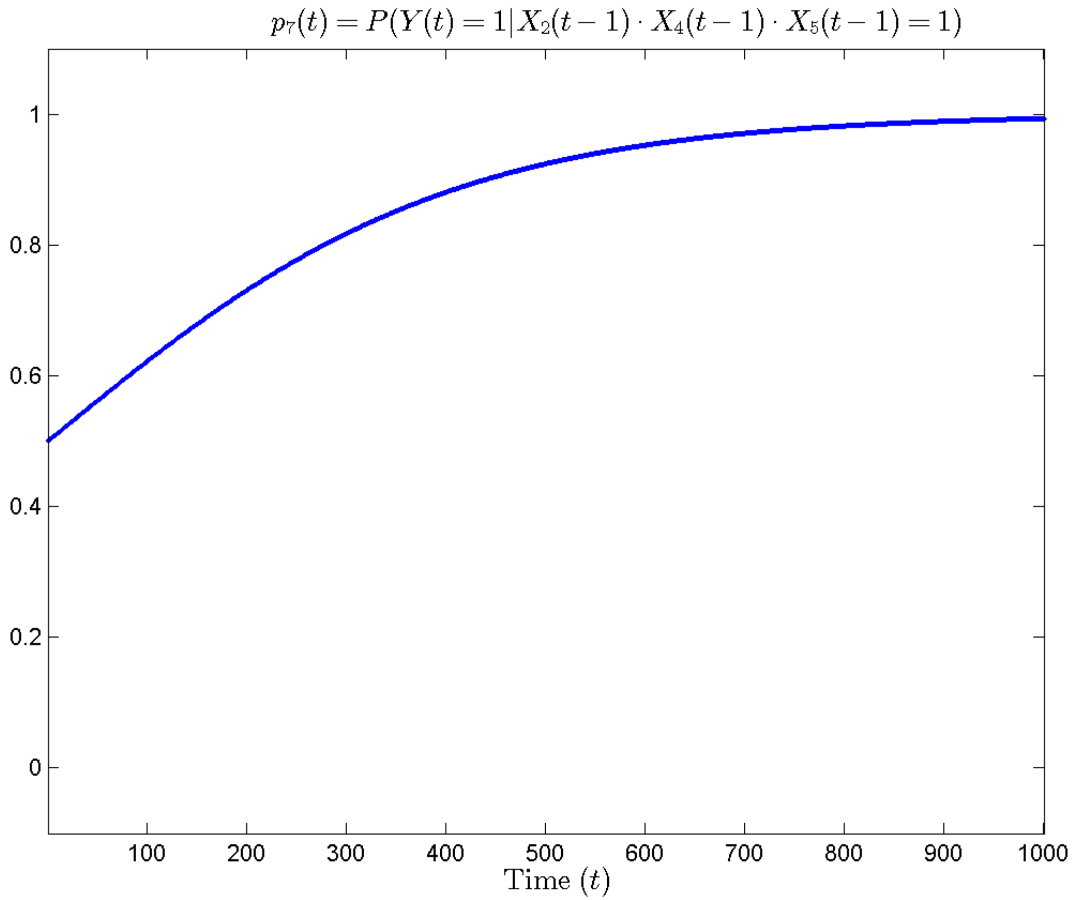
1. If $Y(t-1) = 0$, the container will breach due to internal processes (e.g. internal pressure build-up, etc.) with probability $p_6(t)$.

2. Otherwise, if $X_2(t-1) = 1$ (container wall coating is less than the threshold) and $X_4(t-1) = 1$ (band has failed) and $X_5(t-1) = 1$ (external pressure has reached threshold), the container will breach with probability $p_7(t)$.

Y – Container Breach

(AND-OR Node)



