A RISK ANALYSIS OF THE MOLYBDENUM-99 SUPPLY CHAIN USING BAYESIAN NETWORKS

2017 Mo-99 Topical Meeting

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OVERVIEW

- Motivation
- Background and Problem Description
- Research Questions and Limitations
- Methodology
- Findings
- Conclusions and Future Recommendations

MOTIVATION

- Subject for Dissertation, focusing on Engineering Management
- National Research Universal (NRU) reactor ceased production of Molybdenum-99 (^{99}Mo) in Oct 2016
  - Represents 19% of global ^{99}Mo production
  - Only producer in North America
- Effects of the NRU shutdown on the ^{99}Mo supply chain is the subject of debate
  - National Academy of Sciences: “>50% likelihood of severe shortages”
  - Nuclear Energy Agency: “supply chain capacity should be sufficient”
- Majority of the remaining reactors are over 45 years old

METHODOLOGY

- Bayesian Network
  - Each risk or performance measure is represented as an event
  - Captures the likelihood of a given chain of events occurring
  - Allows for back-propagation to see what parent events caused an outcome

- Modeled Reactor to Processor section of the supply chain
  - Once processed into Generators, ^{99}Mo can be shipped anywhere by air
  - Each reactor and processing facility was a node in the network
  - Quantity of ^{99}Mo produced or processed was the outcome of each node

WHAT IS A BAYESIAN NETWORK?

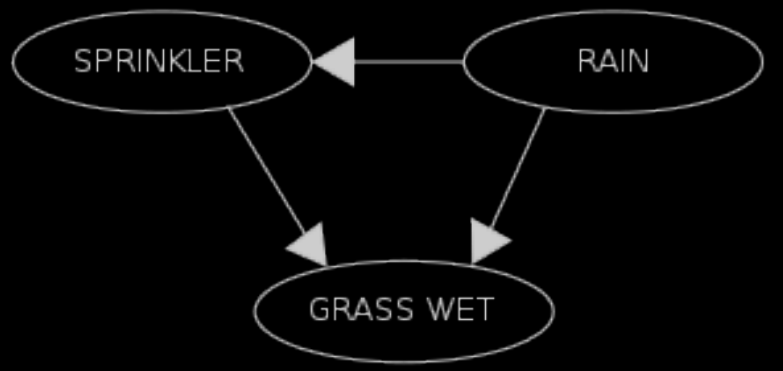
- Extension of Bayes' Theorem, which represents the probability of a hypothesis occurring after considering the effect of evidence on past experience
  - Provides a way to combine both evidence and subjective beliefs
  - Particularly useful in situations where there is a high degree of uncertainty

- The network consists of nodes and arcs
  - Each node represents variables; each arc denotes parent-child relationships
  - Each node has a conditional probability table that lists each of the different combinations of values from parent nodes and the probabilities of that outcome occurring

BAYESIAN EXAMPLE

- 20% Chance of Rain
- If it is not raining, the sprinklers are set to turn on 40% of the time
- If it rains, there is a 1% chance the rain sensor will fail and the sprinkler will still activate
- What is the probability the grass will be wet at any given time?

