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Tritium Production Assurance

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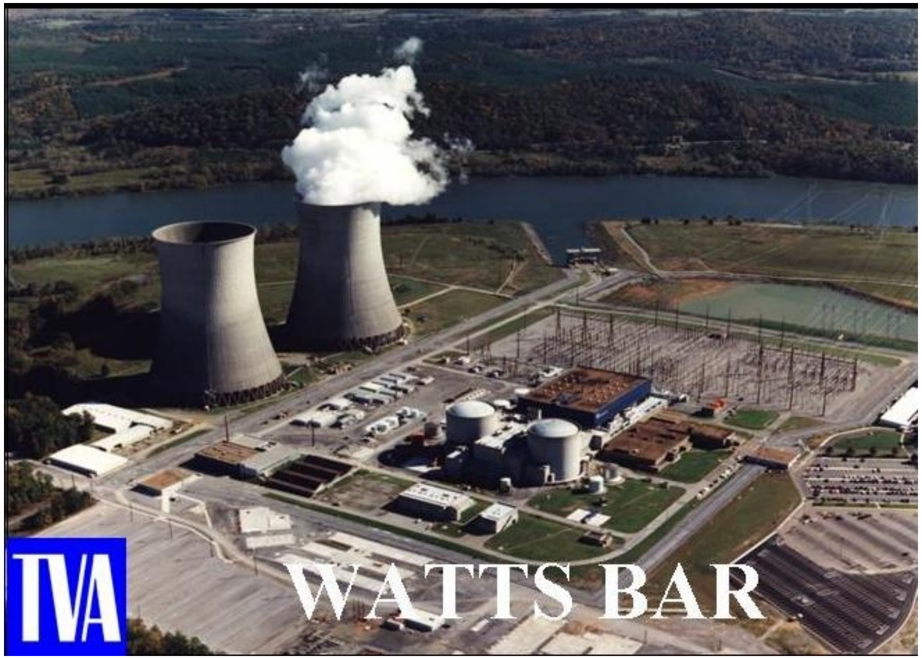
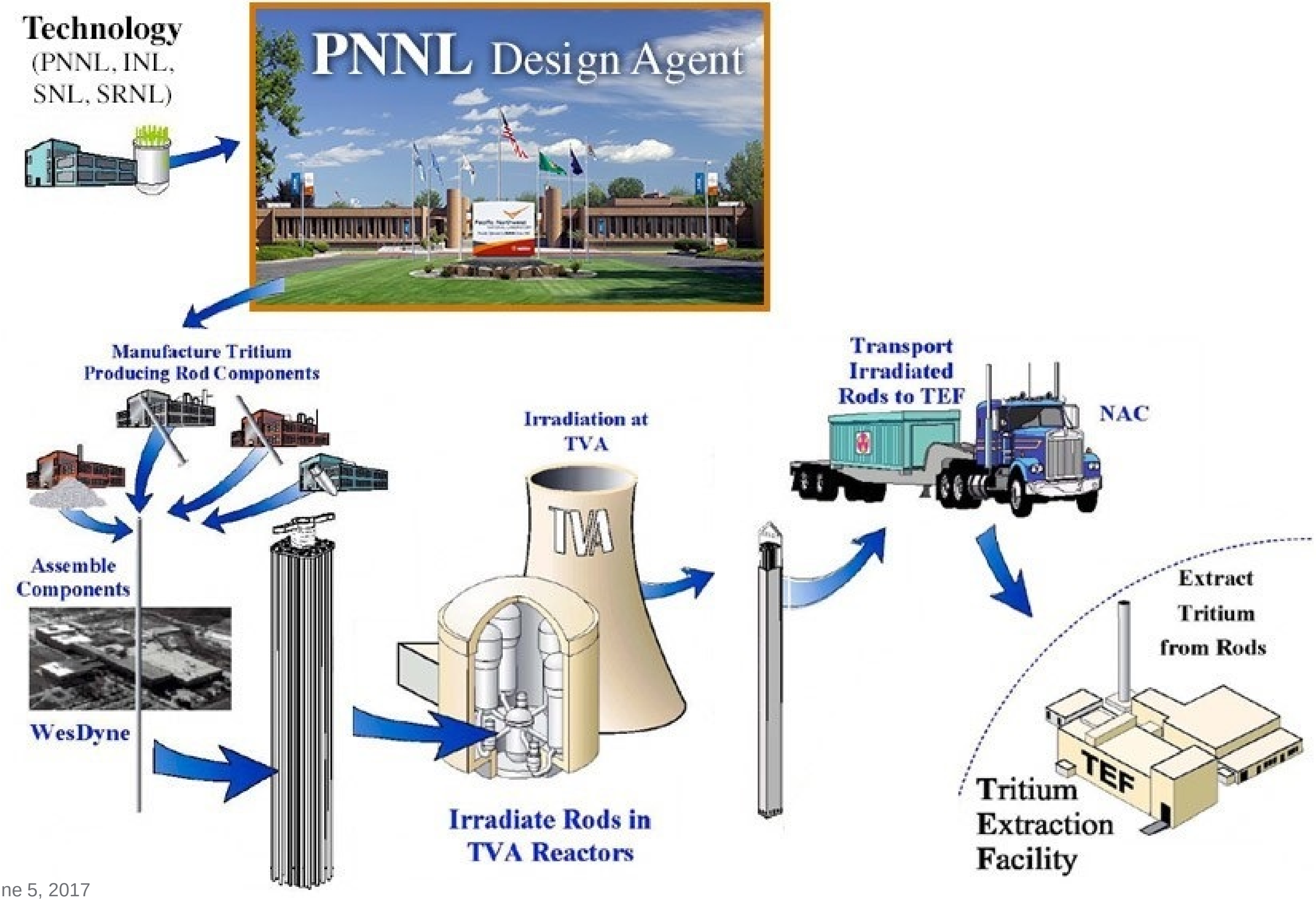
Production for NNSA Tritium Sustainment Project