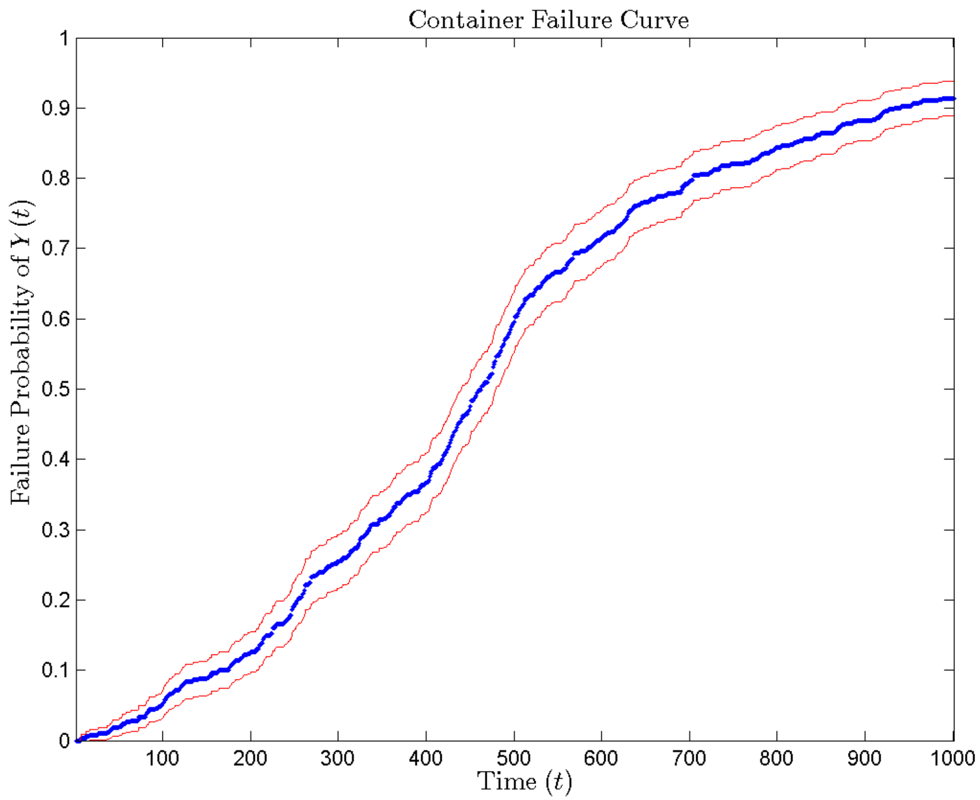


SIMULATION RESULTS

An illustrated example

Causal Network Model – Results

500 Replicates, 1000 Time Steps



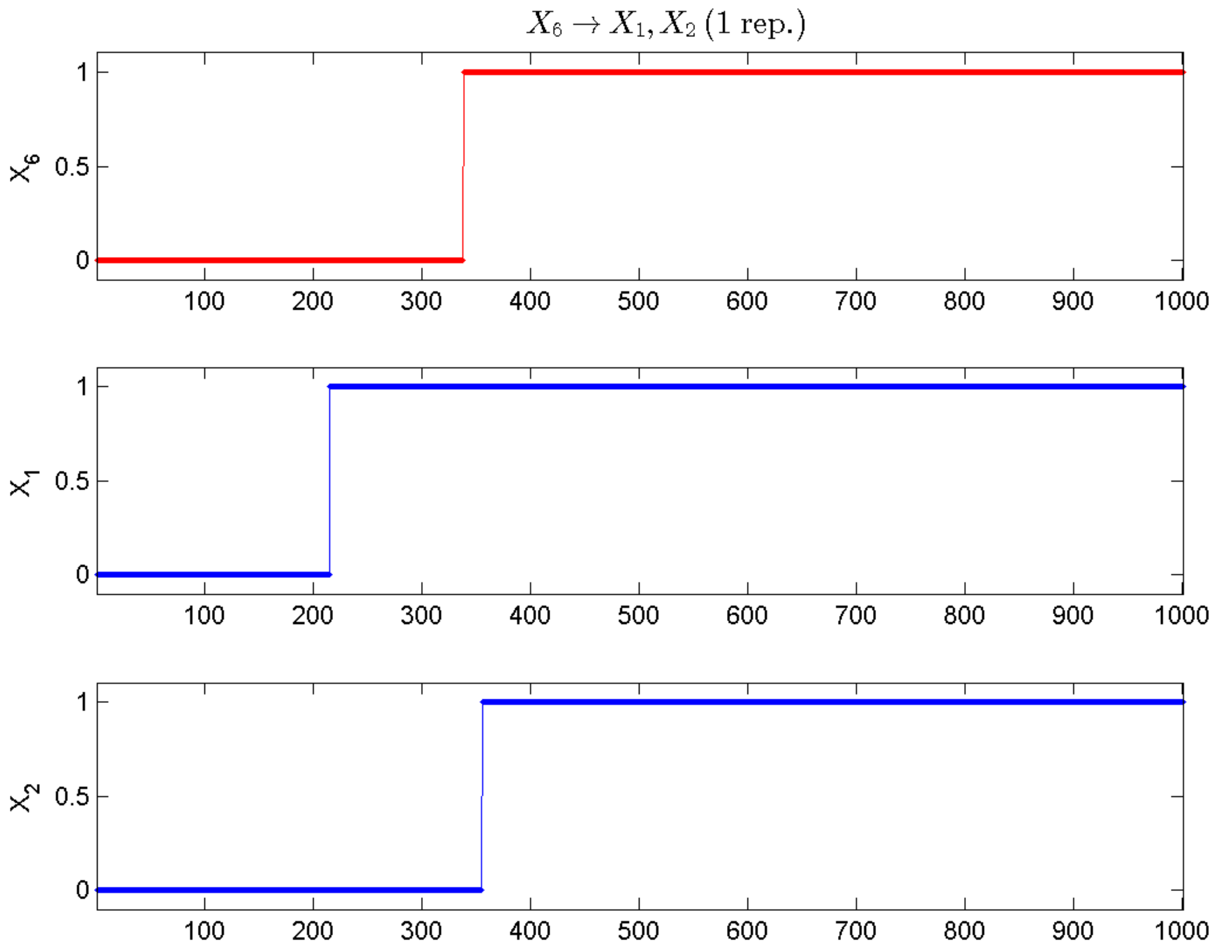
Blue – Prediction; Red – 95% C.I.