	SPRINKLER	
RAIN	T	F
F	0.4	0.6
T	0.01	0.99

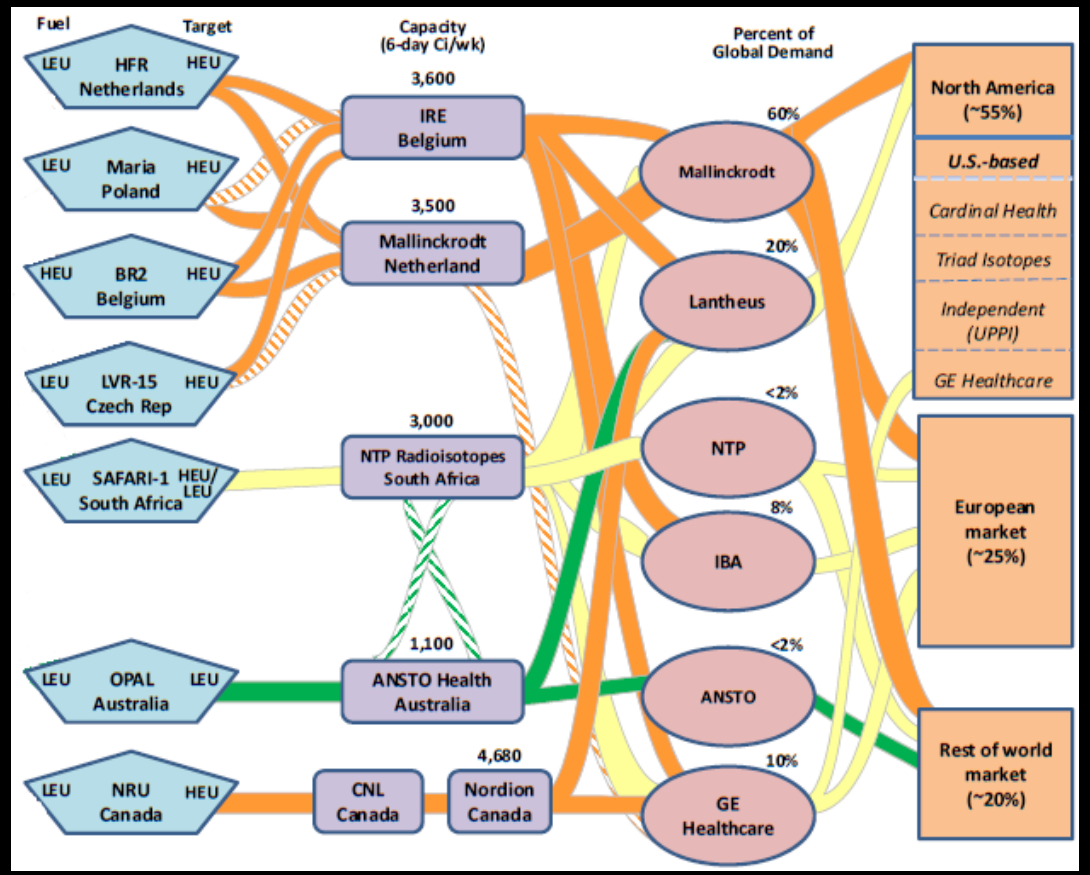


RAIN	
T	F
0.2	0.8

		GRASS WET	
SPRINKLER	RAIN	T	F
F	F	0.0	1.0
F	T	0.8	0.2
T	F	0.9	0.1
T	T	0.99	0.01

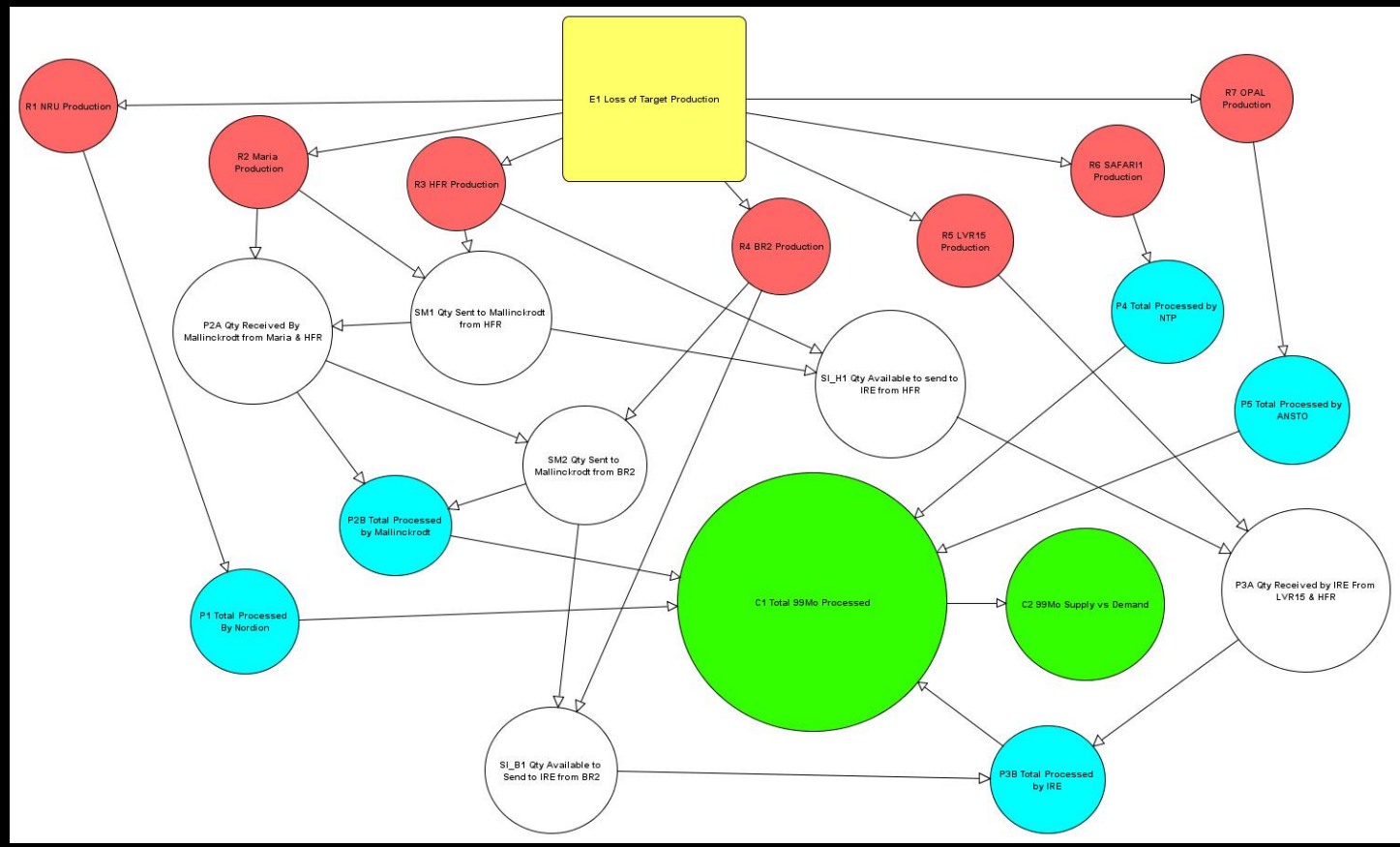
NETWORK DIAGRAM

Mo-99 Supply Chain



Reprinted from “Molybdenum-99 for Medical Imaging” (p. 53), by the National Academies of Sciences, Engineering, and Medicine, 2016, Washington, DC: The National Academies Press.

Bayesian Network Model



LIMITATIONS

- Could not access business-specific operating information
  - Proprietary Information
  - Reactor scheduling or production decisions
  - Processor sourcing decisions
  - Does not include actual vs planned operating data

- Impact on Model
  - Used typical number of operating days to calculate probability of operating
  - Model is focused on determining probability of final production levels
    - Not a system dynamics or stock-and-flow model
    - Does not illustrate how companies would choose where to ship

