TRISO-X Fuel Fabrication Facility Nuclear Criticality Safety

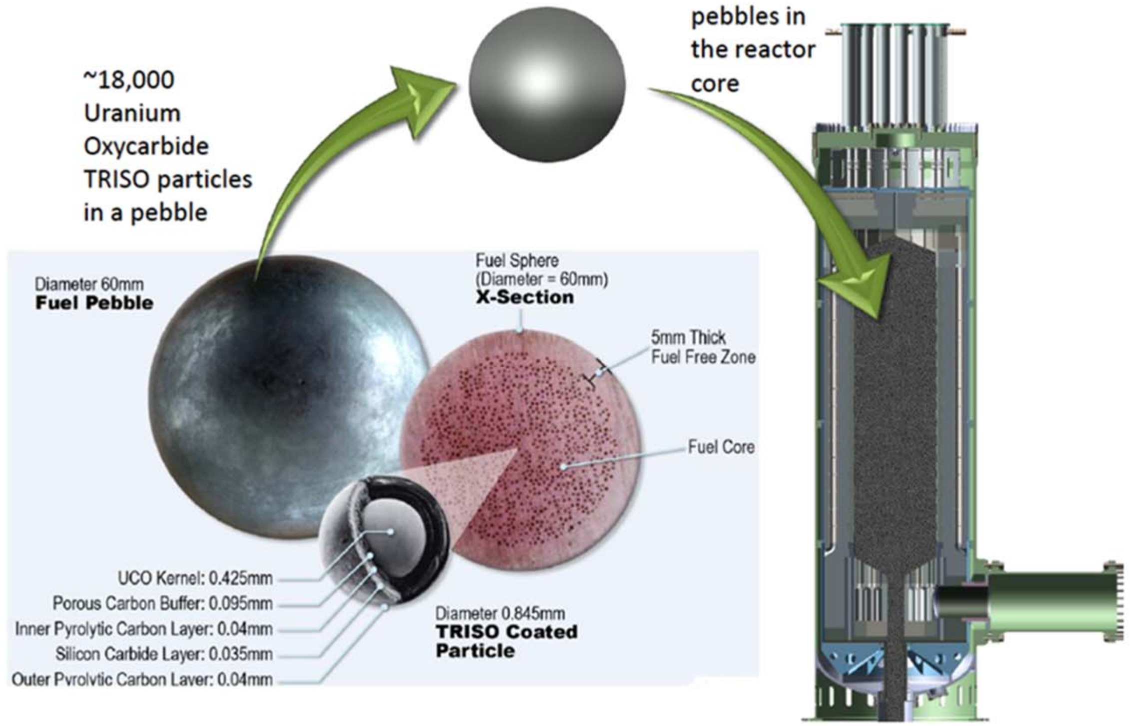
Pre-Application Meeting with the NRC

Dr. Peter Pappano
Vice President Fuel Production

Rockville, MD
December 12, 2018

Presentation Overview

- **Meeting Objectives**
  - Provide overview of criticality safety activities related to TRISO-X fuel fabrication facility license application
  - Enhance communication and minimize regulatory risk in overall NCS program development and implementation
- **NCS Team Overview**
- **Topics**
  - NCS Engineer Qualifications
  - NCS Program
  - Design Philosophy
  - Criticality Safety Evaluations
  - Calculational Methods
  - Integrated Safety Analysis



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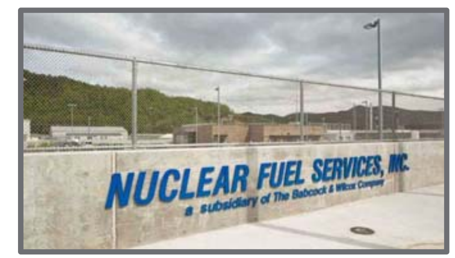
NCS Team Overview

PSI was brought on-board as a strategic partner to provide the NCS support for TRISO-X fuel fabrication facility due to their extensive NCS expertise, proven performance, and positive long-term working relationship with Centrus.

