Systems Verification Analysis Through RAM Simulation

Emmanuel Ohene Opare

NGNP Systems Engineer

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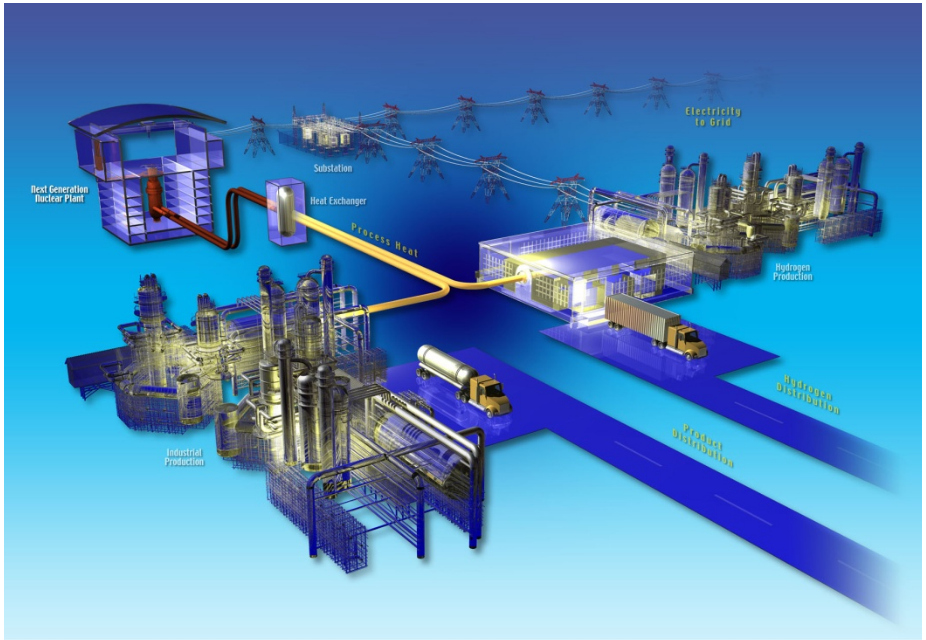

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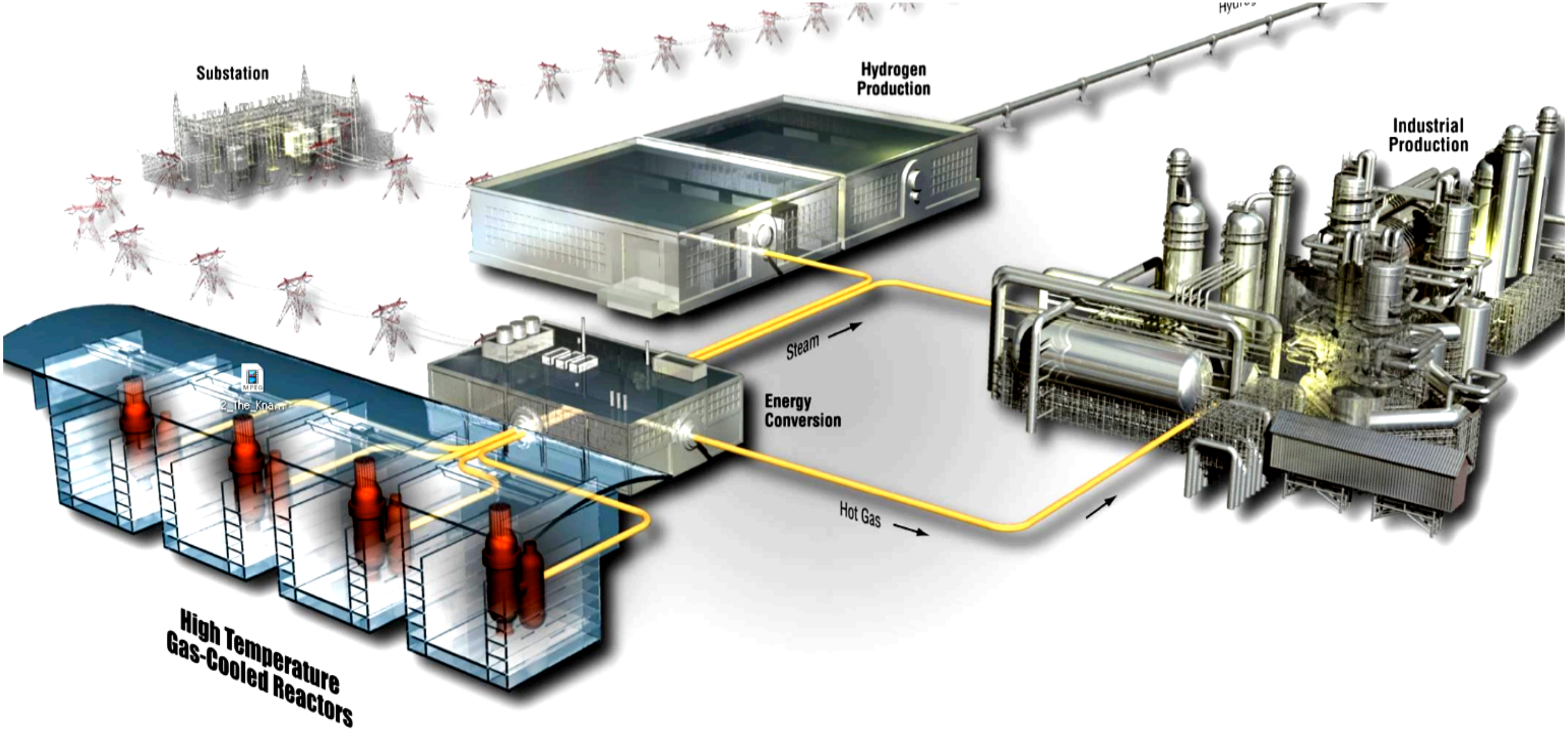
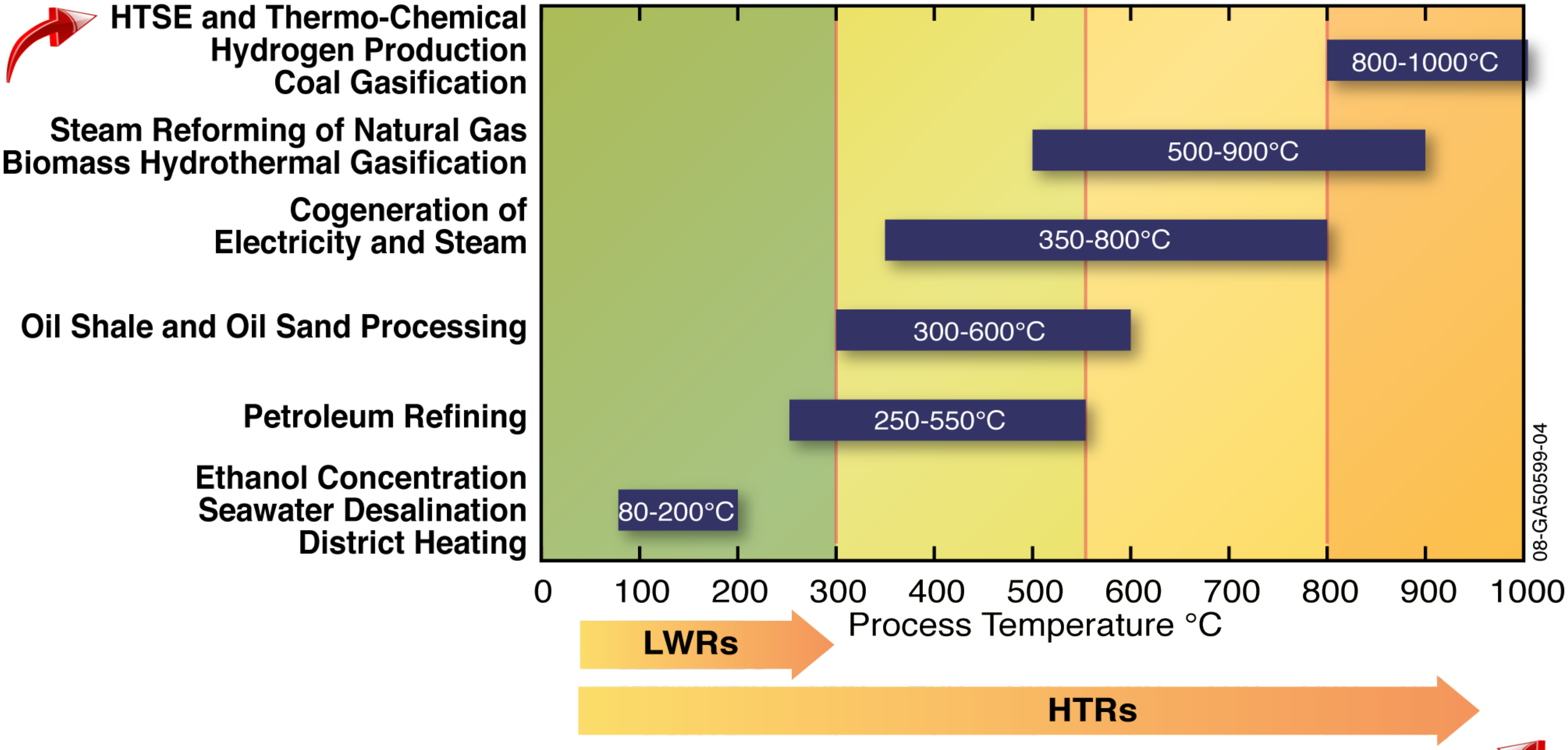
Next Generation Nuclear Plant

Next Generation Nuclear Plant (NGNP) Project



“The country that can harness the power of hydrogen …. will be the country with the healthiest economy, the cleanest environment, and the strongest energy and national security,” said Senator Dorgan.

Beyond Electricity – Applications of High Temperature Gas Reactors (HTGRs)

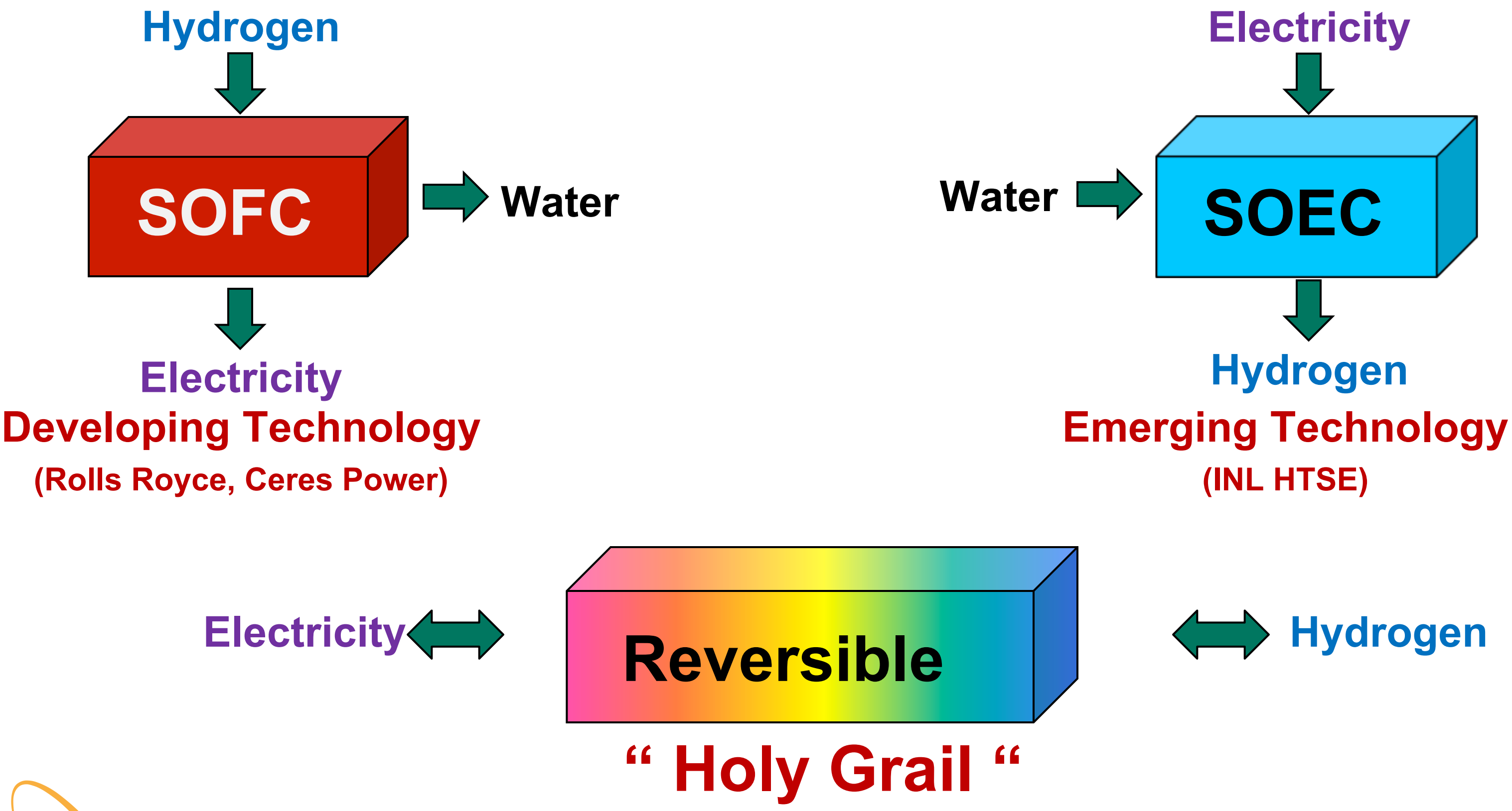


High Temperature Gas Reactors can provide energy production that supports many industrial applications including petrochemical and petroleum industries

Next Generation Nuclear Plant

Solid Oxide Fuel vs. Electrolysis Cells

(High efficiency, long-term stability, fuel flexibility, low emissions, low cost, but higher temperature and material compatibility issues)



Hydrogen

SOFC

Water

Electricity

Developing Technology

(Rolls Royce, Ceres Power)

Electricity

Water

SOEC

Hydrogen

Emerging Technology

(INL HTSE)