Time at which each node fired for the first time, for each replicate.

Node	Replicates									
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**...**	**500**
X_6	339	193	329	23	598	510	679	668	...	302
X_1	216	200	208	60	244	268	216	266	...	253
X_2	356	246	346	99	492	512	434	516	...	336
X_3	391	291	392	212	619	540	681	678	...	374
X_5	500	178	983	N.A.	691	886	231	200	...	138
X_4	393	181	393	214	620	541	232	201	...	167
Y	501	247	984	N.A.	692	887	435	517	...	337

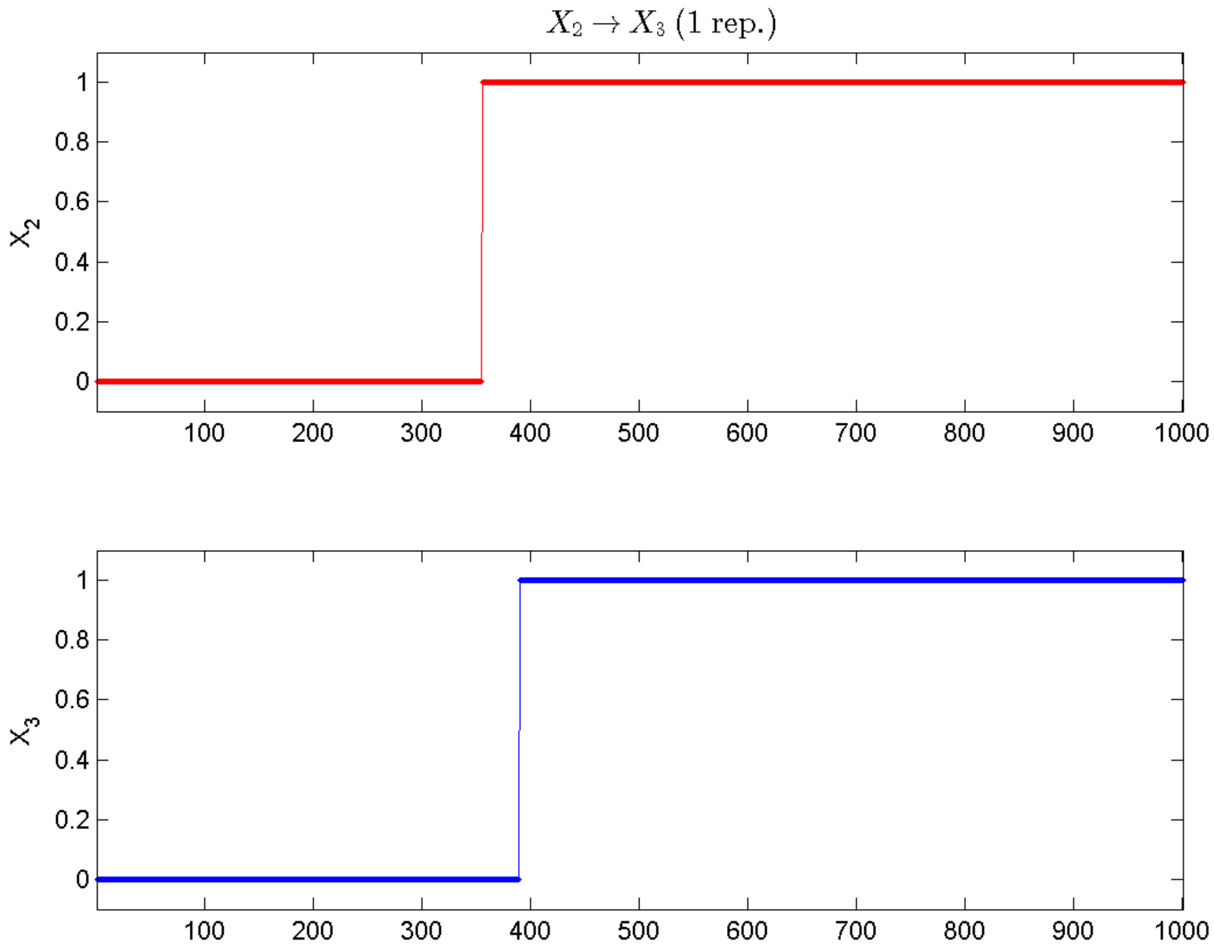
Causal Network Model – Results

System State Variable Profiles – 1 Replicate



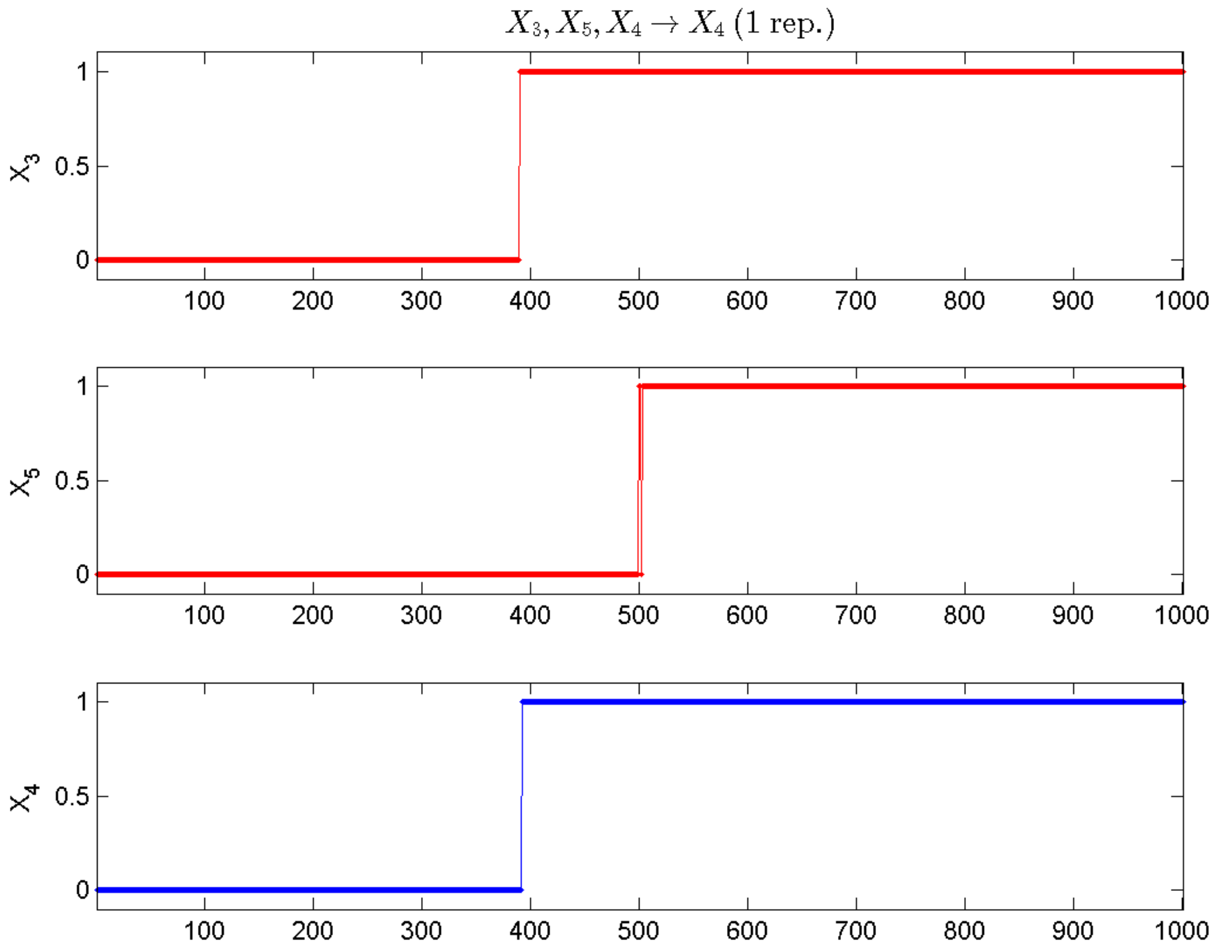
Causal Network Model – Results