- Tritium for U.S. defense was produced in heavy water reactors at Savannah River until 1988
- As a result of the Strategic Arms Reduction Treaty signed in 1991, Cold War tritium stockpiles were adequate to maintain the U.S. arsenal for many years
- U.S. tritium production restarted in 2003 with 240 TPBARs in Unit 1 of the Watts Bar Nuclear Generating Station
- Production is currently ramping up to a level that can sustain projected U.S. defense needs in coming decades



NNSA Tritium Production Team



Production Assurance

- The Tritium Sustainment Project requires complex scheduling and coordination
- The ramp to full production is resulting in a few implementation issues that must be overcome
- “Production Assurance” refers to planning, communication, and risk mitigation activities to ensure that projected tritium needs at a given point in the future will be met by the supply
- This presentation will focus on evaluation of ramp-up strategies in light of previous experience

WBN1	WBN2	Current Plan	
Cycle	Cycle	WBN1	WBN2
14	1	704	0
15	2	1104	0
16	3	1408	0
17	4	1552	704
18	5	1504	1104
19	6	1504	1504
20	7	1504	1504
21	8	1504	1504

Production Assurance Goals

- Develop a better understanding of factors affecting production
  - Analyze historic tritium production to provide a basis for estimating the potential for meeting future needs based on past performance
    - It is recognized that the past provides no guarantee for the future
  - Better evaluate the risks that can affect production to better understand their potential effect on production
    - Fabrication, irradiation, extraction, and programmatic risks characterized
- Develop a method to provide a measure of the confidence DOE should have in production proposals/assumptions
- Use the evaluations to guide generation of options and cost/benefit analyses that can guide DOE in their decision making to improve production outcomes

Tritium Production 2003-2017

WBN1 Cycle	Number of TPBARs	Actual Cycle Burnup as a Percentage of Maximum Design Cycle	Average Tritium Production (grams T/rod)	Tritium Production If Maximum Burnup was Achieved (grams T/rod)
C6	240	90.7%	0.974	1.074
C7	240	90.8%	0.972	1.070
C8	240	91.8%	0.911	0.993
C9	368	88.3%	0.949	1.075
C10	240	95.5%	1.000	1.048
C11	544	83.1%	0.893	1.074
C12	544	90.8%	0.996	1.097
C13	704	93.4%	0.980	1.050
C14	704	87.4% *	0.864 *	0.919 *
	Average	90.2%	0.949	1.044
	Std. dev	3.58%	0.0484	0.0554