Mark McClure
Centrus Energy

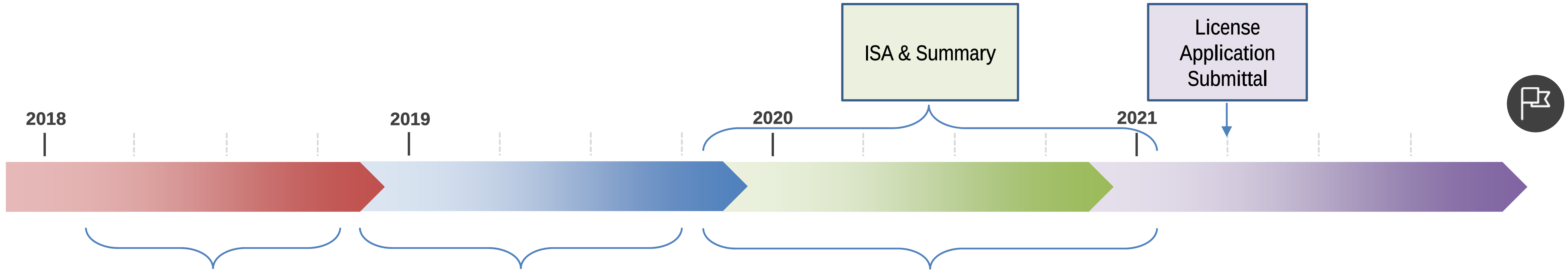
18 Years NRC Experience

Multi-Site 10 CFR 70 Experience



Long-Term Working Relationship

NCS Strategy



Solid NCS Foundation
- NCS Engineer Qualifications
- NCS Orientation to TRISO Process
- Design Team NCS Orientation
- NCS Program Description (Chapter 5 of License Application)
- NCS Program Procedures
- NCS Software Configuration Control
- SCALE Verification & Validation
- MCNP Shielding Verification & Validation
- NCS Scoping Calculations
- NCS Input for Conceptual Design

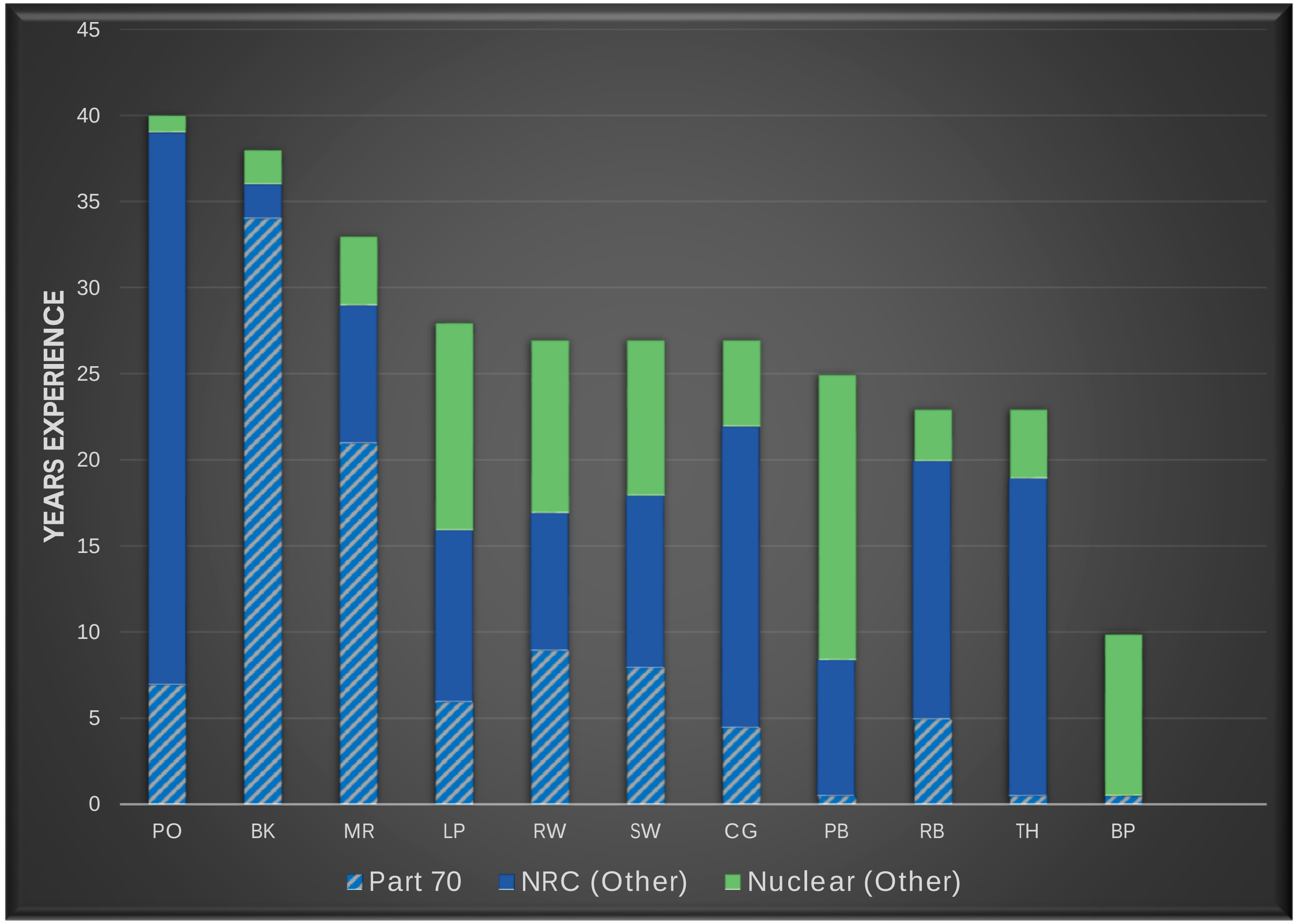
Preliminary Design & Licensing Support
- Preliminary NCSEs
- Design Interface
- License Application Support