System State Variable Profiles – 1 Replicate



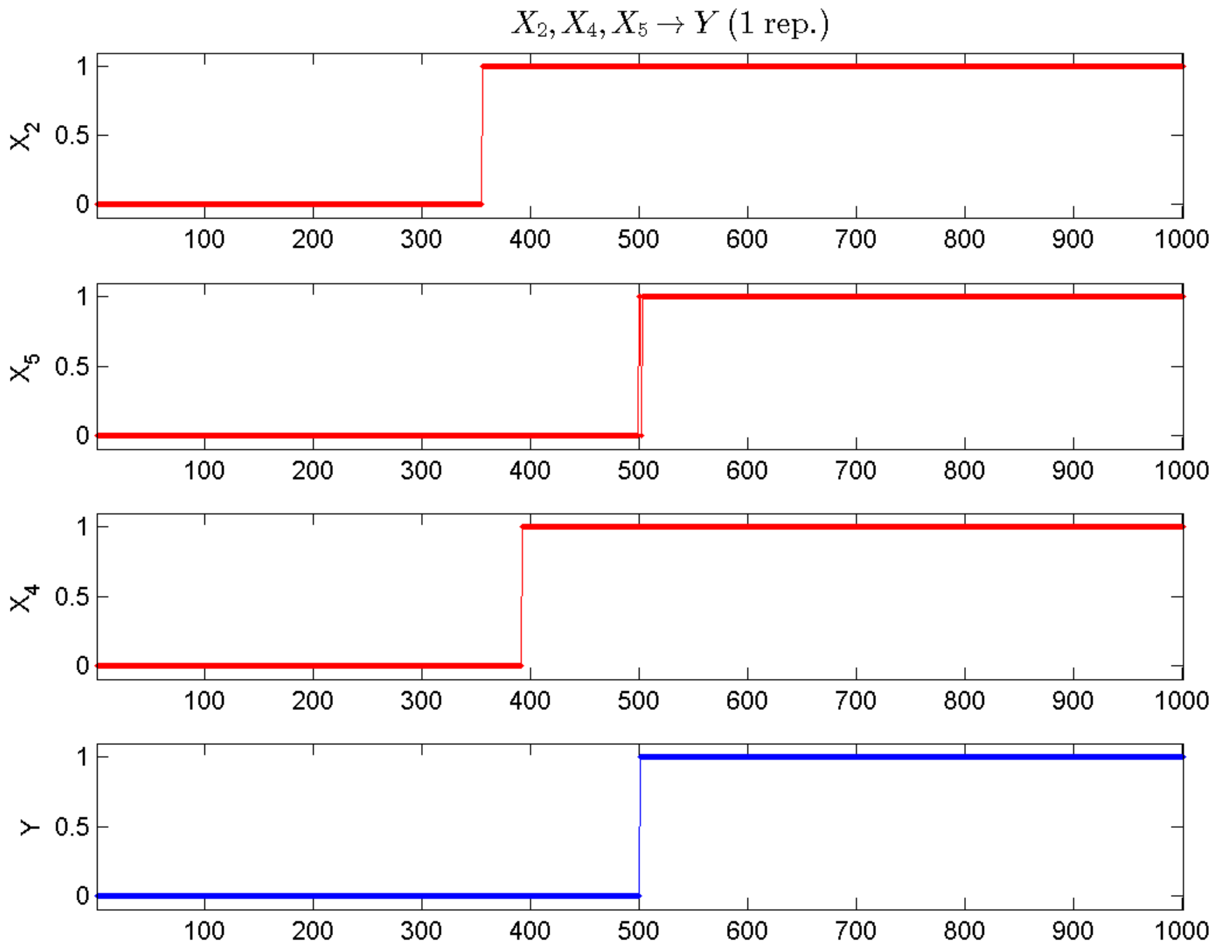
Causal Network Model – Results

System State Variable Profiles – 1 Replicate



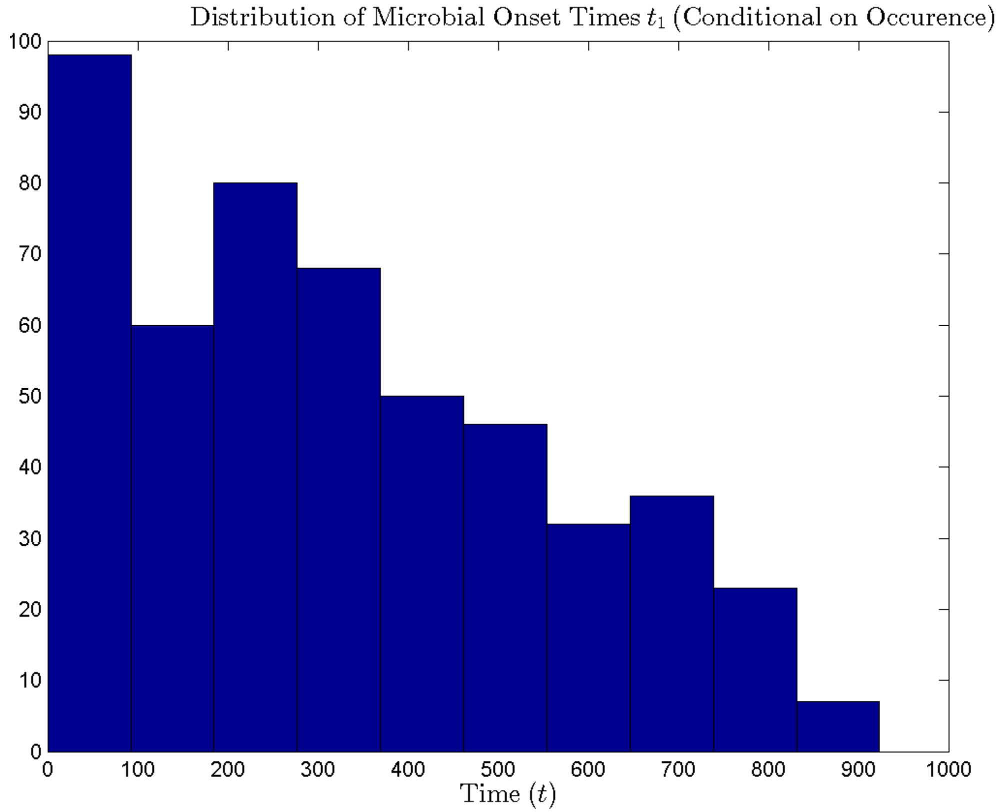
Causal Network Model – Results

System State Variable Profiles – 1 Replicate

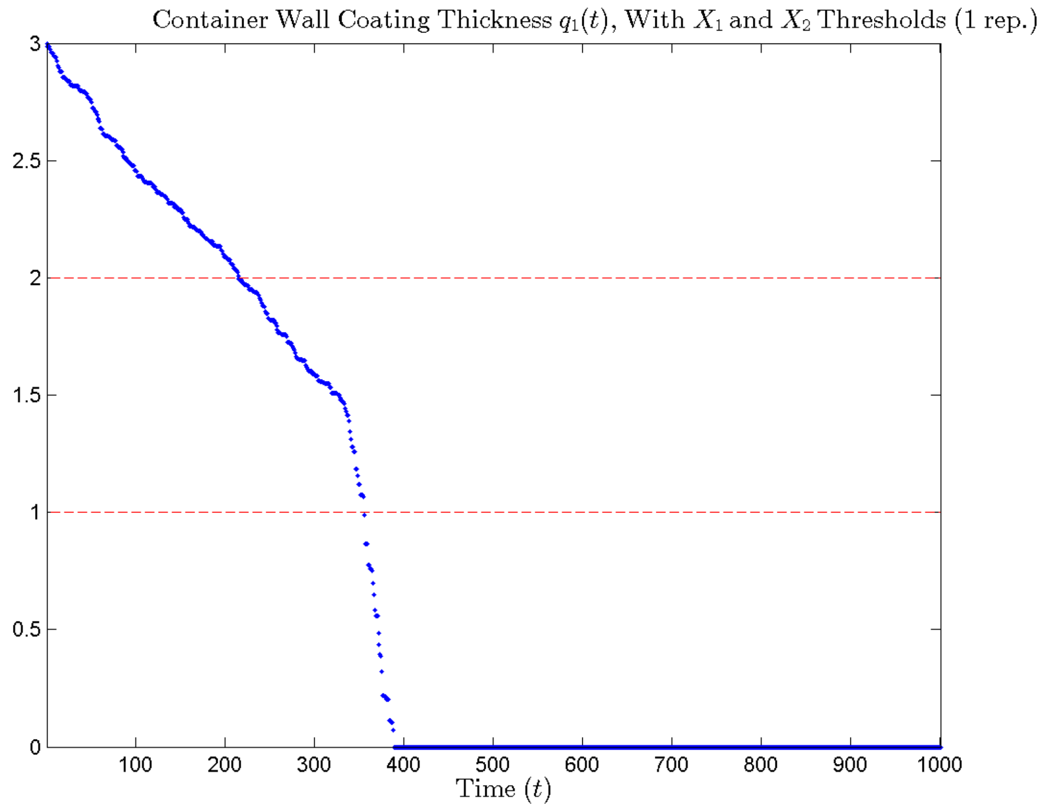


Causal Network Model – Results