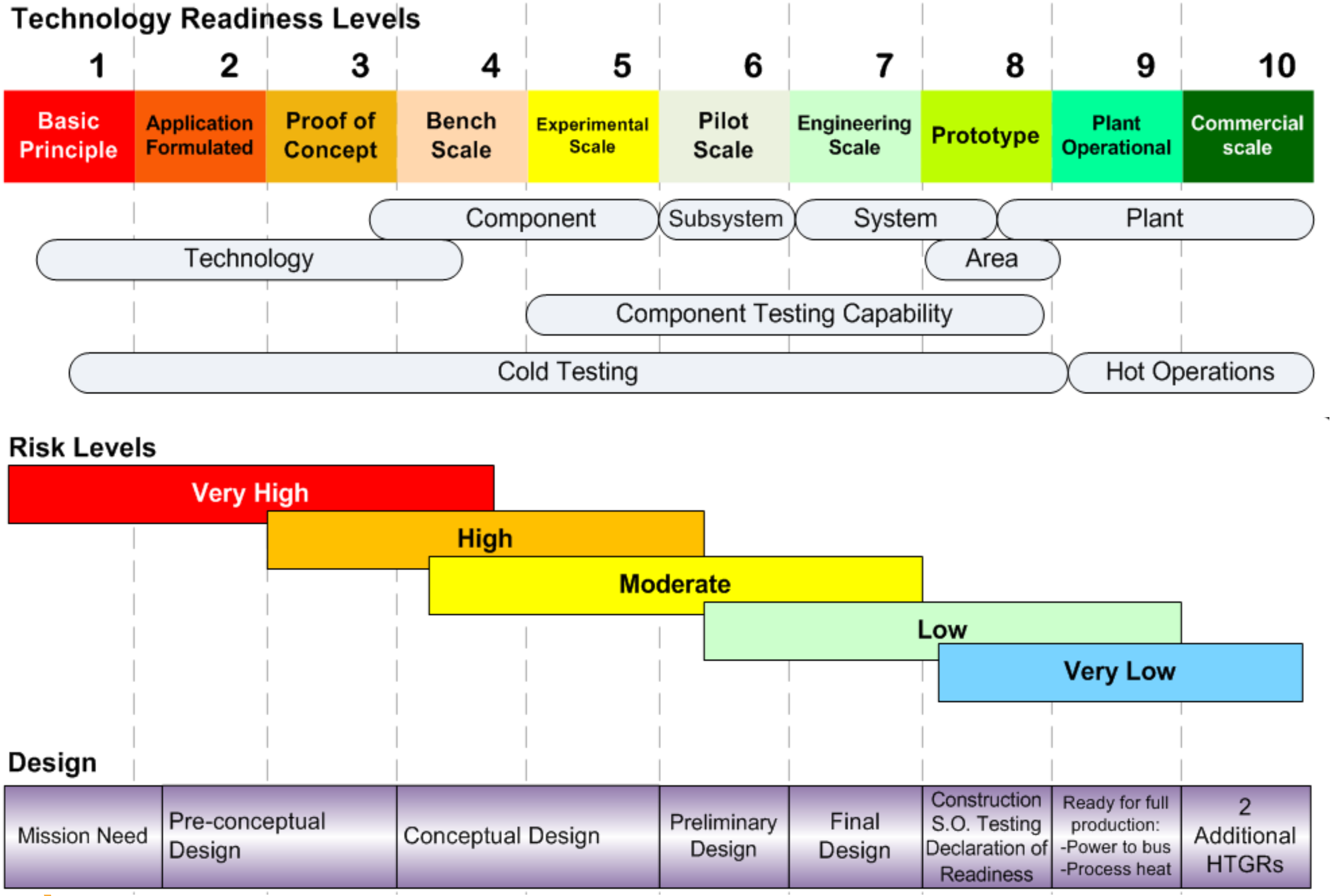
Electricity

Reversible

Hydrogen

“ Holy Grail “

Systems Are Advanced Using Technology Readiness Level (TRL) to Assess Maturity



Technology Readiness Levels

1 Basic Principle
2 Application Formulated
3 Proof of Concept
4 Bench Scale
5 Experimental Scale
6 Pilot Scale
7 Engineering Scale
8 Prototype
9 Plant Operational
10 Commercial scale

Component
Subsystem
System
Plant
Technology
Area
Component Testing Capability
Cold Testing
Hot Operations

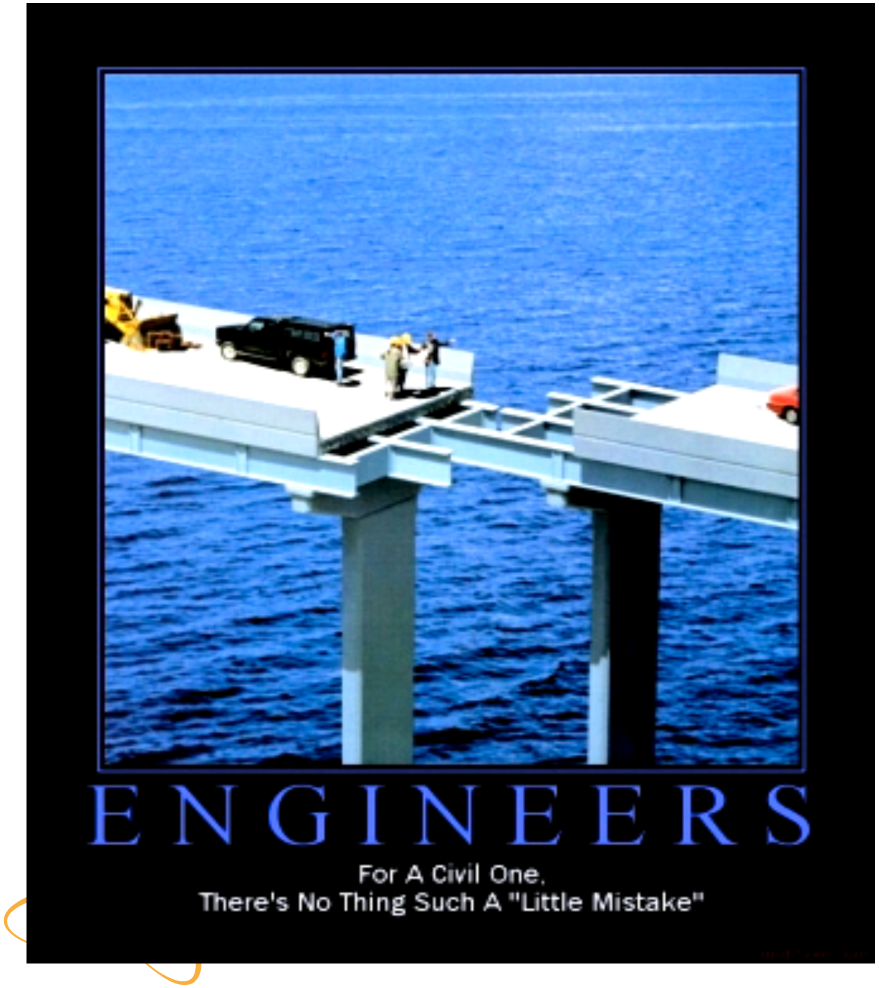
Risk Levels

Very High
High
Moderate
Low
Very Low

Design

Mission Need
Pre-conceptual Design
Conceptual Design
Preliminary Design
Final Design
Construction S.O. Testing Declaration of Readiness
Ready for full production:
-Power to bus
-Process heat
2 Additional HTGRs

System Verification Tools Like BlockSim Enable the Assessment of Important System Metrics Like RAM



- Verification Asks…
  - Did you build it right?
- Verification Activities
  - Analysis
  - Demonstration
  - Inspection
  - Certification
  - Testing
    - Acceptance Test
    - Development Test
    - Qualification Test
    - Operational Test

Customers Complain About System RAM Not Design, When They Own the System

- "This !#%$#@ car has only one reliable part, and that's the wood paneling!!"

- "I bought this car to replace my Corolla. My tires have a bubble in them after a month of ownership. I had to recharge *my car* battery the other day and the air bags just went off – all 4 at the same time! The radio blew up on me the other day when I was setting the time. The car couldn't start this morning… I had to use jumper cables."

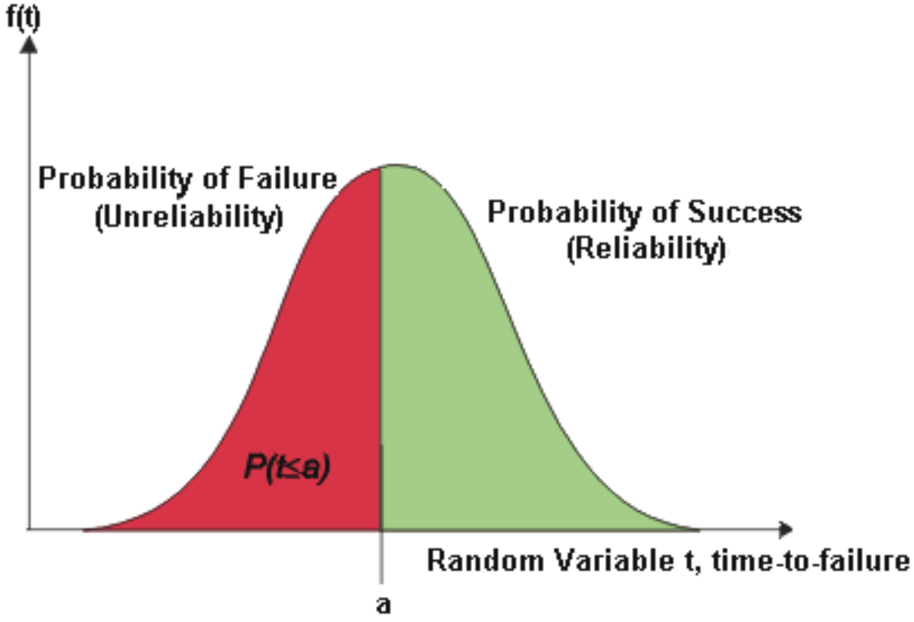
- What is RAM?
  - Interrelationship between Reliability and Maintainability and their impact on Availability

Next Generation
Nuclear Plant

What is Reliability?

- Likelihood an item will successfully perform a required function under stated conditions without failure for a specified period of time

$$\text{Probability of Failure}: F(t) = \int_0^t f(s)\,ds$$



$$\text{Reliability}: R(t) = 1 - F(t)$$

What is Maintainability?

- Measure of the degree to which a system, product or service can be returned from a failed state to a functioning state within time limits established by a performance standard

$$\text{Lognormal Distribution}: \mathrm{M(t)} = \int_0^{T'} \frac{1}{\sigma T' \sqrt{2\pi}} \mathrm{e}^{\frac{-1}{2}\left(\frac{\mathrm{t}-\bar{T}'}{\sigma T'}\right)^2} dt$$

  - *Where*
    - $\bar{T}'$ = *Mean of natural logs of times-to-repair*
    - σT = *Standard deviation of natural logs of times-to-repair*

- Note: Be consistent with how you define repair time
    - *Time to access failed parts, procure or deliver parts to perform repair*
    - *Time to successfully diagnose cause of failure*
    - *Time it takes to remove failed components & replace with functioning ones*

What is Availability?

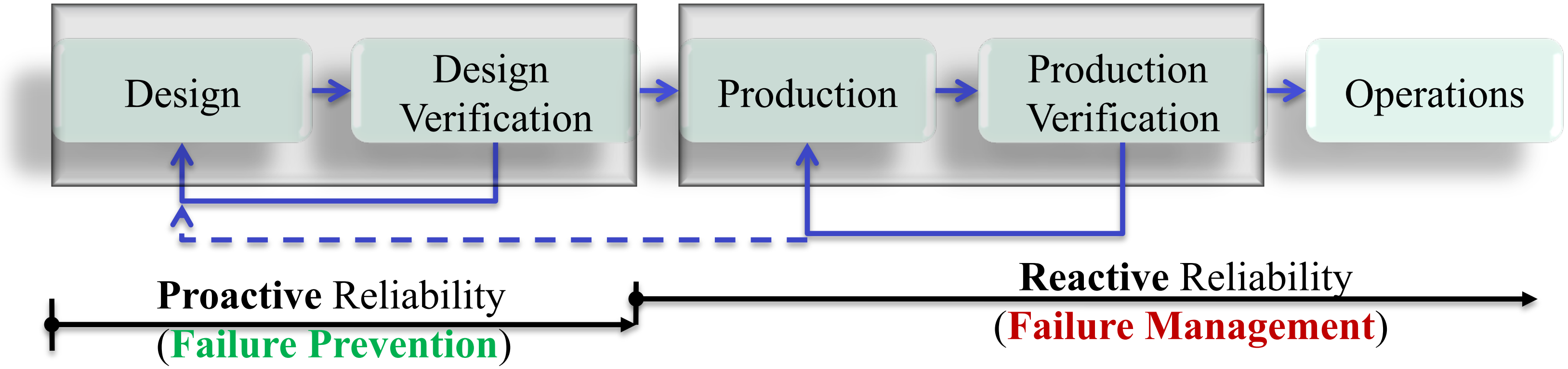
- Likelihood that a system has not failed or undergoing repair when it is needed
  - Operational Availability:
    - Measure of average availability over a period of time and it includes all experienced sources of down time, such as administrative, logistics, preventative and corrective maintenance downtimes, etc.

$$A_0 = \frac{\text{Uptime}}{\text{Operational Cycle}}$$

    - *Where*
      - *Uptime = Total time the system was functioning during operational cycle*
      - *Operational cycle = Overall time period of operation being investigated*

Why RAM Verification During Design?

- RAM Verification:
  - Identifies unseen and avoidable failures in system
  - Influences system design
  - Influences system facility design and planning
  - Ensures Total Ownership Cost (TOC) is within constraints of customer



Source: Common sense on Reliability Engineering, Albertyn Banard

Why RAM Verification During Design Continued…?