PROBABILITY TABLES

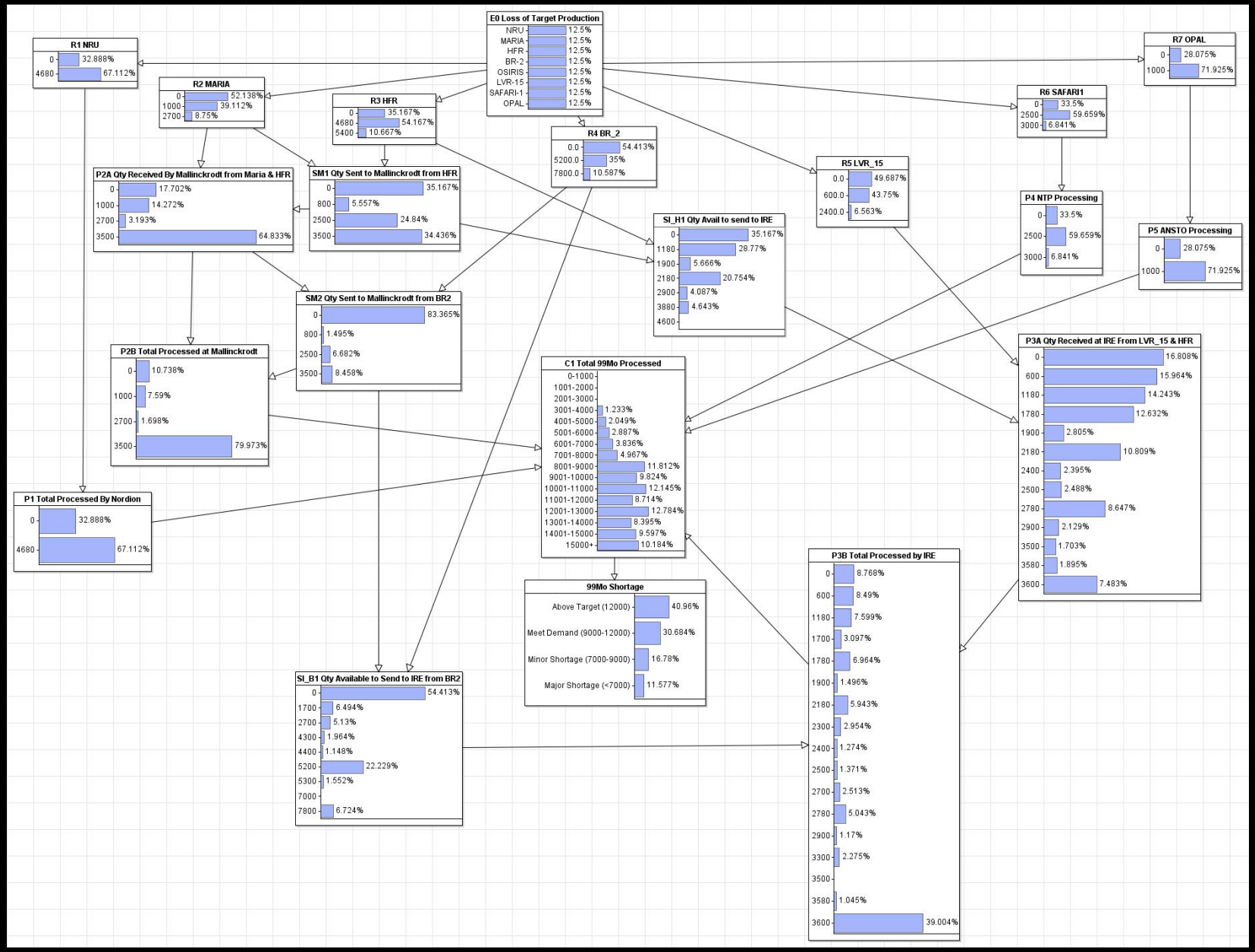
Reactor	Normal Production		Maximum Production	
	Value	Probability	Value	Probability
NRU	0	23.29%	0	23.29%
	4680	76.71%	4680	76.71%
Maria	0	45.21%	0	45.21%
	1500	54.79%	1500	0.00%
	2700	0.00%	2700	54.79%
HFR	0	27.12%	0	27.12%
	4680	72.88%	4680	0.00%
	5400	0.00%	5400	72.88%
BR-2	0	47.95%	0	47.95%
	5200	52.05%	5200	0.00%
	7800	0.00%	7800	52.05%
LVR-15	0	42.67%	0	42.67%
	600	57.33%	0	0.00%
	2400	0.00%	2400	57.33%
SAFARI-1	0	16.44%	0	16.44%
	2500	83.56%	2500	0.00%
	3000	0.00%	3000	83.56%