Follow-On Support
- Complete NCSEs based on final design
- Incorporate NCS hazards into ISA
- Complete CAAS detector placement calculations
- Complete NCS Program implementing procedures (e.g., oversight, training)
- Develop NCS training program (includes NCS engineer qualification training and basic NCS plant training)

NCS Engineer Qualifications

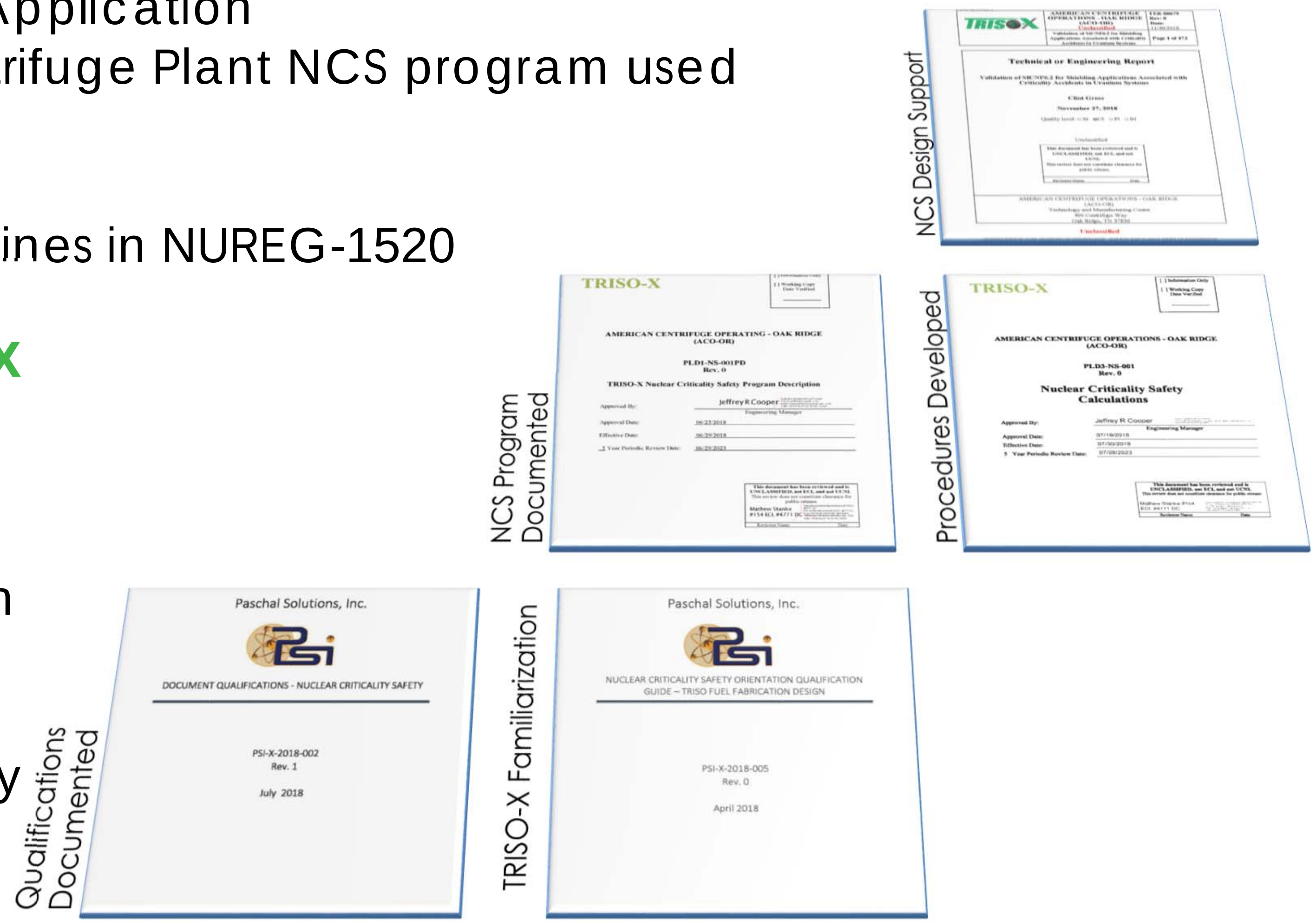
- **NCS Engineering Qualifications**
  - NCS engineer qualifications and experience documented
  - Prior qualifications based on industry standards (ANSI/ANS-8.19, ANSI/ANS-8.26)

- **TRISO-X Familiarization**
  - NCS staff completed orientation qualification guide
  - Orientation included introduction to TRISO process and familiarization with program procedures (Design, QA, etc.)