X_6, X_1, X_2 Internal Variables



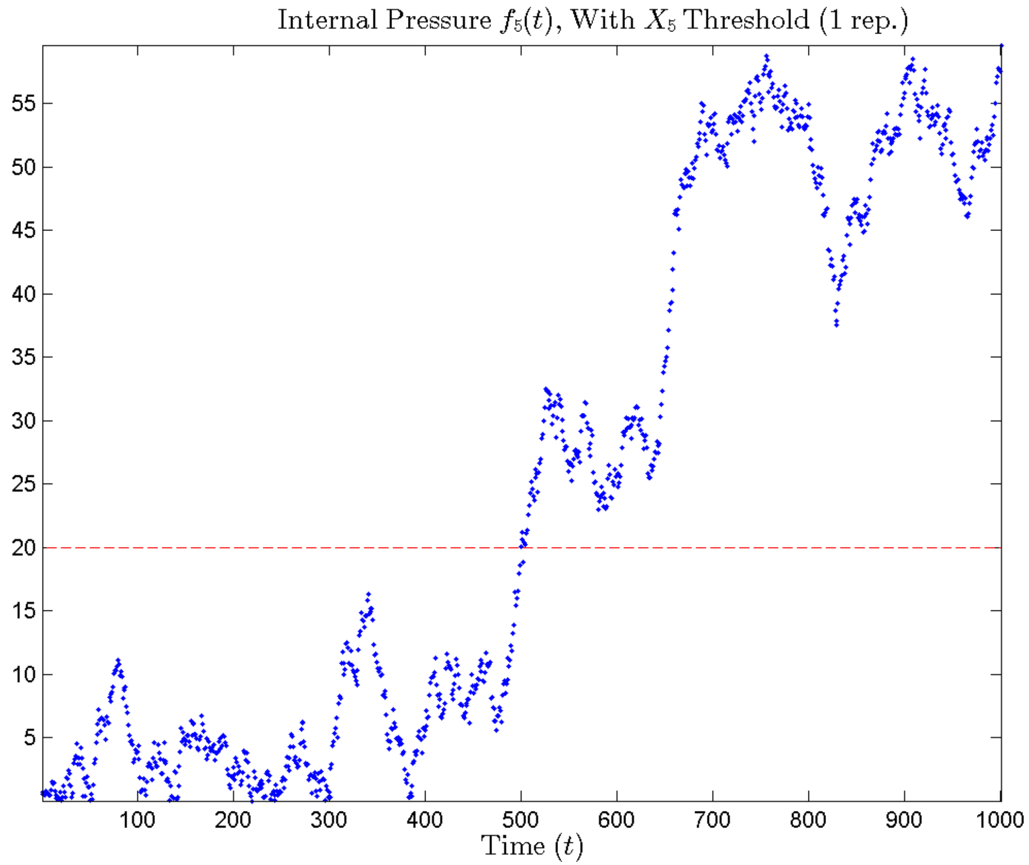
Distribution of Microbial Onset Times (Conditional on Occurrence); Scenario 1, 500 replicates.



Container wall coating thickness profile for a single replicate, with X_1 and X_2 thresholds in red.

Causal Network Model – Results

X_5 – Pressure Profile (Random Walk)



Pressure profile for a single replicate; X_5 threshold in red.

CONSULTING POST-MORTEM

Consulting Post-Mortem

Big proposal (length, time, $$$)

Demo as a tool to convince client (domain experts were not buying-in at first – would have preferred an analytical solution… the consulting team was split on the subject)