- Each reactor node's probability table was based on:
  - Normal operating level
  - Maximum operating level
  - Number of operating days per year

- Not meant to be an accurate model of actual production levels
  - Illustrates the validity of using Bayesian Networks
  - Quantify risk in the supply chain
  - The data in the tables can be updated with more accurate data

Complete Bayesian Network

- Determines the probability of different levels of Mo-99 production in the supply chain
- Allows for "what-if" scenarios
  - What if reactor X has unscheduled downtime?
- Enter an outcome and find the root cause
  - If a major shortage took place, what node(s) were the likely root cause(s)?



SCENARIOS

- Prior to NRU Production Cessation
  - Probability of shortages with normal and maximum production rates

- After NRU Production Cessation
  - Probability of shortages with normal and maximum production rates
  - Probability of shortages if another reactor goes offline
  - Root Causes of a major or minor shortage

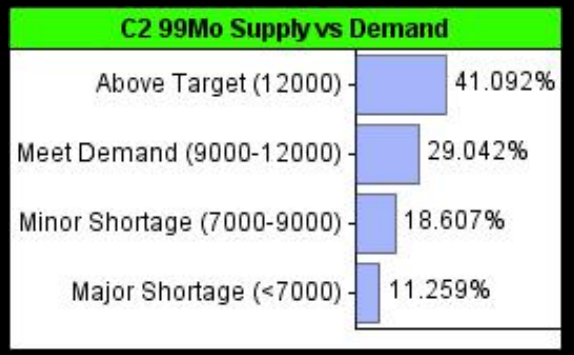
FINDINGS

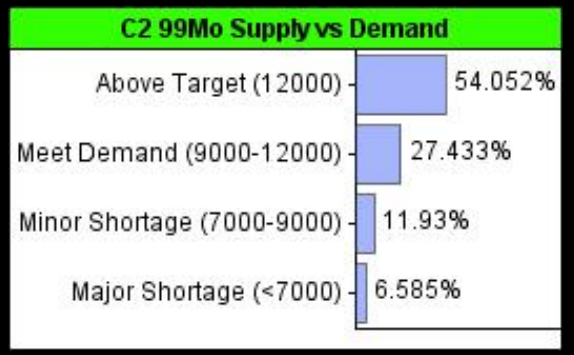
- Supply chain can meet demand after NRU shutdown, but reactor coordination will be critical
- Very difficult to handle additional unscheduled outages