NCS Program

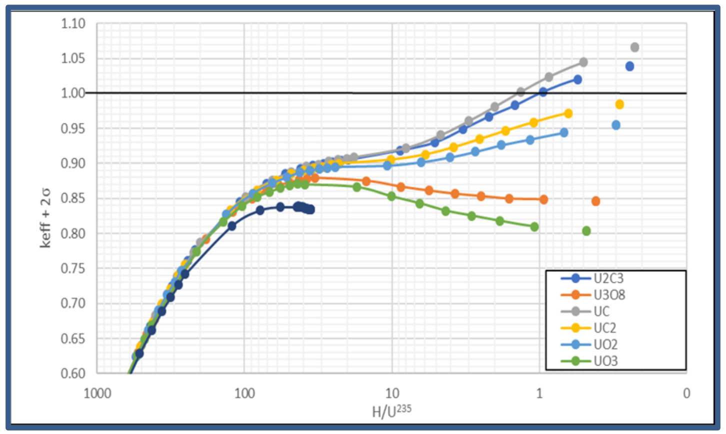
- **NCS Program Documented (PLD1-NS-001PD)**
  - Formatted as Chapter 5 of License Application
  - Previously approved American Centrifuge Plant NCS program used as starting point
  - Updated to reflect latest standards
  - Followed format and content guidelines in NUREG-1520
- **Procedures In Place to Support TRISO-X Design**
  - NCS Program
  - NCS Calculations
  - Computer Workstation Configuration Control Plan
  - Preliminary NCSEs
  - Centrus Program Procedures (Quality Assurance Program, Design Control, Procedure Development, etc.)



Design Philosophy

PLD1-NS-002, *Nuclear Criticality Safety Program*, states, “NCS and Engineering shall ensure double contingency is met in process designs in accordance with the preferred design approach.”

- NCS integrated into design from onset of TRISO-X project
- Input based on **Preferred Design Approach**

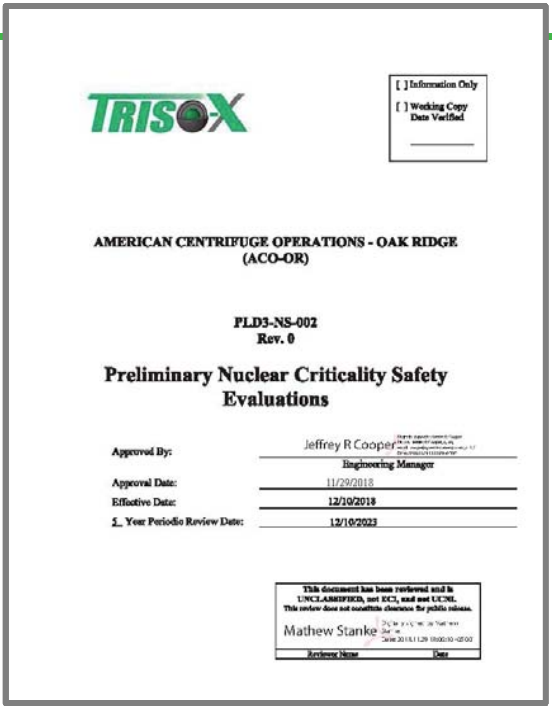


Initial NCS Input Based on Available Data → Scoping Calcs → Preliminary Criticality Safety Evaluations & Calculations → Nuclear Criticality Safety Evaluations → Integrated Safety Analysis → License Application → Deployment

Currently Here (Preliminary Criticality Safety Evaluations & Calculations)

Criticality Safety Evaluations

- The development of NCS controls for a new facility/operation is an iterative process that must incorporate project changes as the design matures.
- The approach for establishing NCS design requirements during the early design stage is through the development of Preliminary Nuclear Criticality Safety Evaluations (PNCSEs).
- PNCSE includes the following:
  - Description of Operation
  - Normal Case (described in terms of parameters and limits on parameters)
  - Hazard Identification
  - Hazard Evaluation
  - Proposed Controls
  - Assumptions
  - Calculational/Data Needs
- PNCSEs converted to final NCSE upon design completion


TRISO-X

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Date Verified

AMERICAN CENTRIFUGE OPERATIONS - OAK RIDGE
(ACO-OR)

PLD3-NS-002
Rev. 0

Preliminary Nuclear Criticality Safety Evaluations

Approved By:	Jeffrey R Cooper
	Engineering Manager
Approval Date:	11/29/2018
Effective Date:	12/10/2018
5 Year Periodic Review Date:	12/10/2023

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This review does not constitute clearance for public release.