* Estimates for recently completed C14

- Projected per-TPBAR production at maximum burnup must be below the 1.2 g limit at maximum cycle length
  - Uncertainties must be factored in
- Production in previous cycles used to estimate probable future production
- Use of the average results in consideration of operational, technical and programmatic issues

Methodology for Production Forecasts

5% and 95% probability prediction interval for future production in two reactors =

$$(N+M)\bar{p} \pm t_{0.95,n-1} S_0 \sqrt{N^2 + M^2 + \frac{(N+M)^2}{n}}$$

$$\bar{p} = \frac{1}{n}\sum_{i=1}^{n} \frac{P_i}{N_i}$$

$$S_0^2 = \frac{1}{n-1}\sum_{i=1}^{n}\left(\frac{P_i}{N_i} - \bar{p}\right)^2$$

Where:

N = number of TPBARS in a future cycle or a given historic cycle i

$\bar{p}$ = historic average per-TPBAR tritium production

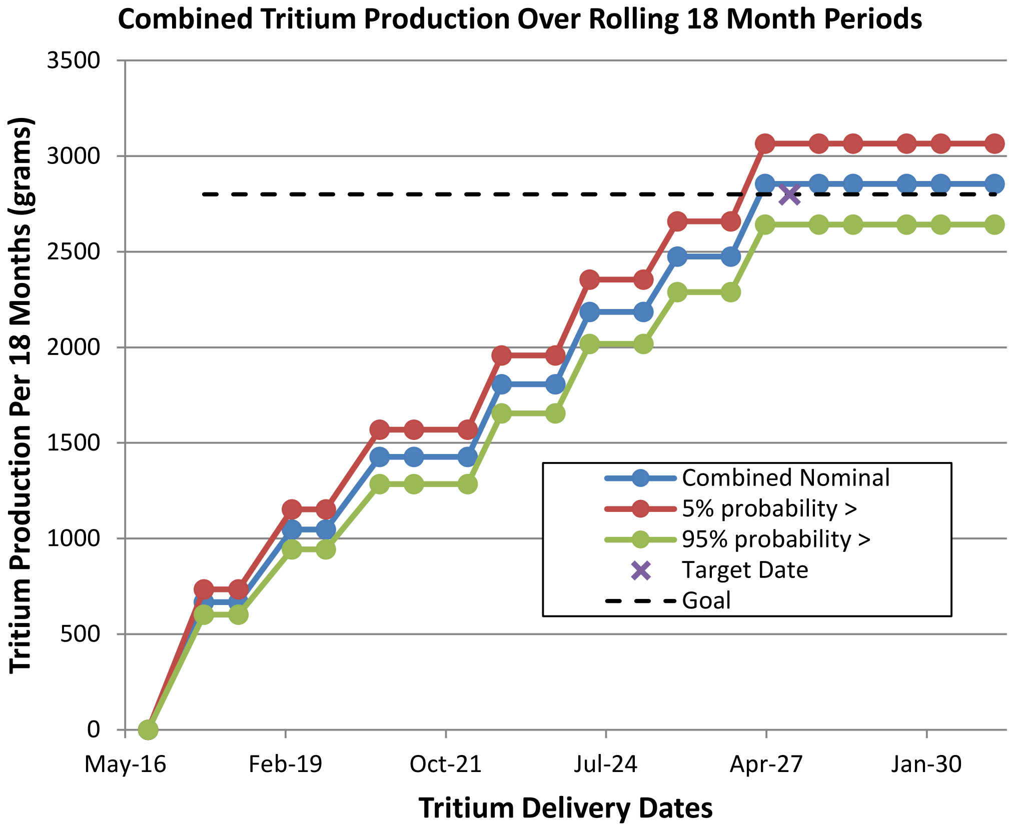
$t_{0.95,n-1}$ = probability point of t distribution

n = sample size (number of previous cycles)

S_0 = unbiased estimator of variance (standard deviation)