Factor of 10 Rule: $ x 10 ^{n}

The cost of not addressing reliability issues increases tenfold as system matures

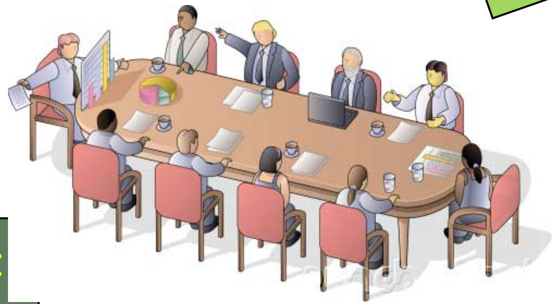
Concept Phase

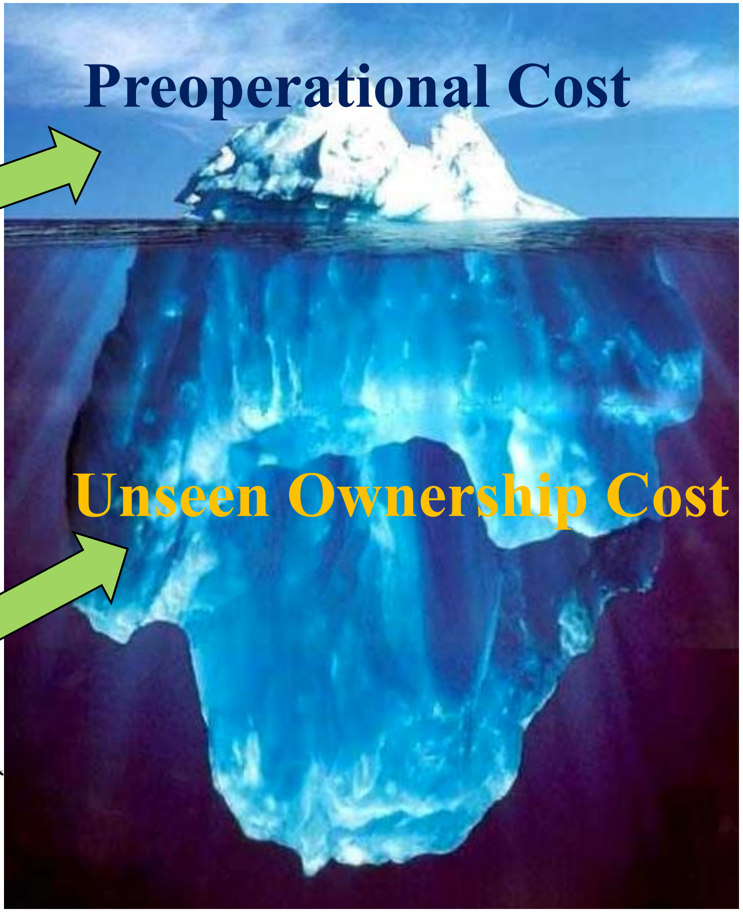
Design Phase:
$ x 10

Development Phase:
$ x 100

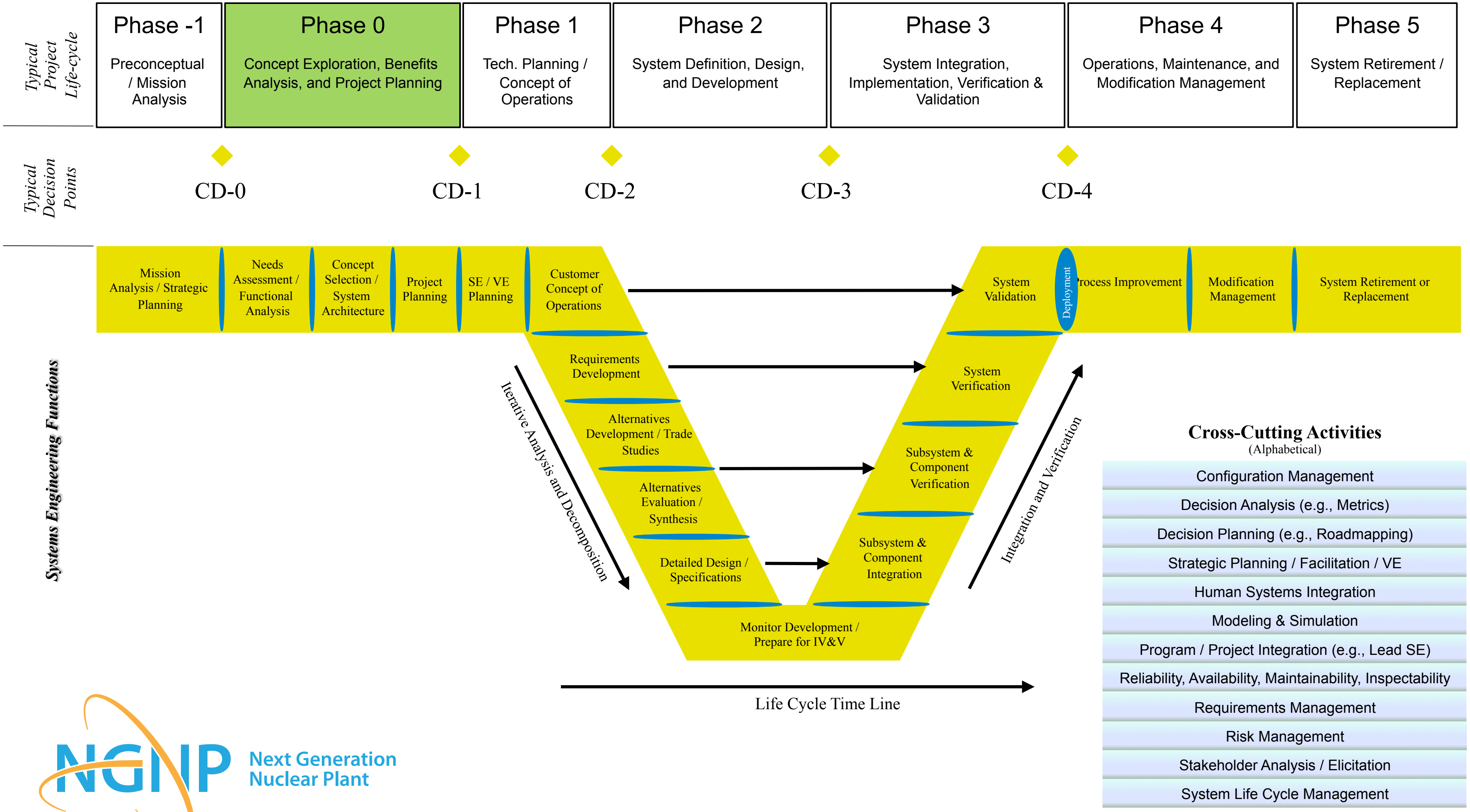
Manufacturing Phase:
$ x 1,000

Operation/Support Phase:
$ x 10,000





Verifying System RAM at Conceptual Phase Reduces Ownership Risk and Cost



Cross-Cutting Activities
(Alphabetical)

- Configuration Management
- Decision Analysis (e.g., Metrics)
- Decision Planning (e.g., Roadmapping)
- Strategic Planning / Facilitation / VE
- Human Systems Integration
- Modeling & Simulation
- Program / Project Integration (e.g., Lead SE)
- Reliability, Availability, Maintainability, Inspectability
- Requirements Management
- Risk Management
- Stakeholder Analysis / Elicitation
- System Life Cycle Management

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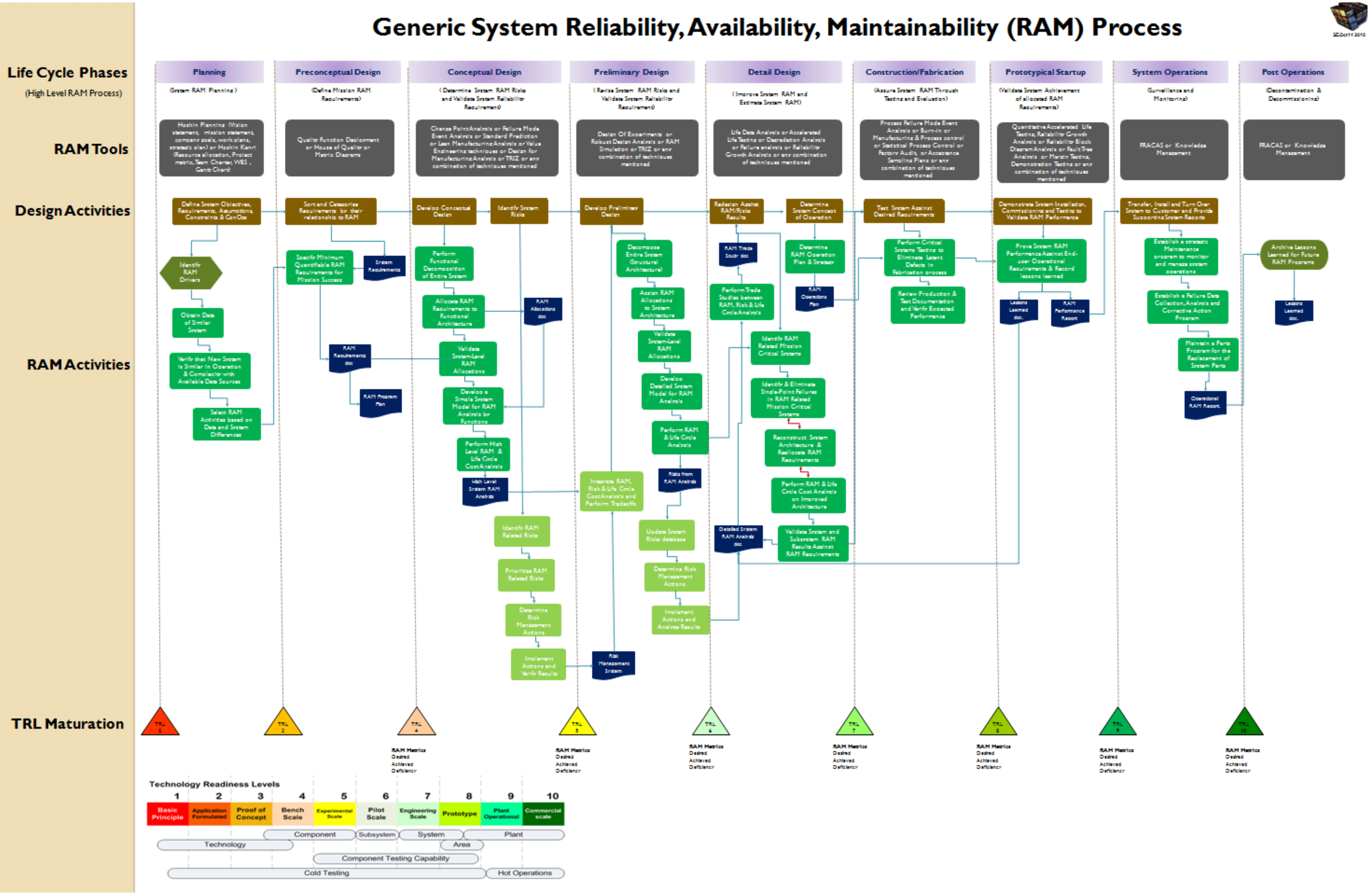
Planning RAM Verification Activities With Design Maturity In TRL Space Ensures System Robustness



Generic System Reliability, Availability, Maintainability (RAM) Process

SEOct14 2010

Life Cycle Phases
(High Level RAM Process)

RAM Tools

Design Activities

RAM Activities

TRL Maturation

Planning
(System RAM Planning)
Hoshin Planning (Vision statement, mission statement, company goals, work plans, strategic plan) or Hoshin Kanri (Resource allocation, Project matrix, Team Charter, WBS, Gantt Chart)
Define System Objectives, Requirements, Assumptions, Constraints & ConOps
Identify RAM Drivers
Obtain Data of Similar System
Verify that New System is Similar in Operation & Complexity with Available Data Sources
Select RAM Activities based on Data and System Differences

Preconceptual Design
(Define Mission RAM Requirements)
Quality Function Deployment or House of Quality or Matrix Diagrams
Sort and Categorize Requirements by their relationship to RAM
Specify Minimum Quantifiable RAM Requirements for Mission Success
System Requirements
RAM Requirements doc
RAM Program Plan

Conceptual Design
(Determine System RAM Risks and Validate System Reliability Requirement)
Change Point Analysis or Failure Mode Event Analysis or Standard Prediction or Lean Manufacturing Analysis or Value Engineering techniques or Design for Manufacturing Analysis or TRIZ or any combination of techniques mentioned
Develop Conceptual Design
Identify System Risks
Perform Functional Decomposition of Entire System
Allocate RAM Requirements to Functional Architecture
RAM Allocations doc
Validate System-Level RAM Allocations
Develop a Simple System Model for RAM Analysis by Functions
Perform High Level RAM & Life Cycle Cost Analysis
High Level System RAM Analysis
Identify RAM Related Risks
Prioritize RAM Related Risks
Determine Risk Management Actions
Implement Actions and Verify Results

Preliminary Design
(Revise System RAM Risks and Validate System Reliability Requirement)
Design Of Experiments or Robust Design Analysis or RAM Simulation or TRIZ or any combination of techniques mentioned
Develop Preliminary Design
Integrate RAM, Risk & Life Cycle Cost Analysis and Perform Tradeoffs
Risk Management System
Decompose Entire System (Structural Architecture)
Assign RAM Allocations to System Architecture
Validate System-Level RAM Allocations
Develop Detailed System Model for RAM Analysis
Perform RAM & Life Cycle Analysis
Risks from RAM Analysis
Update System Risks database
Determine Risk Management Actions
Implement Actions and Analyze Results

Detail Design
(Improve System RAM and Estimate System RAM)
Life Data Analysis or Accelerated Life Testing or Degradation Analysis or Failure analysis or Reliability Growth Analysis or any combination of techniques mentioned
Redesign Against RAM/Risks Results
Determine System Concept of Operation
RAM Trade Study doc
Perform Trade Studies between RAM, Risk & Life Cycle Analysis
Determine RAM Operation Plan & Strategy
RAM Operations Plan
Identify RAM Related Mission Critical Systems
Identify & Eliminate Single-Point Failures in RAM Related Mission Critical Systems
Reconstruct System Architecture & Reallocate RAM Requirements
Perform RAM & Life Cycle Cost Analysis on Improved Architecture
Detailed System RAM Analysis doc
Validate System and Subsystem RAM Results Against RAM Requirements

Construction/Fabrication
(Assure System RAM Through Testing and Evaluation)
Process Failure Mode Event Analysis or Burn-in or Manufacturing & Process control or Statistical Process Control or Factory Audit, or Acceptance Sampling Plans or any combination of techniques mentioned
Test System Against Desired Requirements
Perform Critical Systems Testing to Eliminate Latent Defects in Fabrication process
Review Production & Test Documentation and Verify Expected Performance

Prototypical Startup
(Validate System Achievement of allocated RAM Requirements)
Quantitative Accelerated Life Testing, Reliability Growth Analysis or Reliability Block Diagram Analysis or Fault Tree Analysis or Margin Testing, Demonstration Testing or any combination of techniques mentioned
Demonstrate System Installation, Commissioning and Testing to Validate RAM Performance
Prove System RAM Performance Against End-user Operational Requirements & Record lessons learned
Lessons Learned doc.
RAM Performance Report

System Operations
(Surveillance and Monitoring)
FRACAS or Knowledge Management
Transfer, Install and Turn Over System to Customer and Provide Supporting System Reports
Establish a strategic Maintenance program to monitor and manage system operations
Establish a Failure Data Collection, Analysis and Corrective Action Program
Maintain a Parts Program for the Replacement of System Parts
Operational RAM Report.

Post Operations
(Decontamination & Decommissioning)
FRACAS or Knowledge Management
Archive Lessons Learned for Future RAM Programs
Lessons Learned doc.