Normal Production

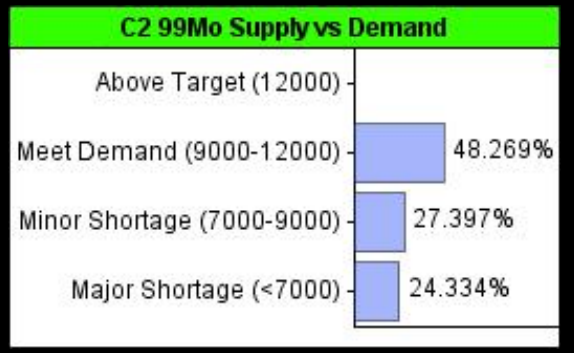
Maximum Production

Pre-NRU Cessation





Post-NRU Cessation



ROOT CAUSE ANALYSIS

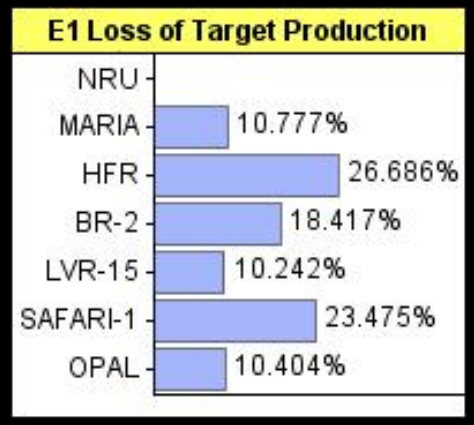
- HFR is largest source of risk
  - Not largest producer
  - Longest operating period
- SAFARI-1 has significant impact despite being mid-level producer
  - Single supplier to NTP
  - Loss of entire NTP supply

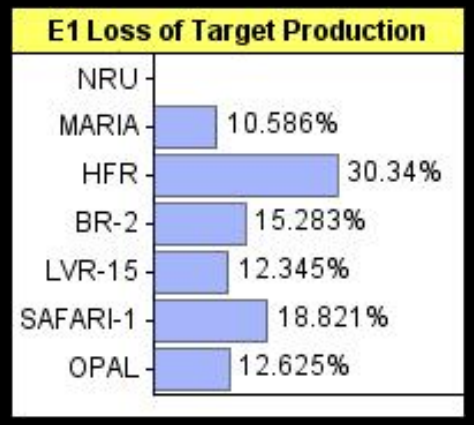
Normal Production

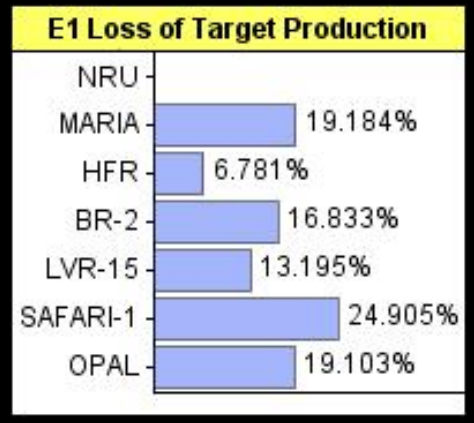
Maximum Production

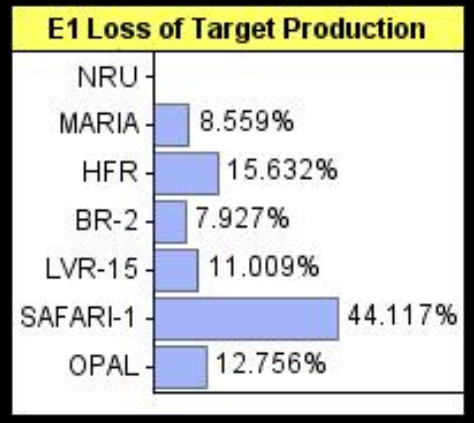
Major Shortage

Minor Shortage









CONCLUSIONS

- Theoretically there is enough production capacity in other reactors to compensate for the loss of NRU, but there are significant sources of risk:
  - Processing facilities do not have the capacity to processing more targets
  - Multiple processing facilities can only be supplied by one reactor

- Results are a middle ground between NASM and NEA assessments
  - 24% chance of major shortage (NASM: >50%, NEA: no impact)
  - Operating schedule is just as important as production capacity
  - SAFARI-1 and NTP will guarantee a shortage if offline

CONTRIBUTIONS/FUTURE WORK

- Contributions
  - Existing assessments focused on only maximum production scenarios
  - Prior studies do not quantify the risk each node introduces
  - Prior work did not quantify probability of shortages based on different reactor outages

- Future Work
  - Extending the model
    - Different production levels for reactors
    - Incorporate actual scheduling/coordination
    - Real-time decision making tool
  - Geographic analysis of facility locations
    - Where to build new facilities mitigate the most risk
    - Which facilities are best suited for adding capacity

QUESTIONS?