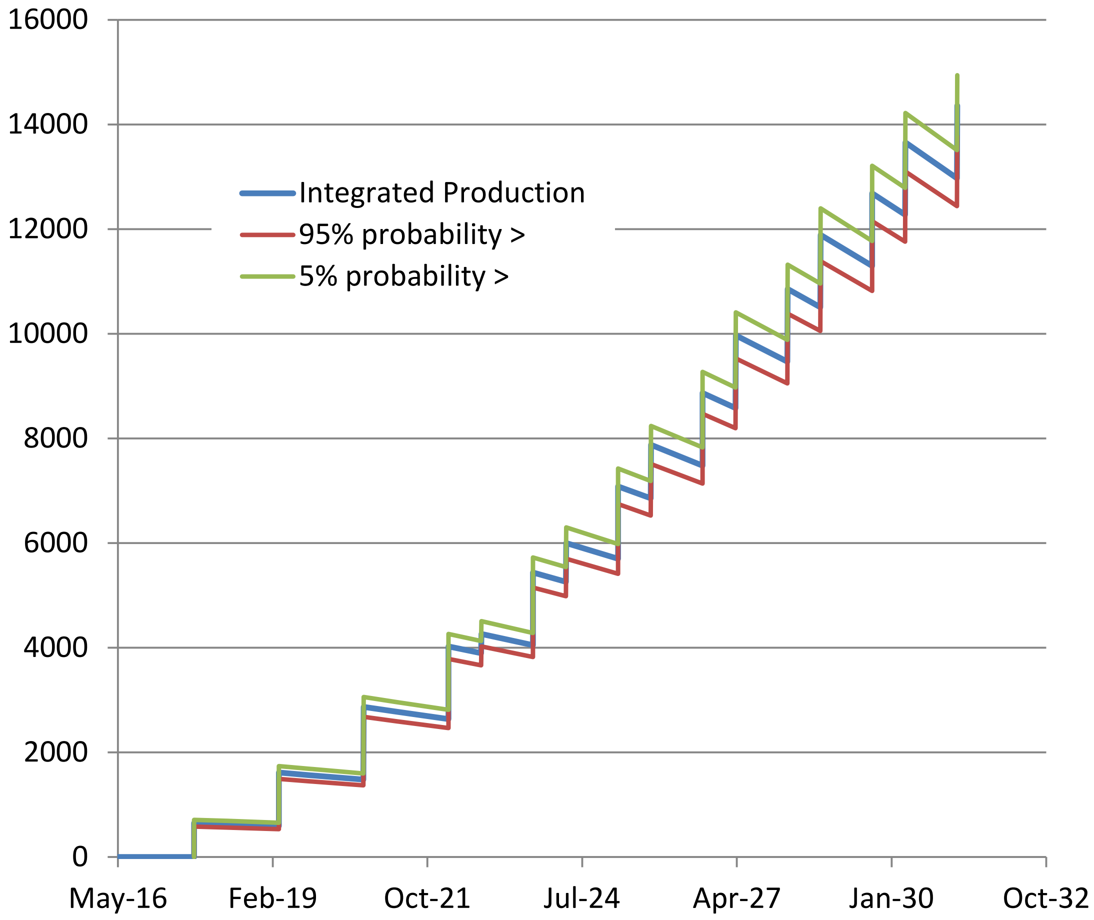
- Splitting production between two reactors will even out high and low production cycles to some extent - reducing variability of total production
- A similar calculation is used to combine variability between multiple cycles, as total production is integrated over time
- Major caveats:
  - Assumes previous production is representative of future
  - Upsets such as long outages or interruptions in TPBAR supply not included