TRL 2
TRL 3
TRL 4
RAM Metrics
Desired
Achieved
Deficiency
TRL 5
RAM Metrics
Desired
Achieved
Deficiency
TRL 6
RAM Metrics
Desired
Achieved
Deficiency
TRL 7
RAM Metrics
Desired
Achieved
Deficiency
TRL 8
RAM Metrics
Desired
Achieved
Deficiency
TRL 9
RAM Metrics
Desired
Achieved
Deficiency
TRL 10
RAM Metrics
Desired
Achieved
Deficiency

Technology Readiness Levels

1	2	3	4	5	6	7	8	9	10
Basic Principle	Application Formulated	Proof of Concept	Bench Scale	Experimental Scale	Pilot Scale	Engineering Scale	Prototype	Plant Operational	Commercial scale

Component
Subsystem
System
Plant
Technology
Area
Component Testing Capability
Cold Testing
Hot Operations

System Vulnerability Determined Through RAM Analysis Are Addressed In Risk Management Space

Probability and Consequence Product Table

	Negligible	Marginal	Significant	Critical	Crisis
Very Likely	Low 0.9	Moderate 2.7	High 4.5	Very High 6.3	Very High 8.1
Likely	Low 0.7	Moderate 2.4	High 4.4	Very High 6.1	Very High 7.9
Somewhat Likely	Low 0.5	Moderate 1.9	High 3.8	High 5.3	Very High 6.8
UnLikely	Very Low 0.3	Low 1.2	Moderate 2.6	High 4.2	High 5.4
Very Unlikely	Very Low 0.1	Low 0.5	Low 1.0	Moderate 1.8	Moderate 2.7

Technology Readiness Levels

1	2	3	4	5	6	7	8	9	10
Basic Principle	Application Formulated	Proof of Concept	Bench Scale	Experimental Scale	Pilot Scale	Engineering Scale	Prototype	Plant Operational	Commercial scale

Technology — Component — Subsystem — System — Plant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HPS - H.T.E RISK REDUCTION TASKS

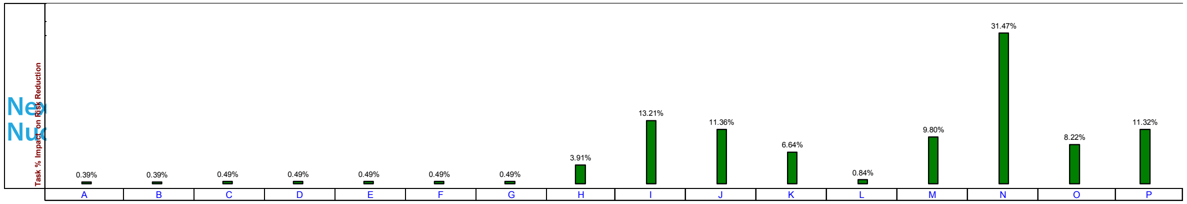
Task	Description	TRL
A	Perform twenty 10x10 cm longterm degradation tests	TRL 4-5
B	Analyze cell degradation mechanisms	TRL 4-5
C	Test NASA cells	TRL 4-5
D	Test St. Gobain cells	TRL 4-5
E	Validate Recuperator performance	TRL 4-5
F	Validate sweepgas/oxygen Handling performance	TRL 4-5
G	Validate Hydrogen Recycle performance	TRL 4-5
H	Perform 5000hr cell test with less than 10% degradation per 1000hrs	TRL 5-6
I	Demonstrate heat and pressure management systems at 3 MPa	TRL 5-6
J	Demonstrate gas management systems at 3MPa	TRL 5-6
K	Demonstrate I&C systems at 3 Mpa	TRL 5-6
L	Perform 10,000 hr cell test with less than 5% degradation per 1000 hrs	TRL 6-7
M	Demonstrate heat and pressure management systems at 5Mpa	TRL 6-7
N	Demonstrate Tritium Detection and Removal	TRL 6-7
O	Develop and use System Model (analytica model)	TRL 7-8
P	Perform 20,000 hr cell test with less than 5% degradation per 1000hrs	TRL 8-9

Each task column holds ΔC, ΔPc and ΔPe cells, with the risk score after the task beneath them.

ID	HPS - H.T.E TECHNICAL RISKS	BASELINE C	Pc	Pe		Risk Score After Task Completion	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Risk % Reduction	Unreduced Risk %
273	Tritium Migration - et al.	9.00	1.00	0.90	8.10	4.05	8.10	8.10	8.10	8.10	8.10	8.10	8.10	8.10	8.10	8.10	8.10	8.10	8.10	ΔPe 0.50 4.05	4.05	4.05	50%	50%
275	I&C for HPS Environment -INL/EXT-05-00952(PLN-2489 Rev 3)	9.00	1.00	0.90	8.10	2.84	8.10	8.10	8.10	[illegible]	8.10	8.10	8.10	8.10	8.10	8.10	ΔPe 0.15 6.89	6.89	6.89	ΔPe 0.20 5.27	ΔPe 0.15 4.05	ΔPe 0.15 2.84	65%	35%
277	Integrity of Manifolds, Seals, Valves in H.T.E Environment - INL/EXT - 08 - 15148	7.00	1.00	0.70	4.90	2.55	4.90	4.90	4.90	4.90	[illegible]	4.90	4.90	4.90	ΔPe 0.12 4.31	ΔPe 0.12 3.72	3.72	3.72	ΔPe 0.12 3.14	3.14	3.14	ΔPe 0.12 2.55	48%	52%
280	Reactor I&C and HPS I&C Interaction - INEEL/EXT-04-01816	7.00	1.00	0.70	4.90	2.84	4.90	4.90	4.90	4.90	4.90	4.90	[illegible]	ΔPe 0.10 4.41	ΔPe 0.15 3.68	ΔPe 0.12 3.09	3.09	3.09	3.09	3.09	ΔPe 0.05 2.84	2.84	42%	58%
N	Impact of HTSE subsystem configurations on system availability	7.00	1.00	0.70	4.90	2.84	4.90	4.90	4.90	4.90	4.90	4.90	4.90	ΔPe [illegible] 4.41	ΔPe 0.15 [illegible]	ΔPe 0.12 3.09	3.09	3.09	3.09	3.09	ΔPe 0.05 2.84	2.84	42%	58%
N	HTSE vessel Insulation challenges	7.00	1.00	0.70	4.90	2.84	4.90	4.90	4.90	4.90	4.90	4.90	4.90	ΔPe 0.10 4.41	ΔPe 0.15 3.68	ΔPe [illegible] 3.09	[illegible]	3.09	3.09	3.09	ΔPe 0.05 2.84	2.84	42%	58%
150	Pressure Impact and Control in H.T.E-TDRM doc_01_09	3.00	1.00	0.30	0.90	0.51	0.90	0.90	0.90	0.90	0.90	0.90	0.90	ΔPe 0.05 0.86	ΔPe 0.20 0.68	ΔPe 0.15 0.54	0.54	0.54	[illegible]	0.54	ΔPe 0.03 0.51	0.51	43%	57%
190	H.T.E Process Efficiency - INL/EXT - 08 - 15151	3.00	1.00	0.30	0.90	0.12	0.90	0.90	0.90	0.90	ΔPe 0.10 0.81	ΔPe 0.10 0.72	ΔPe 0.10 0.63	ΔPe 0.05 0.59	ΔPe 0.10 0.50	ΔPe 0.10 0.41	0.41	ΔPe 0.05 0.36	ΔPe 0.10 0.27	ΔPe 0.10 0.18	ΔPe 0.02 0.16	ΔPe 0.05 0.12	87%	13%
149	Degradation of Cell in H.T.E Environment-TDRM doc_01_09	3.00	1.00	0.30	0.90	0.20	ΔPe 0.08 0.83	ΔPe 0.08 0.76	ΔPe 0.10 0.67	ΔPe 0.10 0.58	0.58	0.58	0.58	ΔPe 0.15 0.44	0.44	0.44	0.44	ΔPe 0.12 0.33	0.33	0.33	0.33	ΔPe 0.15 0.20	78%	22%
281	Effect of Chemical Releases Outside HPS - NUREG/CR-6944 NGNP Process Heat & Hydrogen Cogeneration (NGNP PIRT VOL.6)	3.00	1.00	0.30	0.90	0.50	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	ΔPe 0.10 0.81	ΔPe 0.10 0.72	0.72	0.72	ΔPe 0.15 0.59	0.59	0.59	ΔPe 0.10 0.50	45%	55%

Legend :
- 🟩 Risk Reduced
- 🟥 Unreduced Risk

NOTIONAL DATA

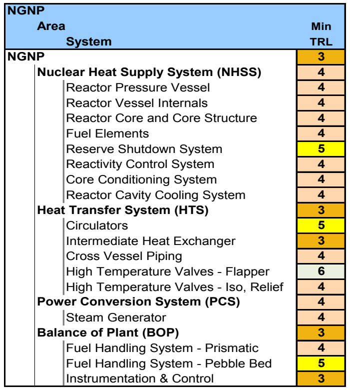


System Level Results

Baseline-Average Score	2.23
Final Ave RVI Risk Score	0.97

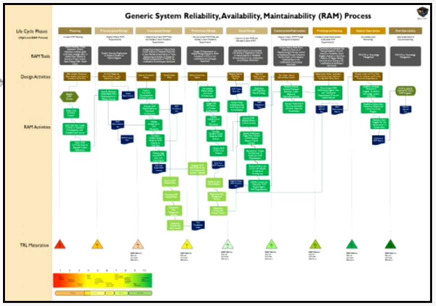
RAM Verification and Technology Maturation Activities are Iterative Processes

Assess Technology Maturity

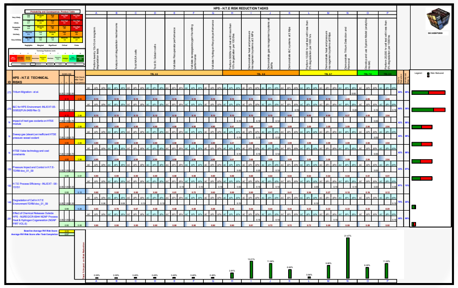


NGNP	Area	System	Min TRL
NGNP			3
	Nuclear Heat Supply System (NHSS)		4
		Reactor Pressure Vessel	4
		Reactor Vessel Internals	4
		Reactor Core and Core Structure	4
		Fuel Elements	4
		Reserve Shutdown System	5
		Reactivity Control System	4
		Core Conditioning System	4
		Reactor Cavity Cooling System	4
	Heat Transfer System (HTS)		3
		Circulators	5
		Intermediate Heat Exchanger	3
		Cross Vessel Piping	4
		High Temperature Valves - Flapper	6
		High Temperature Valves - Iso, Relief	4
	Power Conversion System (PCS)		4
		Steam Generator	4
	Balance of Plant (BOP)		3
		Fuel Handling System - Prismatic	4
		Fuel Handling System - Pebble Bed	5
		Instrumentation & Control	3

Evaluate Verification Activities & Refine Path Forward



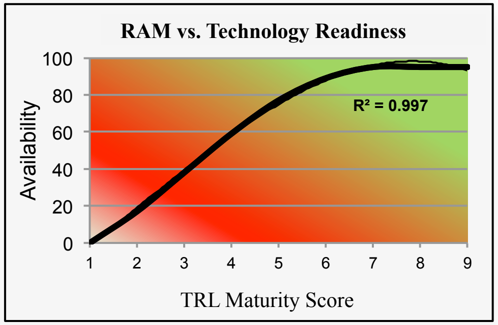
Risks

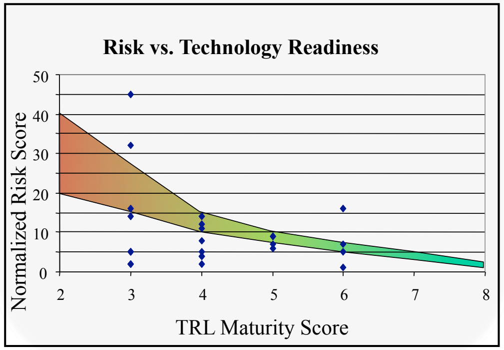


Define Tasks, Address Risks to Mature Technology

Output

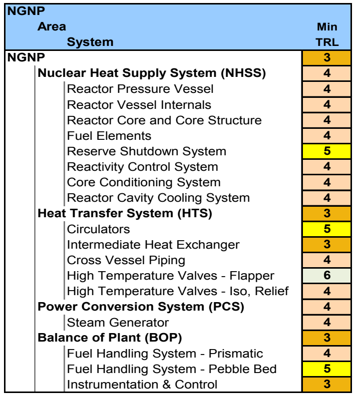
Advance TRLs & Improve RAM





Advance TRLs & Reduce Risk

Reassess Technology Maturity



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		Fuel Elements	4
		Reserve Shutdown System	5
		Reactivity Control System	4
		Core Conditioning System	4
		Reactor Cavity Cooling System	4
	Heat Transfer System (HTS)		3
		Circulators	5
		Intermediate Heat Exchanger	3
		Cross Vessel Piping	4
		High Temperature Valves - Flapper	6
		High Temperature Valves - Iso, Relief	4
	Power Conversion System (PCS)		4
		Steam Generator	4
	Balance of Plant (BOP)		3
		Fuel Handling System - Prismatic	4
		Fuel Handling System - Pebble Bed	5
		Instrumentation & Control	3