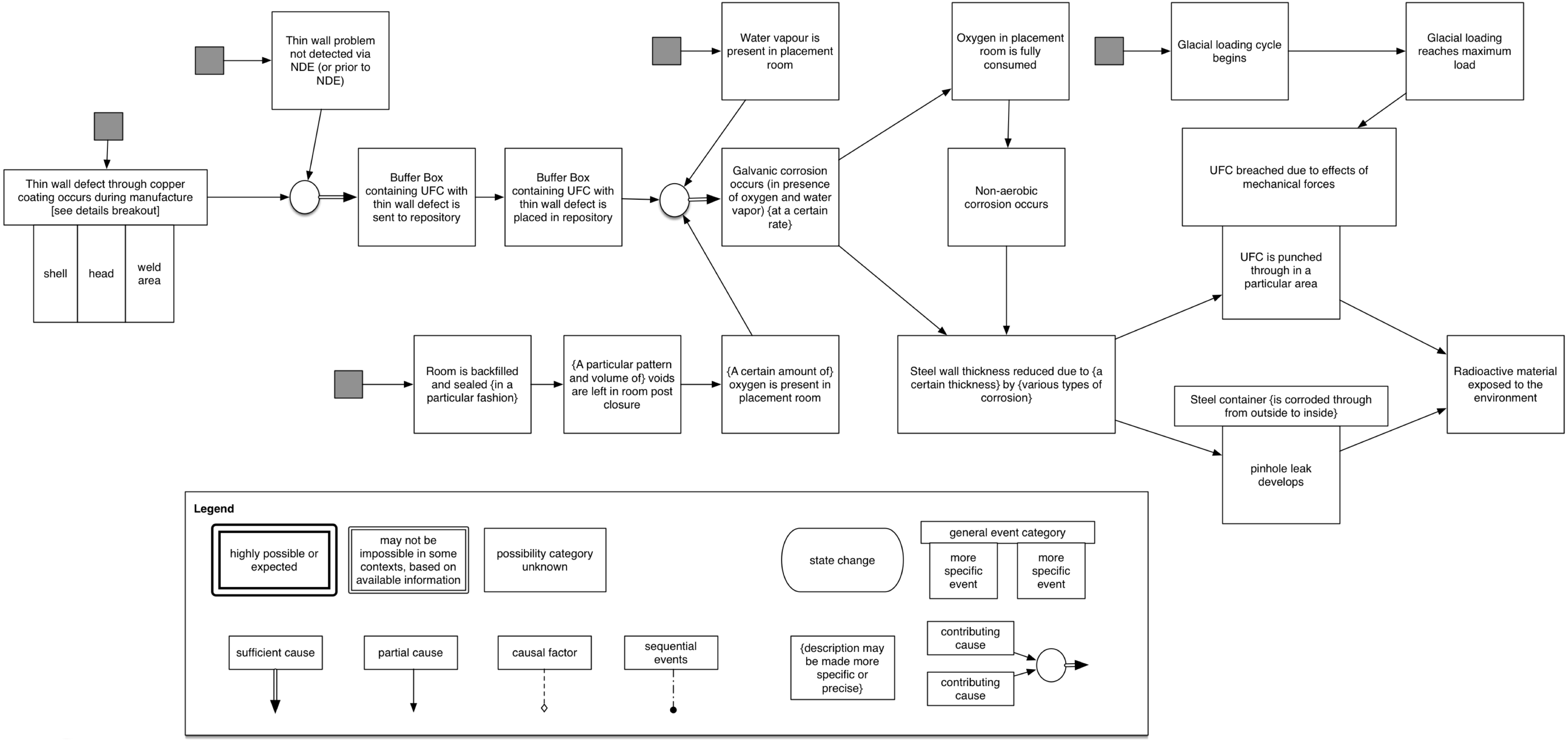
Complexity of problem would have required multi-year, multi-phase project

Prototype causal chain was substantially more complicated than demo, substantially less complicated than suggested final chain

Client asked for a completely different project to be tacked on half-way through

Forced vacation (project had to be rushed to meet deadline)

Client declined to pursue project after phase I, claiming a change of direction in org. (turns out that we were competing against another consulting group)


Thin wall problem not detected via NDE (or prior to NDE)
Thin wall defect through copper coating occurs during manufacture [see details breakout]
shell
head
weld area
Buffer Box containing UFC with thin wall defect is sent to repository
Buffer Box containing UFC with thin wall defect is placed in repository
Water vapour is present in placement room
Galvanic corrosion occurs (in presence of oxygen and water vapor) {at a certain rate}
Oxygen in placement room is fully consumed
Non-aerobic corrosion occurs
Glacial loading cycle begins
Glacial loading reaches maximum load
UFC breached due to effects of mechanical forces
UFC is punched through in a particular area
Room is backfilled and sealed {in a particular fashion}
{A particular pattern and volume of} voids are left in room post closure
{A certain amount of} oxygen is present in placement room
Steel wall thickness reduced due to {a certain thickness} by {various types of corrosion}
Steel container {is corroded through from outside to inside}
pinhole leak develops
Radioactive material exposed to the environment
Legend
highly possible or expected
may not be impossible in some contexts, based on available information
possibility category unknown
state change
general event category
more specific event
more specific event
sufficient cause
partial cause
causal factor
sequential events
{description may be made more specific or precise}
contributing cause
contributing cause