Forecast for Notional Schedule



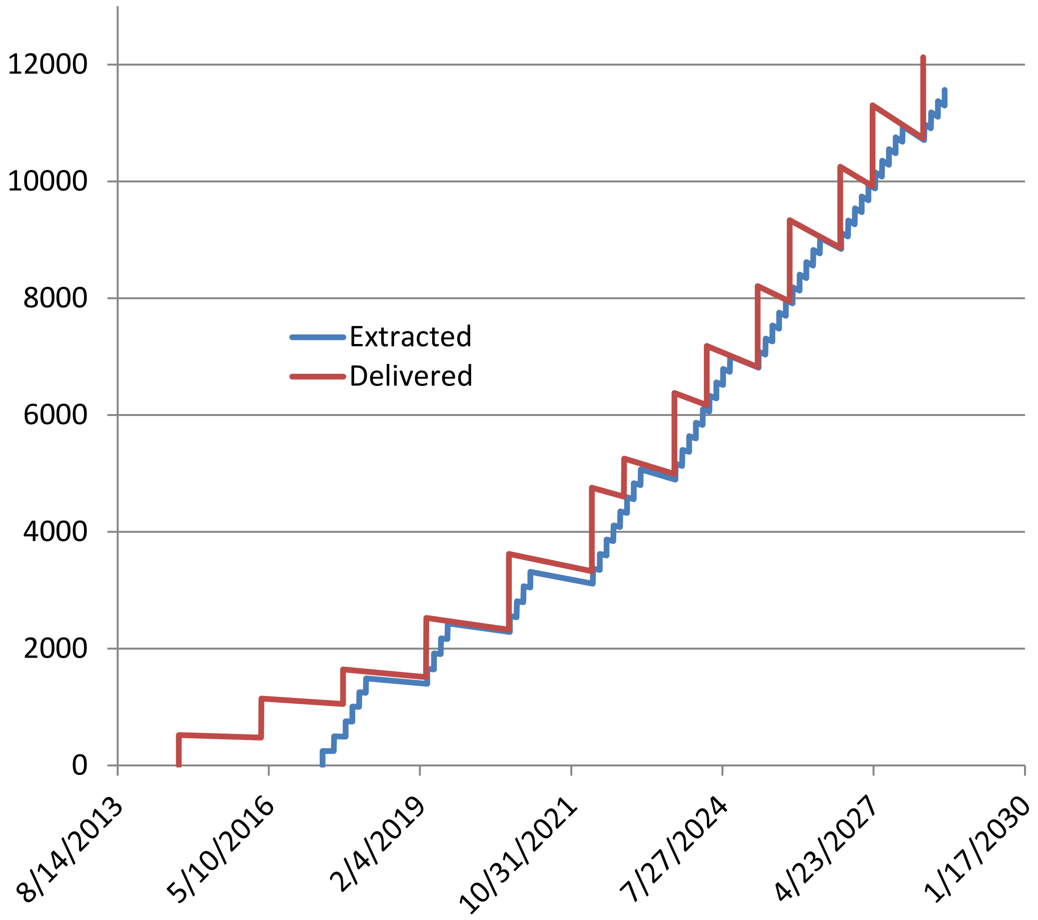
- Tritium is assumed to be "delivered" six months after the end of each cycle, when it is available for extraction
- Probability of reaching the 2800 gram goal is 67.7%, assuming historic production is representative
- Measures to increase per-TPBAR production above the historic average could increase confidence in meeting the goal

Integrated Production



- Success of mission is ultimately determined by the ability to provide required total quantity of tritium when it is needed
- Integrated curve shows decay of previously produced tritium and injections after each production cycle
- Uncertainty in predicted total increases with size and number of contributing cycles

Extraction Schedule



- Timing of actual tritium availability will also depend upon operation of the Tritium Extraction Facility
- Schedule shown assumes:
  - 300 TPBARS per consolidation container
  - 7 day transit time to TEF
  - 45 days per extraction
- Would allow ~140 day outages every 18 months for scheduled maintenance, etc.

Analysis Results and Mitigating Actions

- The analysis shows that the likelihood of making the needed tritium quantity is high, but the confidence isn't high enough (95% confidence desired) and there are known issues on the horizon
  - Programmatic and operational issues resulted in less tritium than desired in WBN1 C14 and will likely result in less than desired in C15
  - Operational issues will limit tritium production in WBN1 C16
  - Based on current information, DOE wants as much tritium as possible as early as they can get it
- To mitigate these issues, efforts are being made to increase tritium production in the short term
- One obstacle identified was that the wording used formerly to specify the tritium need was being interpreted differently by various stakeholders