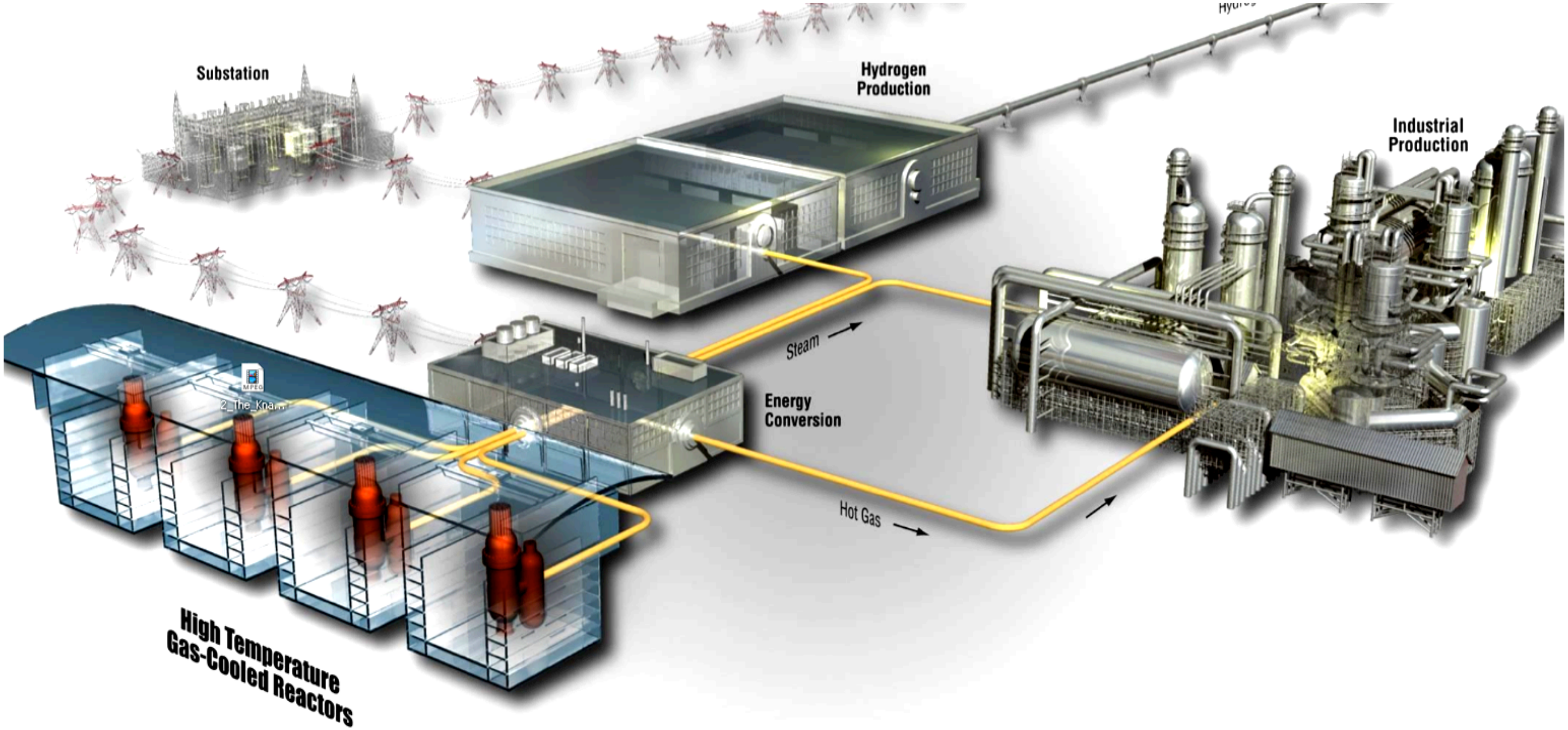
TRL: Technology Readiness Level

Is RAM Verification Possible at the Conceptual Phase?

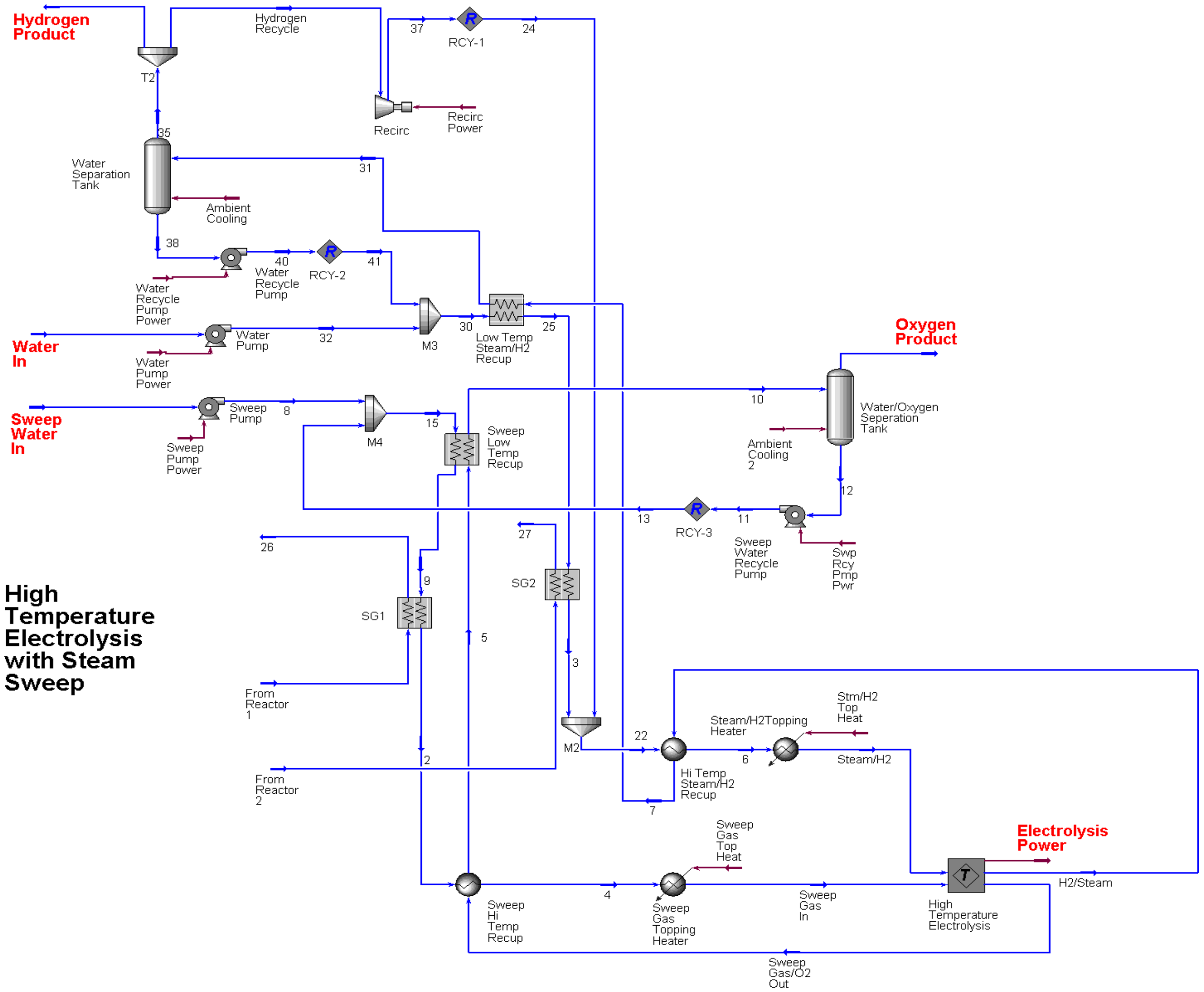
- **Common Barriers**
  - Unclear system design concept
  - Uncertain and vague requirements

- **Rules of Thumb**
  - Most new technologies, products or systems are built from existing technologies which are reconfigured or readjusted in new ways to perform new functions
  - Most failure in new systems are caused when old system elements are reconfigured in new ways

Defining And Establishing System Boundary



Granularity of System Decomposition is Based on What You Can Take Action on



High Temperature Electrolysis with Steam Sweep

Functional Decomposition of HTSE System Establishes Relationship Between System Elements

Water Input

- Water supply system

Water Conditioning

- Water purification system

Water /Gas Transport

- Water recycle pump
- Sweep water recycle pump
- Water pump
- Sweep water pump
- H_2 recirculator
- HTSE piping
- Mixing chamber

Water Heat up

- Sweep hi-temp recuperator
- High-temp steam/H_2 recuperator
- Steam/H_2 topping heater
- Sweep gas topping heater
- Steam generator 1
- Steam generator 2

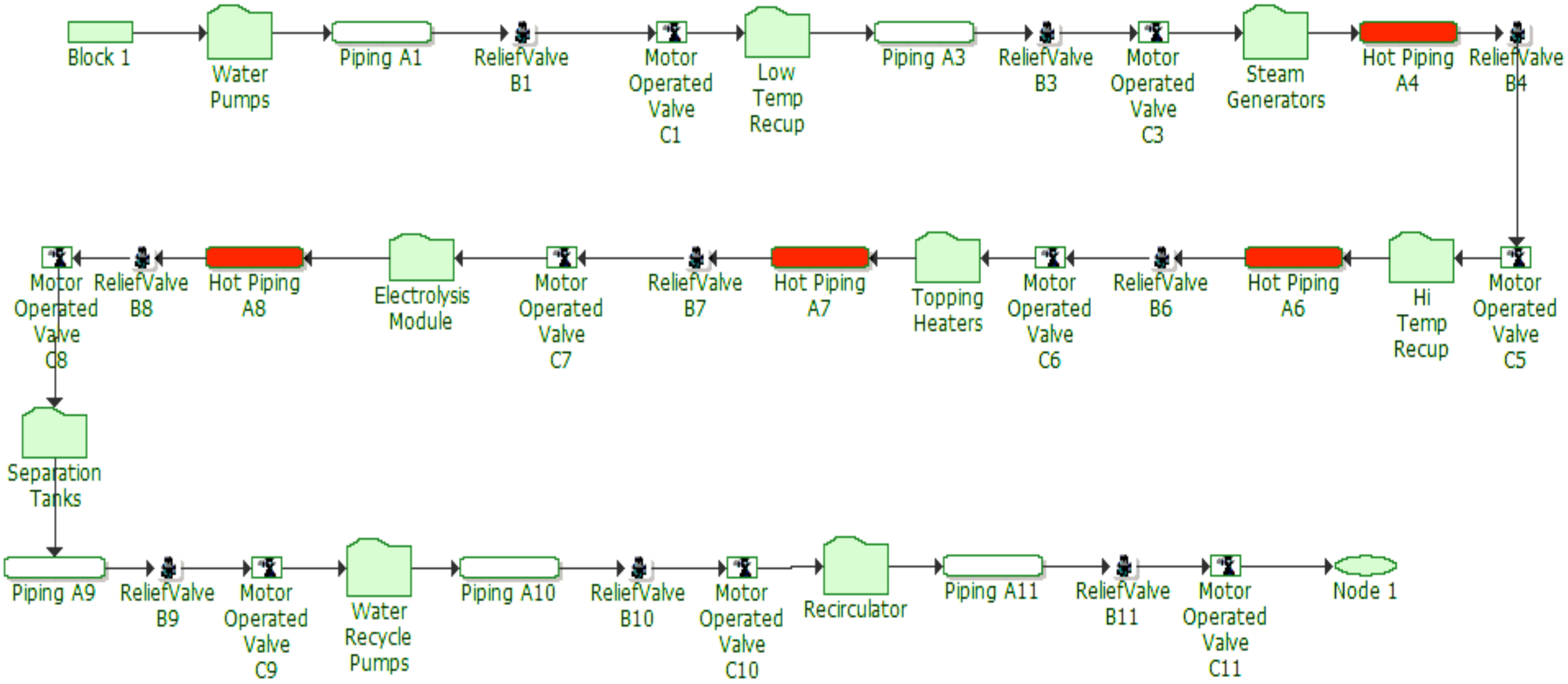
Water Dissociation

- Solid Oxide Electrolyzers

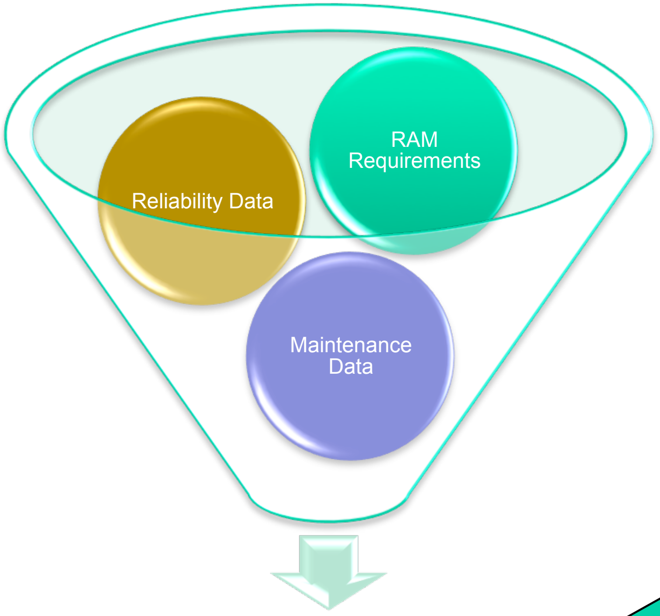
Product Handling

- Water separation tank hydrogen product
- Water/oxygen separation tank oxygen product

System Elements Configured in a Reliability Block Diagram



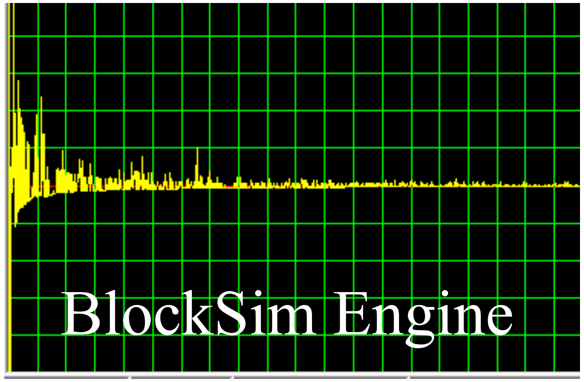
BlockSim – Design & Verification Tool, Uses RAM Data to Estimate System Operational Performance Over Time