Mathew Stanke

Reviewer Name | Date

PNCSE BENEFITS

- Provides documented NCS analyses without having final design complete
- Provides mechanism to identify issues early in design to prevent major redesign if hazards identified later
- Provides mechanism to identify data and calculational needs for final NCSE

Calculational Methods

Computer Workstation Configuration Control Plan

- Prevent unauthorized changes to software
- Ensure changes to hardware, software, or data libraries are systematically evaluated and controlled
- Restrict access to approved system users
- Ensure reliable calculation results
- Require initial and periodic software verification testing
- Require validation in accordance with ANSI/ANS-8.1 and ANSI/ANS-8.24 with consideration for known exceptions to NRC endorsement (e.g., Reg Guide 3.71)


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Computer Workstation Configuration Control Plan

25-May-2018

The American Centrifuge™

Approval

Approval: Jeffrey R Cooper
Engineering Manager

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Mathew Stanke
Reviewer Name | Date

Calculational Methods

TRISO-X FFF will be operated below 20 wt.% ^{235}U.

- Validation includes full enrichment range to 100 wt.% ^{235}U.
- Wherever possible NCS is limiting the design based on HEU (100 wt.%) rather than HALEU (< 20 wt.%).

- Design limits based on calculated k_{eff}
  - Parameter limits are based on HEU (> 90 wt.% ^{235}U) wherever possible.
  - The same USL is used for HALEU as for HEU (i.e. the HEU minimum margin of subcriticality is conservatively applied to HALEU cases).

SCALE Validation

- Performed validation of SCALE 6.2.3 with the V7-252 group ENDF/B-VII.1 cross-section library.
- Validation performed in accordance with ANSI/ANS-8.24-2017, *Validation of Neutron Transport Methods for Nuclear Criticality Safety Calculations*.
  - Consistent with exceptions identified by NRC in Reg. Guide 3.71.

- Consistent with guidance provided in NUREG/CR-6698, Guide for Validation of Nuclear Criticality Safety Calculational Methodology
- Implements requirements of Section 5.4.3.1.7 of NUREG-1520.

Validation for k_{eff}

Validation uses benchmark model simulations to "sample" the larger population of possible code performance for calculating k_{eff}.

- Objective: Establish an Upper Subcritical Limit (USL) for $k_{eff}+2\sigma$ based on:
  1. bias in k_{eff} results
  2. bias uncertainty

- Our approach is to maximize the sample size (i.e. number of benchmark simulations) **and then rigorously interrogate** that data set to identify adverse clusters or trends.

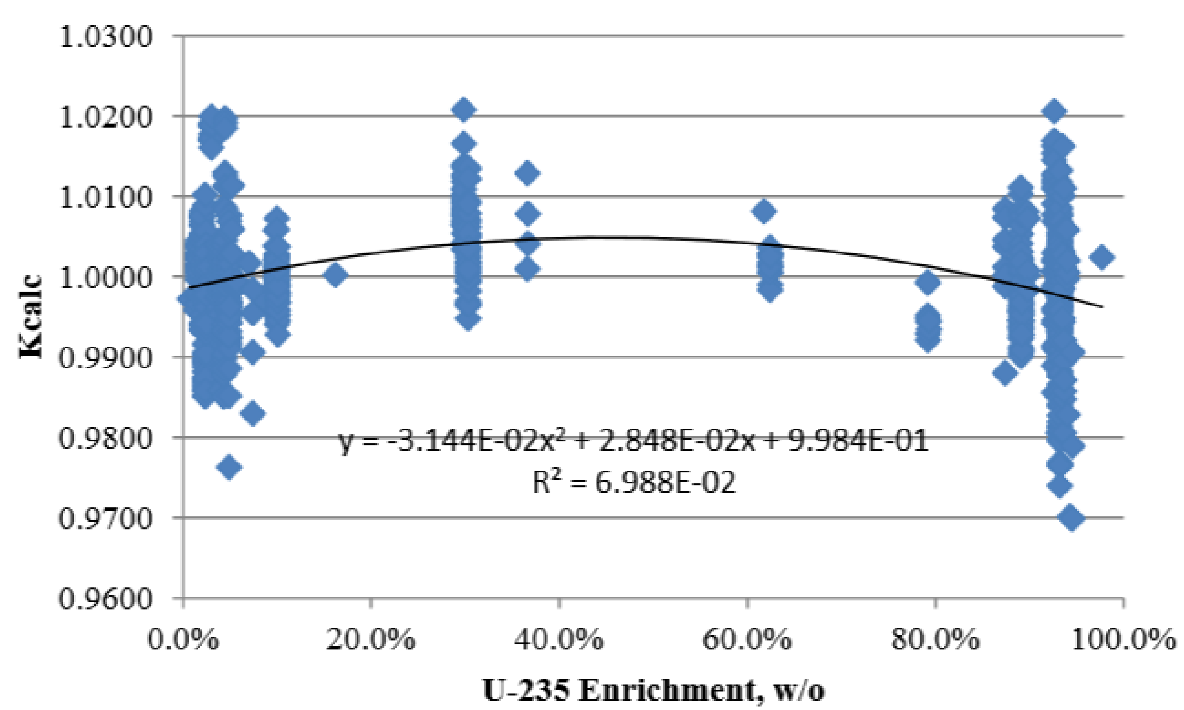
"Adverse" would be conditions that indicate a tendency to under-predict k_{eff}.