Tritium Specification

- DOE desires sufficient TPBARs to produce 2800 grams of tritium in TVA reactors by end of FY2025, but also requires certain quantities during the ramp
- Problem: How to specify production to meet requirements, given practical constraints and operational flexibility needed for nuclear power generation, and to clearly convey the need to multiple stakeholders
  - Necessity to ensure with high confidence that ramp and steady state meet the need
  - Core design and operations
    - Primary mission is to meet the energy production need
    - Plan for reactivity, limitations on numbers and placement of TPBARs
    - Account for possibility of outages, reduced power operation
  - Stakeholders:
    - Utility/core designers
    - Management
    - Congress
    - Weapon designers

Tritium Specification Solutions

- Tailor the messages to the specific stakeholders
- Root the specification in the desired tritium quantities and not in the number of TPBARs
- First step taken – define the minimum acceptable tritium production need in grams for each WBN1 and WBN2 cycle

Reactor	**Operating Cycle**	**Estimated Cycle Start**	**Minimum Production (grams of tritium)**
WBN1	C16	Fall 2018	1400
	C17	Spring 2020	1400
	C18	Fall 2021	1400
	C19	Spring 2023	1400
	C20	Fall 2024	1400
WBN2	C4	Fall 2020	375
	C5	Spring 2022	745
	C6	Fall 2023	1030
	C7	Spring 2025	1400
WBN1 WBN2	C21-C23 C8-C9	Rolling 18 months	2800 total both plants
WBN1 WBN2	C24-C29 C10-C16	Rolling 18 months	2800 total both plants

Increase Average Tritium Production per TPBAR

- Is it possible to increase average production per TPBAR? Yes!
  - WBN1 cycles 10/12 showed that it is achievable without significant optimization
- Likely reasons we didn't have higher production per TPBAR in the past:
  - TVA/Westinghouse were told to irradiate a number of TPBARs
    - No specification for the *amount* tritium desired
    - No optimization on tritium production
  - Core designs needed to accommodate the available lithium loadings; limited flexibility in loading does not easily allow for production optimization
  - Operational variabilities affected production
- Reasons we could see higher average production per TPBAR in the future:
  - DOE is now asking for a tritium quantity, so tritium quantity can be an optimization parameter during core design
    - After safety and cycle energy
  - New pellet manufacture increases ability to optimize lithium loading

Options for Enhanced Tritium Production

- The Tritium Production Planning Group (TPPG) has been evaluating enhanced tritium production options from two perspectives
  - WBN1 Cycle 16 (starts fall 2018)
  - Longer term options
- C16 is the first opportunity to consider options (C15 just started)
- Options for C16 are limited and the decision window is short
  - Historical operational risks are limiting the C16 fresh fuel loading to 88 assemblies; with newer materials and current core designs, the risk of loading 92 fresh fuel assemblies is being reevaluated
    - Could result in ability to load additional TPBARs (~72) and provide ~60 extra grams
    - Additional fuel reactivity would carry forward to C17 also
  - Evaluating the planned burnup window to obtain more tritium
    - May reduce operational flexibility
  - Manufacturing semi-custom pellet Li-6 loadings to allow for better optimization of the core design

Options for Enhanced Tritium Production

- Longer term options
  - Optimizations for C16 can carry forward to future cycles
  - Provide flexibility for the core designers to specify custom lithium loadings at the last moment by producing “preforms” that can be quickly ground to the desired loading
  - Consider axial variation in TPBAR lithium loadings (~1% improvement)
  - Consider development of custom Integral Fuel Burnable Absorber (IFBA) loading patterns for TPBAR cores (~1-5% improvement)
  - Evaluate movement of secondary sources to allow for TPBARs to be inserted in additional fresh fuel assemblies
  - Ensure that WBN2 tritium production starts on schedule
  - Plan for initial WBN2 production levels to exceed the 400 TPBAR baseline

Summary / Conclusions

- Historic tritium production can be used to estimate probability of producing desired amounts of tritium in planned TPBAR irradiation schedules
- Initial conclusions are that the desired tritium can be produced, but not with the desired confidence
- Projected shortfalls in tritium production from C14, 15, and 16 have prompted actions to improve the confidence that the desired production can be achieved
- Practical remedial options available to enhance tritium production in both the short and long term in WBN1
- WBN2 production needs to stay on schedule
- Production goals have a high likelihood of being achieved if we continue to work to ensure that there is contingency for further unexpected events