Reliability Data

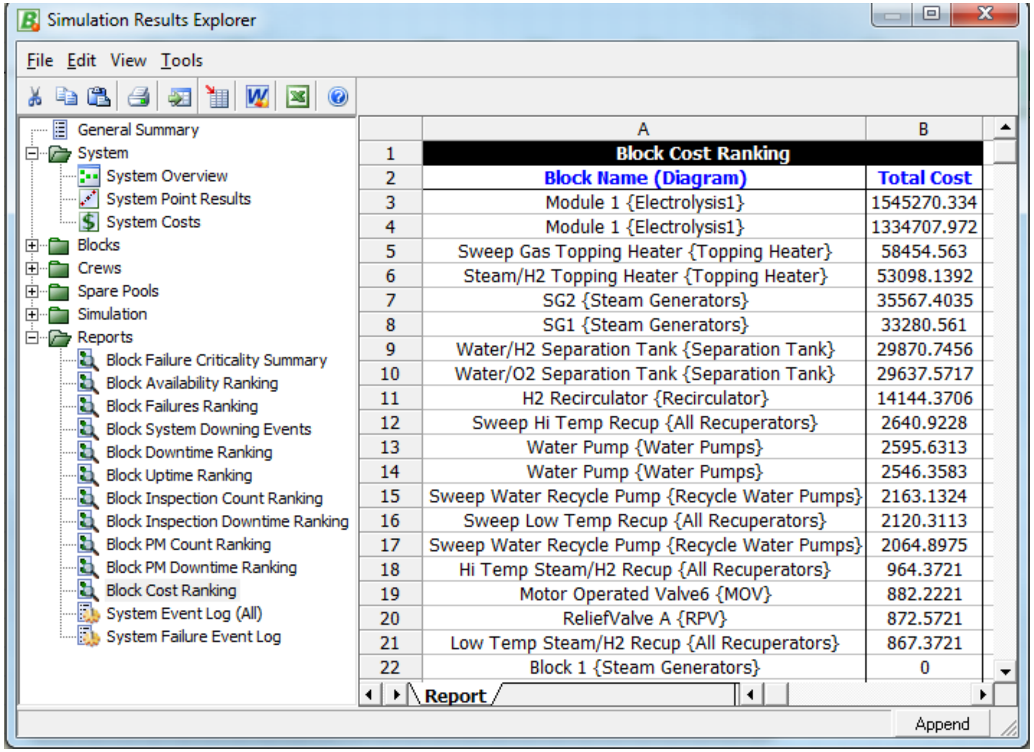
RAM Requirements

Maintenance Data



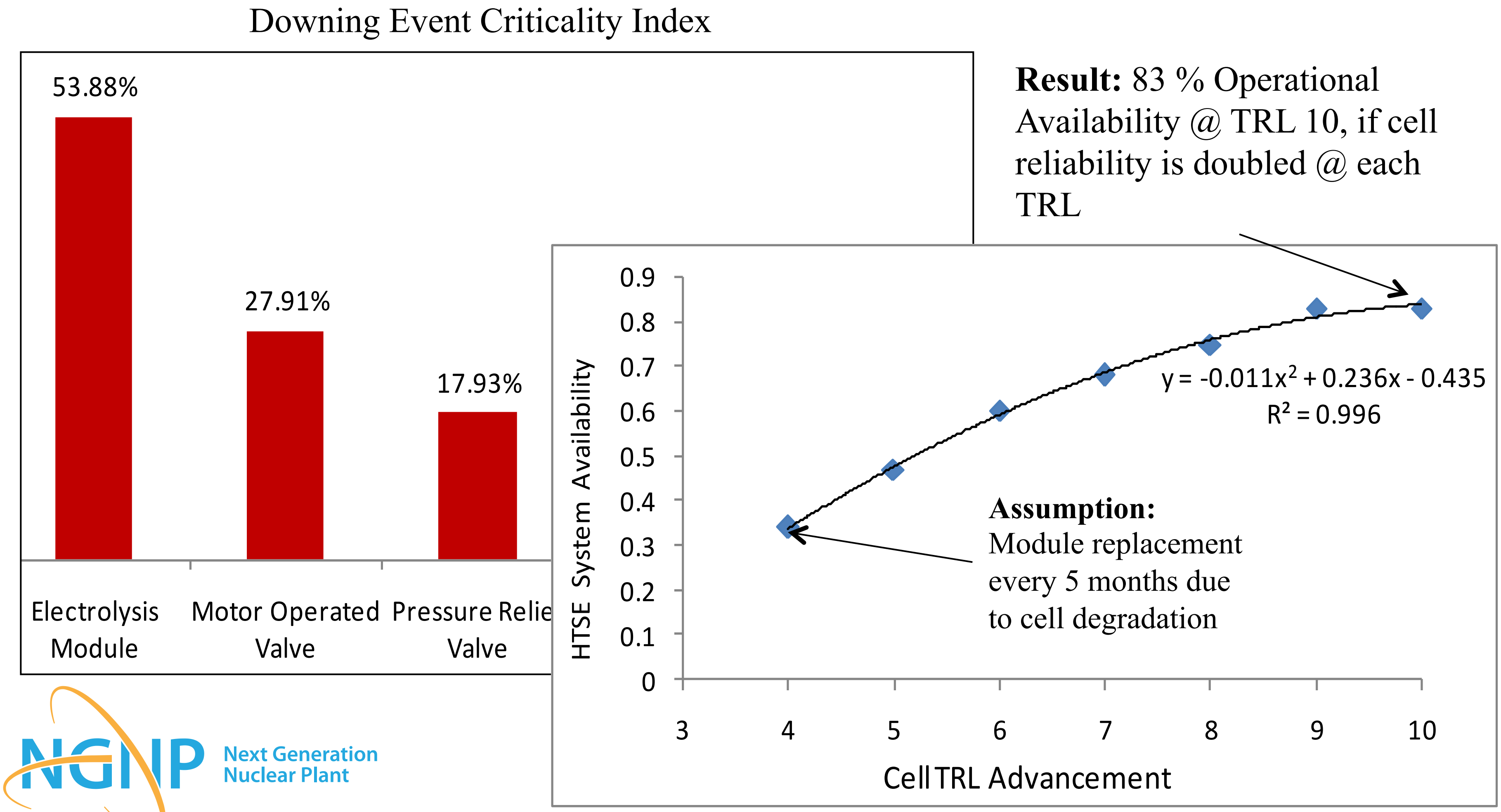
BlockSim Engine

A good reliability requirement has a time factor



	A	B
1	**Block Cost Ranking**	
2	**Block Name (Diagram)**	**Total Cost**
3	Module 1 {Electrolysis1}	1545270.334
4	Module 1 {Electrolysis1}	1334707.972
5	Sweep Gas Topping Heater {Topping Heater}	58454.563
6	Steam/H2 Topping Heater {Topping Heater}	53098.1392
7	SG2 {Steam Generators}	35567.4035
8	SG1 {Steam Generators}	33280.561
9	Water/H2 Separation Tank {Separation Tank}	29870.7456
10	Water/O2 Separation Tank {Separation Tank}	29637.5717
11	H2 Recirculator {Recirculator}	14144.3706
12	Sweep Hi Temp Recup {All Recuperators}	2640.9228
13	Water Pump {Water Pumps}	2595.6313
14	Water Pump {Water Pumps}	2546.3583
15	Sweep Water Recycle Pump {Recycle Water Pumps}	2163.1324
16	Sweep Low Temp Recup {All Recuperators}	2120.3113
17	Sweep Water Recycle Pump {Recycle Water Pumps}	2064.8975
18	Hi Temp Steam/H2 Recup {All Recuperators}	964.3721
19	Motor Operated Valve6 {MOV}	882.2221
20	ReliefValve A {RPV}	872.5721
21	Low Temp Steam/H2 Recup {All Recuperators}	867.3721
22	Block 1 {Steam Generators}	0

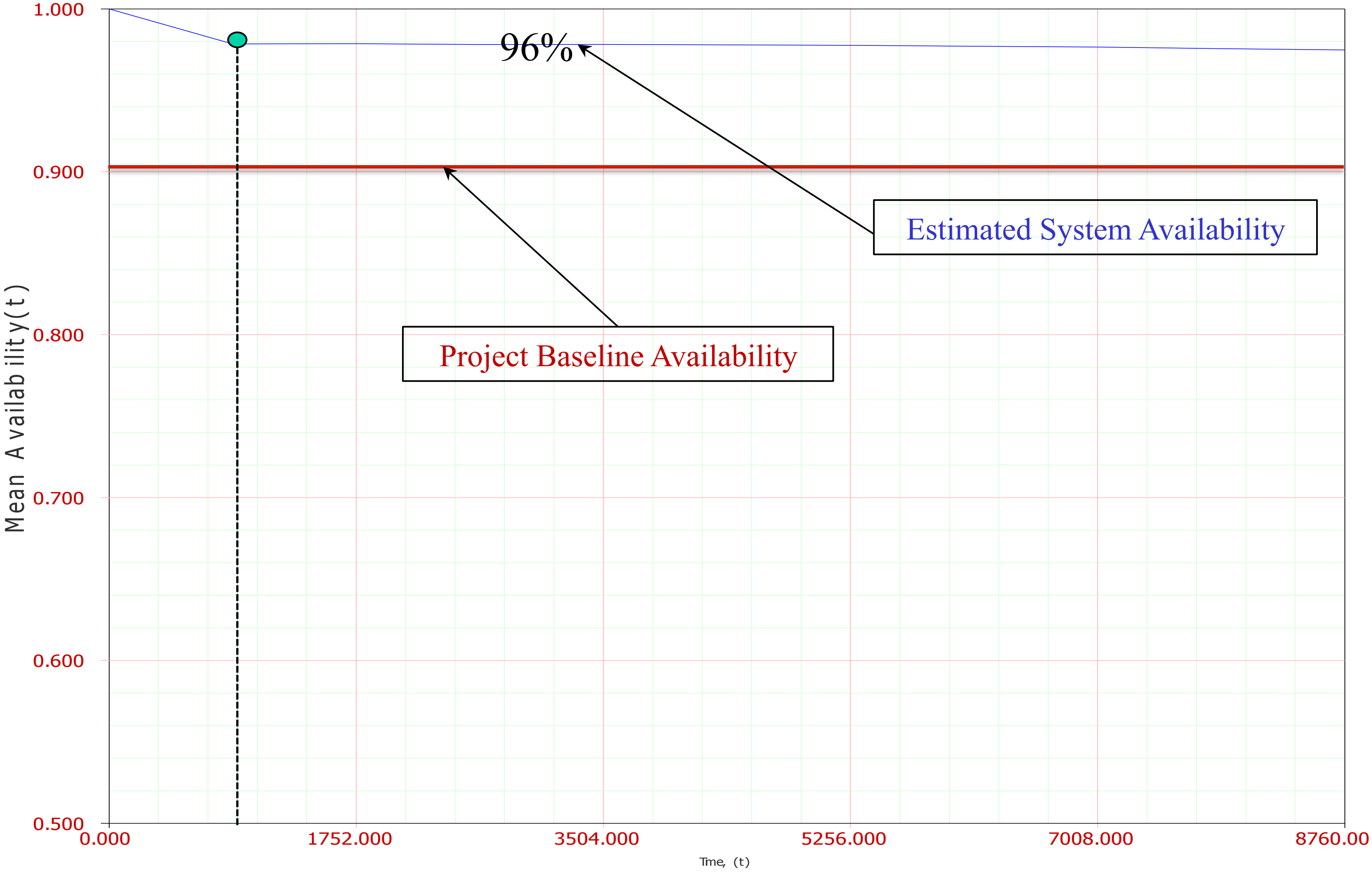
BlockSim Outputs: Knowing the Right Metric to Measure is Important



Result: 83 % Operational Availability @ TRL 10, if cell reliability is doubled @ each TRL

Assumption:
Module replacement every 5 months due to cell degradation

Addressing Big Hitters While Doubling Cell Reliability Improves System Operational Availability

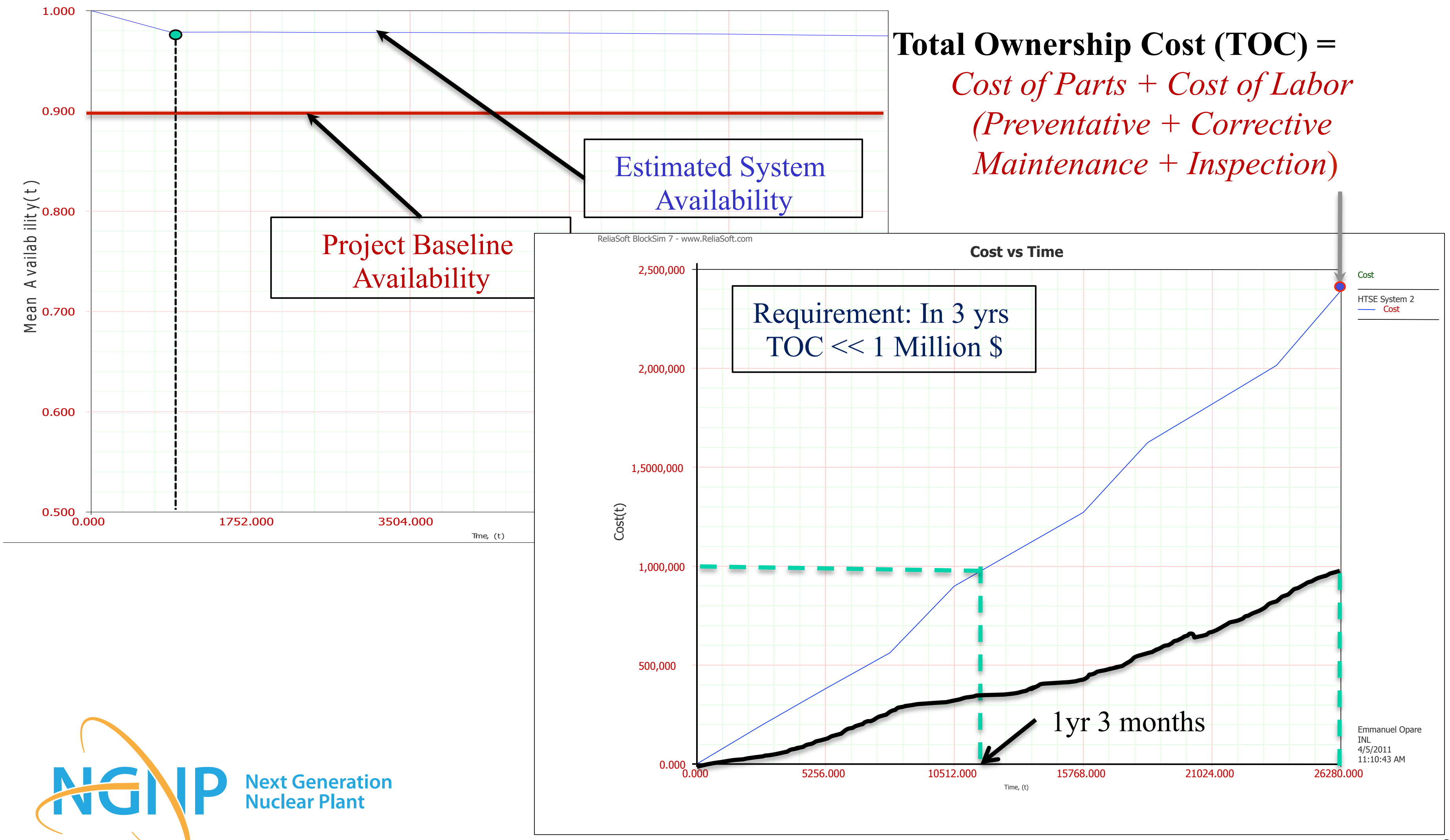


Translating What 96% Operational Availability Means for the Customer Can Influence Decision Making

Tradeoff Between TOC and Operational Availability

Total Ownership Cost (TOC) =

Cost of Parts + Cost of Labor (Preventative + Corrective Maintenance + Inspection)



Estimated System Availability

Project Baseline Availability

ReliaSoft BlockSim 7 - www.ReliaSoft.com

Requirement: In 3 yrs TOC << 1 Million $

1yr 3 months

Emmanuel Opare
INL
4/5/2011
11:10:43 AM

Verification Process Using RAM Simulation

1. Define requirements and decide method to verify requirements
2. Write system description document
3. Define system boundary
4. Perform functional decomposition of system
5. Select appropriate RAM tool
6. Collect appropriate data
7. Compute and verify system RAM against requirements
   - Optional: External certification
8. Communicate results to stakeholders and decision makers

Take Away

- Use RAM simulation to:
  - Identify tasks to enhance roadmap and reduce risk
  - Inform concept selection by estimating system TOC impact on enterprise
  - Verify and provide basis to inform system performance

NGNP
Next Generation
Nuclear Plant

Contact:

emmanuel.opare@inl.gov

208.526.0189

Charles.park@inl.gov

208.526.1091

Idaho National Laboratory

Best References

- **Practical Reliability Engineering 4th Edition,** Patrick O' Connor, David Newton, and Richard Bromley. John Wiley & Sons Inc, 2002.