- Benchmark interrogation is performed by:
  – Trending k_{eff} by parameters
  – Reviewing data by clusters
  – Determining USL by subsets.

Validation: Benchmark Trending

- Trending: Extensive trending performed for k_{eff} versus the following parameter sets:
  - Enrichment (0 to 100 wt.% ^{235}U)
  - LEU and HALEU (0 to 30 wt.% ^{235}U)
  - IEU range (30 to 90 wt.% ^{235}U)
  - HEU range (90 to 100 wt.% ^{235}U)
  - Moderation (e.g., H/X trending)
  - Neutron energy spectra
  - Nuclides: Plotted k_{eff} versus the mass of each nuclide in each benchmark model

- No trend was identified that resulted in a non-conservative systematic under-estimate of k_{eff}.

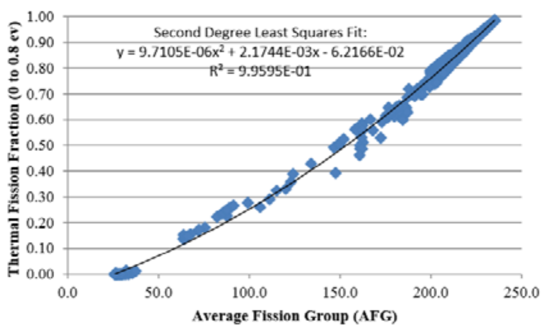


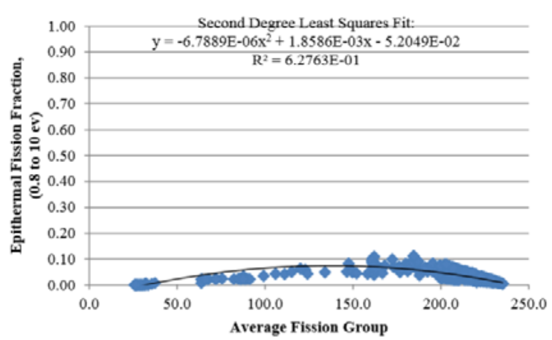
NOTE: USL results above 1.0 are set to 1.0 to determine bias, which conservatively reduces the USL.

Small positive bias in cases near 30 wt.% indicates tendency of code to over-predict k_{eff} at that enrichment, which is conservative.

Spectra: Epi-thermal Fission Fraction

- Spectra
  - Thermal Fission Fraction (0 to 0.8 eV)
  - Epi-thermal Fission Fraction (0.8 eV to 10 eV)
  - Average Fission Group
- AFG highly correlated with TFF
- AFG not correlated with EPI