- **System Analysis, Design, and Development: Concepts, Principles, and Practices**, Wasson, Charles. John Willey & Sons Inc, 2006. 615-49.

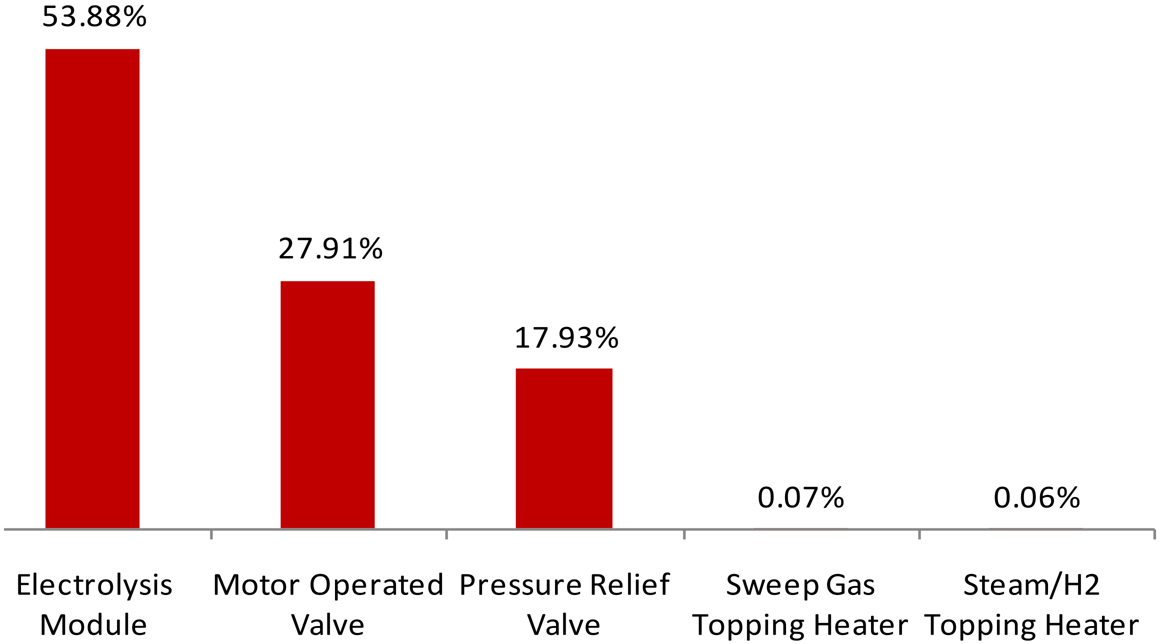
- **Engineering robust designs with Six Sigma Creveling**, Clyde, Jeff Slutsky, Dave Antis, Clyde Creveling, and John Wang. Prentice Hall, 2005. 449-66,687-705.

- **Department of Energy Office of Field Management/Office of Project and Fixed Asset Management**, Good Practice Guide: RMA Planning. GPG-FM-004. 1996.

- Fundamentals of Design For Reliability, ReliaSoft RS 560 Training.

Doubling Cell Reliability Does Not Meet Target Operational Availability (90%) at TRL 10

- Remedy
  - Redundancy in module design and/or address other big hitters



RAM Verification Ensures the System is Built Right and Meets Customer RAM Expectations

- Systems Engineering role in RAM analysis is to:
  - Represent the voice of the customer in the design and fabrication process and not to replace the designer

- SE performs RAM verification throughout design cycle to:
  - Ensure system is built right and will satisfy customer requirements
  - Highlight the consequence of not addressing RAM
  - Relate customer system/product needs to enterprise bottom-line
  - Communicate potential barriers to achieving target metrics
  - Inform system design and development

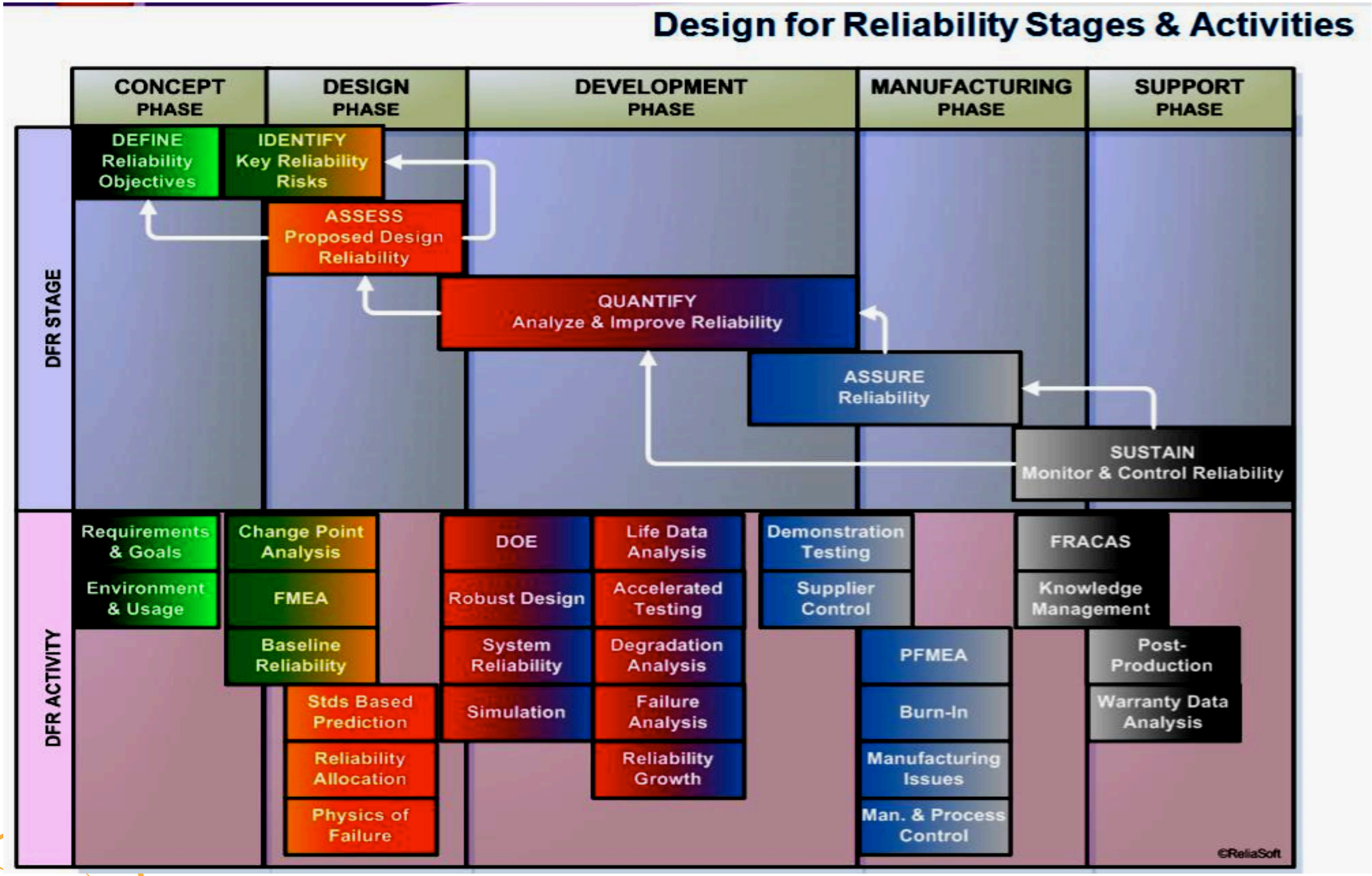
Project Outcome

- Identify components that required significant research and development (R&D)
- Identified performance targets to be achieved as the system matures
- Identify design data needs (DDNs)
- Identify components requiring redundancy
- Clarify funding allocation as system transitions from TRL4 – TRL 5
- Enabled near- and long-term cost and schedule planning

RAM Analysis Data Sources

- GENERIC, Component Failure Database for Light Water and Liquid Sodium Reactor (EGG-SSRE-8875-1990) (EGG-1990)
- Nuclear Computerized Library for Assessing Reactor Reliability (NUCLARR)
- Industry-Average Performance for Components and Initiating Events at U.S Commercial Nuclear Power Plants – 2006 (NUREG)
- Generic component reliability data for research reactor PSA, IAEA-TECDOC-930 (IAEA-930)

Verification Tools – One Tool Does Not Fit All



What RAM Activities Are Pursued @ Conceptual Phase ?

Design Phases	TRL	Criteria	High Level Concurrent RAM Activity
	1	Basic principles observed and reported.	
Planning	2	Technology concept and or application formulated.	Create a system's description document and gather relevant data for RAM analysis
Planning → Pre-conceptual	3	Analytical and experimental critical function and/or characteristic proof of concept: Lab level for pieces of components.	Define system RAM requirements, and develop RAM program plan
Pre-conceptual → Conceptual	4	Lab-scale component validation in lab environment: Demonstrate technical feasibility and functionality. Beginning of integration of some interfacing components into sub-assemblies.	Perform a high level RAM analysis to identify system risks and vulnerabilities and recommend improvement methods.
Conceptual → Preliminary Design	5	Lab-scale component or sub-assembly validation in relevant environment. Beginning of integration of sub-assemblies into sub-systems.	Perform a high level RAM analysis to identify system risks and vulnerabilities and recommend improvement methods.
Preliminary Design → Detail Design	6	Subsystem model or prototypical scale demonstration in relevant environment.	Repeat RAM analysis to mitigate system vulnerabilities and improve system RAM.
Detail Design → Fabrication/ Construction	7	Subsystem prototype demonstration in an operational environment. Beginning integration of subsystems into complete system.	Address all system vulnerabilities through RAM analysis to improve system RAM before construction and deployment. Verify that system RAM will not be compromised by manufacturing constraints.

Data Used – Error Factor of 10 -15%

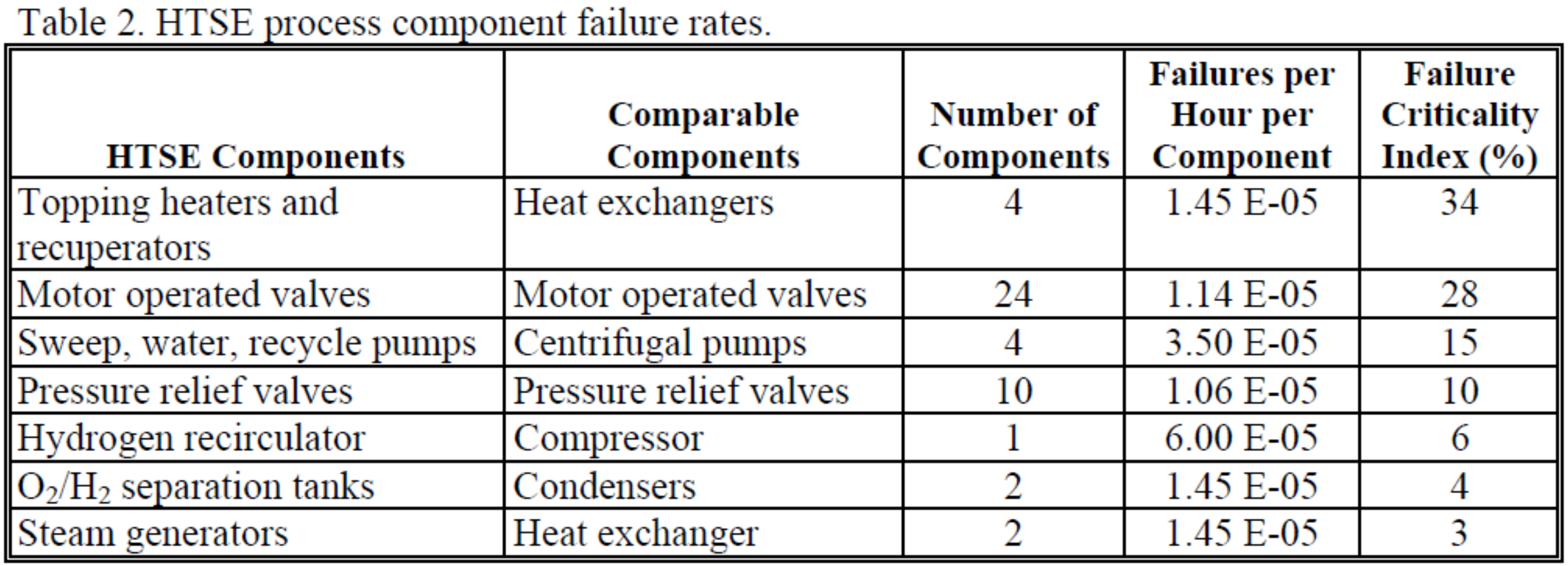


Table 2. HTSE process component failure rates.

HTSE Components	Comparable Components	Number of Components	Failures per Hour per Component	Failure Criticality Index (%)
Topping heaters and recuperators	Heat exchangers	4	1.45 E-05	34
Motor operated valves	Motor operated valves	24	1.14 E-05	28
Sweep, water, recycle pumps	Centrifugal pumps	4	3.50 E-05	15
Pressure relief valves	Pressure relief valves	10	1.06 E-05	10
Hydrogen recirculator	Compressor	1	6.00 E-05	6
O_2/H_2 separation tanks	Condensers	2	1.45 E-05	4
Steam generators	Heat exchanger	2	1.45 E-05	3

External Verification Data Source

- Savannah River Site Generic Data Base Development (WSRC-TR-93-262, REV. 1) dated May 1982.
  - These data represent large gas systems, both at nuclear power plants and from Savannah River Site systems, and provide a starting point for analyzing component reliability.
- A number of approximations were necessary in order to apply comparable failure data for existing components to future
- HTSE process components that have not yet been designed. Error factors for each of these failure rates is 10, which indicates a reasonable level of confidence.