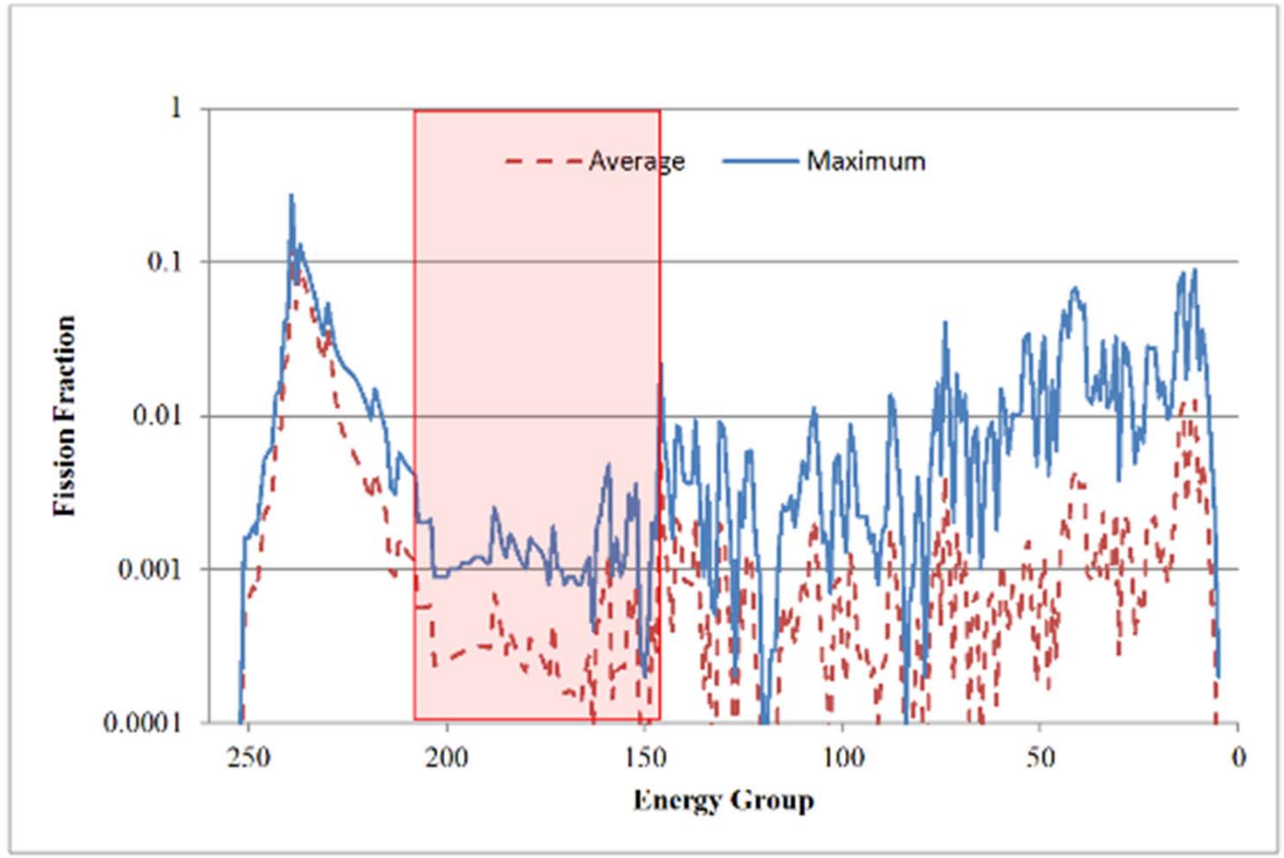
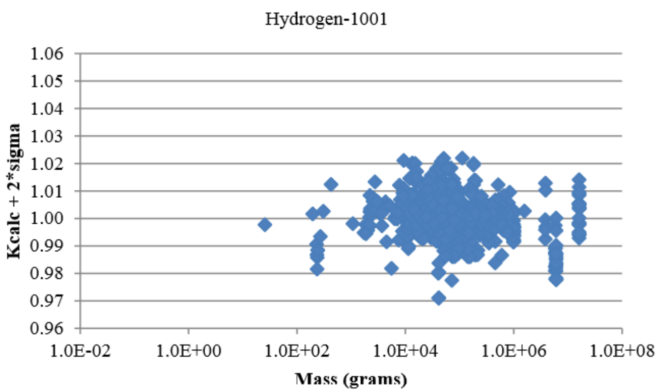
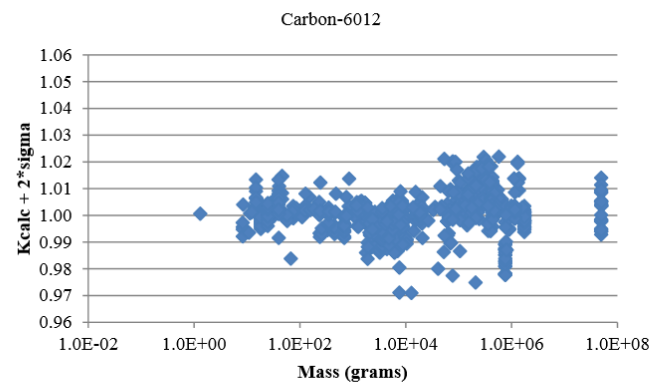
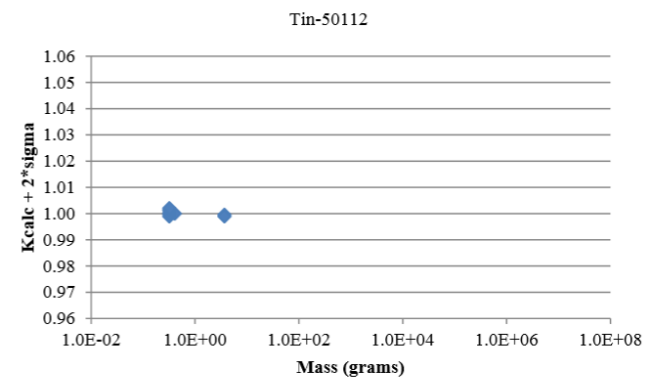


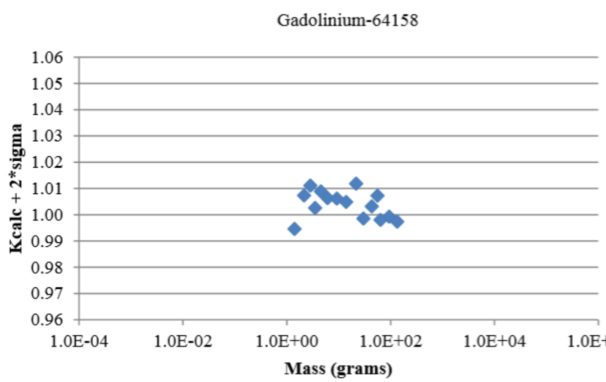
Figure 31 Maximum and Average Fission Fraction versus Energy Group: All Benchmarks