TRL Definitions

TRL	Technology Readiness Level Definition	TRL Abbreviated Definition
1	**Basic principles observed** and reported in white papers, industry literature, lab reports, etc. Scientific research without well defined application.	Basic principles observed
2	**Technology concept and application formulated.** Issues related to performance identified. Issues related to technology concept have been identified. Paper studies indicate potentially viable system operation.	Application formulated
3	**Proof-of concept:** Analytical and experimental critical function and/or characteristic proven in laboratory. Technology or component tested at laboratory scale to identify/screen potential viability in anticipated service.	Proof of Concept
4	**Technology or Component is tested at bench scale to** demonstrate technical feasibility and functionality. For analytical modeling, use generally recognized benchmarked computational methods and traceable material properties.	Bench scale testing
5	**Component demonstrated at experimental scale in relevant environment**. Components have been defined, acceptable technologies identified and technology issues quantified for the relevant environment. Demonstration methods include analyses, verification, tests, and inspection.	Component Verified at Experimental Scale

TRL Definitions

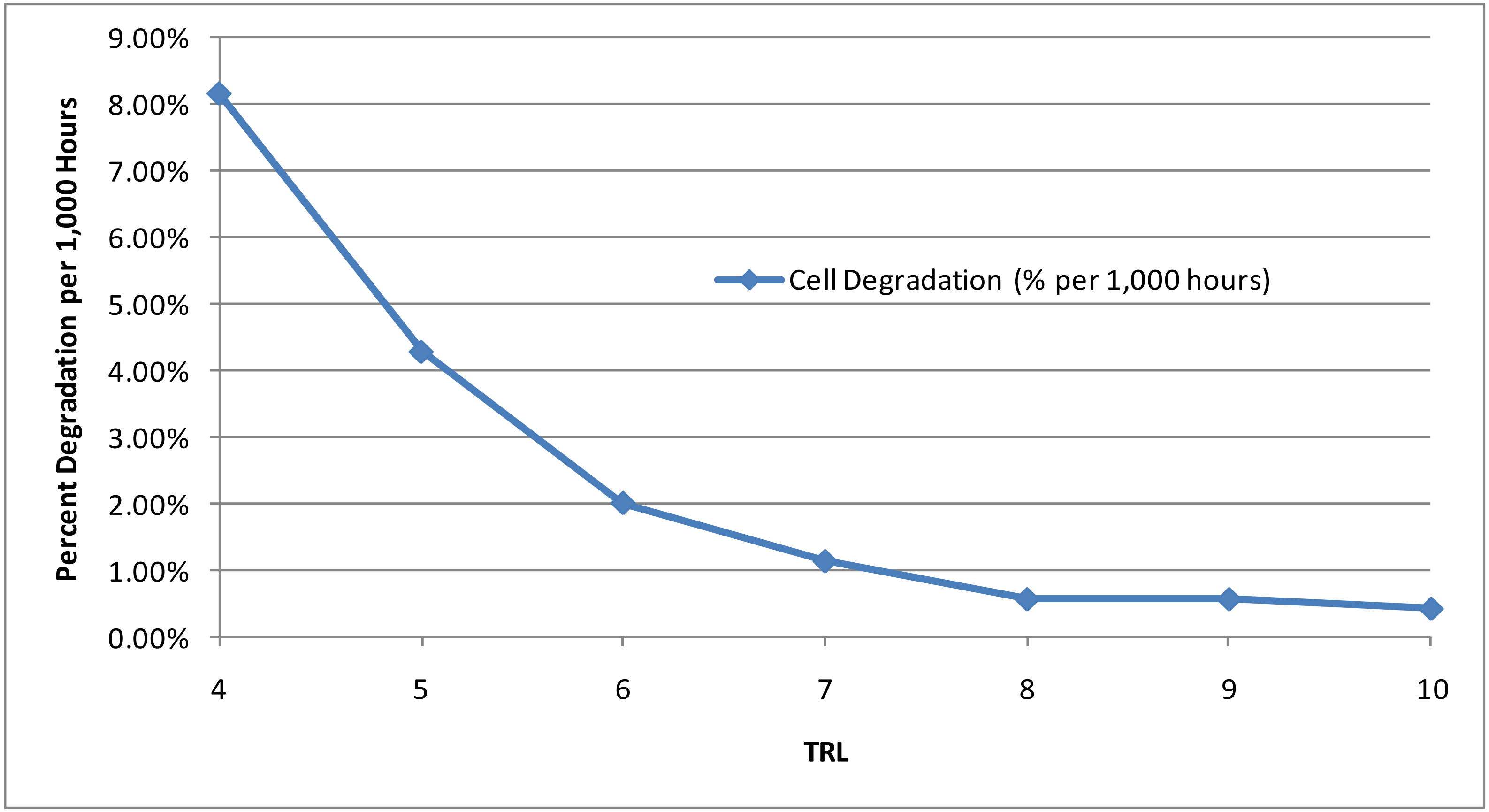
6	**Components have been integrated into a subsystem** and demonstrated at a pilot scale in a relevant environment.	Subsystem Verified at **Pilot scale**
7	**Subsystem integrated into a system** for integrated engineering scale demonstration in a relevant environment.	System demonstration at **Engineering Scale**
8	**Integrated prototype of the system is demonstrated** in its operational environment with the appropriate number and duration of tests and at the required levels of test rigor and quality assurance. Analyses, if used support extension of demonstration to all design conditions. Analysis methods verified and validated. Technology issues resolved pending qualification (for nuclear application, if required). Demonstrated readiness for hot startup	Integrated Prototype Tested and Qualified
9	**The project is in final configuration** tested and demonstrated in operational environment.	Plant Operational **NGNP, First of a kind (FOAK)**
10	**Commercial-scale demonstration** is achieved. Technological risks minimized by multiple units built and running through several years of service cycles.	**Commercial** Scale – Multiple Units **Nth of a kind (NOAK)**

Action To Be Taken To Address System Vulnerability Issues

Near-term needs include:

- Resolve cell delimitation issues
- Demonstrate SOEC performance at pressure
- Select a cell configuration and size
- Select balancing gas and use strategy
- Select air or steam sweep
- Select and procure a cell fabricator from industry
- Demonstrate increased cell area size
- Procure cells/stacks for testing in a pilot plant
- Design and build a pilot scale test facility

Target Cell Degradation for Future TRL Maturation



Assumptions For HTSE

1. The HTSE operating environment is similar to the operating environment of current high-temperature industrial processes and the failure data for similar components can be used
2. Subsystems and components are mature technologies, except the SOECs
3. Components developed by NGNP (generally for higher temperature and pressure) can be used for HTSE. Some R&D for high temperature oxygen and hydrogen handling will be required.
4. When one of the component types fails, the entire HTSE system fails because this initial analysis includes no redundancy (this is the customary assumption when analyzing systems prior to the completion of a pre-conceptual design)
5. When HTSE is down, the maintenance crew responsible for restoring the system to full operation will be well trained and able to restore the system within an acceptable time
6. Spares parts are available upon system failure
7. When failed parts are replaced, the entire system will be good as new
8. Target availability for NGNP systems is 83%
9. Failure distribution for the components does not include premature failures during the early stages of the system’s operation
10. SOEC module failure occurs when hydrogen production decreases to 70% of capacity
11. Failure rates of mature SOECs (TRL-10) will be similar to failure rates for mature solid oxide fuel cells (SOFCs). Modules will be replaced every 6 years.
12. Current SOECs (TRL-4) are expected to have a useful life of about 9 months (6,000 hours). Subsequent failure rates will be reduced by ½ (or performance duration doubled) at each of the subsequent TRL levels.
13. SOEC modules will be “replaced” by switching a valve resulting in no operational downtime

What is Project Risk?

- Includes Technical & Programmatic Risk

$$R = \underbrace{(P_e \text{ x } P_c)} \text{ x } C$$

Indicates
“How risky is it?”

Risk
Likelihood

Loss if risk
occurs

Consequence Definition

Consequence	Technical	Schedule	Use for calculation (risk units)
Negligible	Minimal or no impact	Schedule delays that do not affect milestones or the critical path	**1**
Marginal	Small change needed to design or path forward. Minor damage to equipment or facilities. Minor, temporary loss of capabilities.	Schedule delays that may affect external milestones or are threatening a slip along the critical path	**3**
Significant	Moderate change needed to design or path forward. Moderate, but repairable damage to equipment or facilities. Moderate, temporary loss of capability.	Schedule delays that will slip the critical path end date by up to 6 months	**5**
Critical	Major change needed to design or path forward, workaround available. Significant, repairable damage to equipment or facilities.	Schedule delays that will slip the critical path end date by more than 6 months but less than 1 year	**7**
Crisis	Major change needed to design or path forward, no workaround available now. Loss of equipment or facilities.	Schedule delays that will slip the critical path end date 1 year (schedule slips in excess of 1 year are anticipated to cause a loss of the program)	**9**

Next Generation Nuclear Plant

Probability Definition

Probabilities	Range	Technology Criteria	Scale Criteria	Use for calculation
Beyond Design Basis	$< 10^{-4}$		Not evaluated since it is beyond the basis of the design	**N/A**
Very Unlikely	10^{-4} to 0.1%	Technology are well understood and are routinely used in similar, integrated applications and conditions.	The scale of the system/component needed is similar to existing successful applications.	**0.1**
Unlikely	**0.1% to 1%**	Technology is understood and has been used in applications and conditions close to, but not identical to required conditions. A small amount of development needed before deployment.	Majority of the components are similar in scale to existing applications.	**0.3**
Somewhat Likely	**1% to 10%**	Technology needs a moderate amount of research, development, and design before deployment at required operating conditions.	About half of components are similar in scale to existing applications.	**0.5**
Likely	**10% to 50%**	Technology needs a major amount of research, development, and design before deployment at required operating conditions.	Some of the components are scaled similar to existing applications, with the remainder needing significant design changes to achieve deployment.	**0.7**
Very Likely	**> 50%**	Low maturity; complex, unclear development path; multiple unproven technologies must work together.	All components needed have never been attempted at the necessary scale.	**0.9**

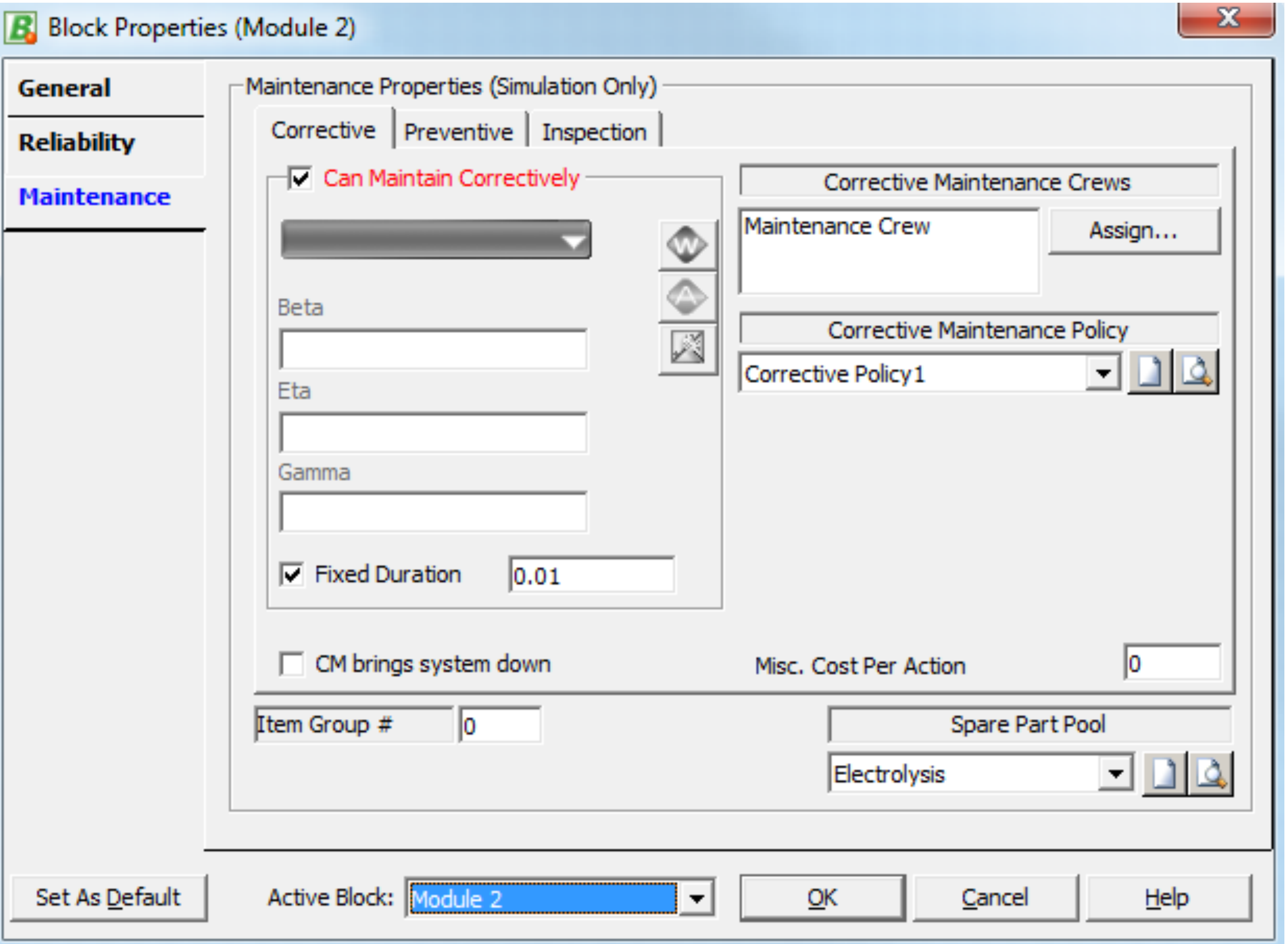
Risk = Probability X Consequence

Probability

	Negligible	Marginal	Significant	Critical	Crisis
Very Likely	**Low 0.9**	**Moderate 2.7**	**High 4.5**	**Very High 6.3**	**Very High 8.1**
Likely	**Low 0.7**	**Moderate 2.4**	**High 4.4**	**Very High 6.1**	**Very High 7.9**
Somewhat Likely	**Low 0.5**	**Moderate 1.9**	**High 3.8**	**High 5.3**	**Very High 6.8**
UnLikely	**Very Low 0.3**	**Low 1.2**	**Moderate 2.6**	**High 4.2**	**High 5.4**
Very Unlikely	**Very Low 0.1**	**Low 0.5**	**Low 1.0**	**Moderate 1.8**	**Moderate 2.7**

Consequence

BlockSim Maintenance Tab



Block Properties (Module 2)

- **General**
- **Reliability**
- **Maintenance**

Maintenance Properties (Simulation Only)

Corrective | Preventive | Inspection

☑ Can Maintain Correctively

Beta

Eta

Gamma

☑ Fixed Duration 0.01

Corrective Maintenance Crews: Maintenance Crew

Corrective Maintenance Policy: Corrective Policy1

☐ CM brings system down

Misc. Cost Per Action 0

Item Group # 0

Spare Part Pool: Electrolysis

Active Block: Module 2