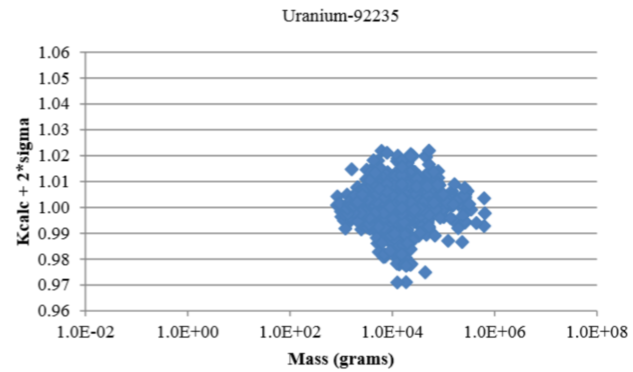
Sample Trending by Nuclide

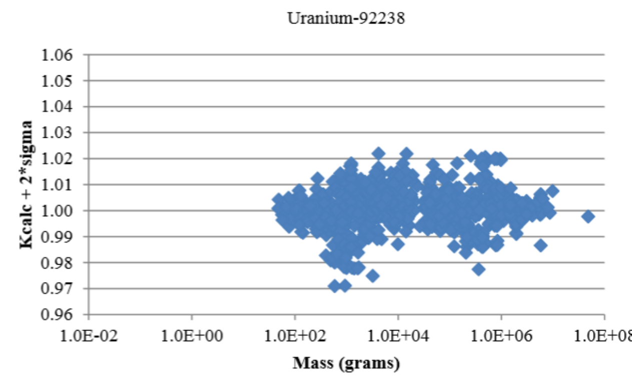






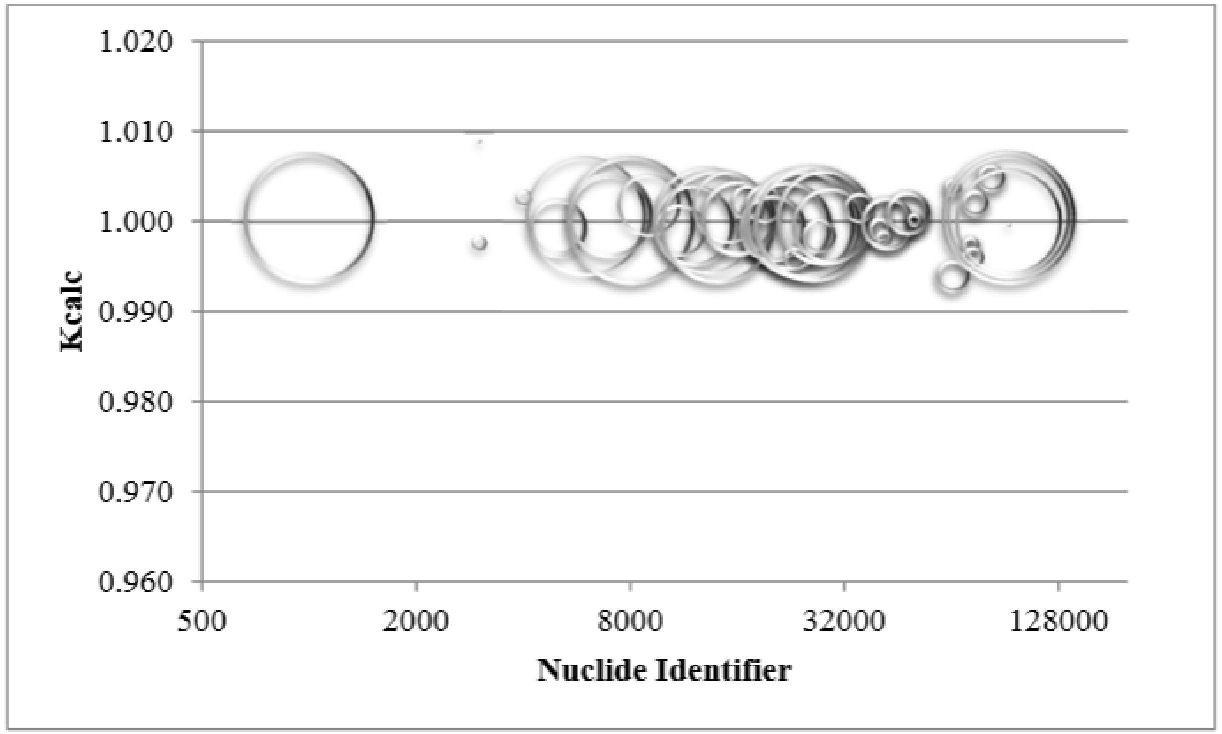




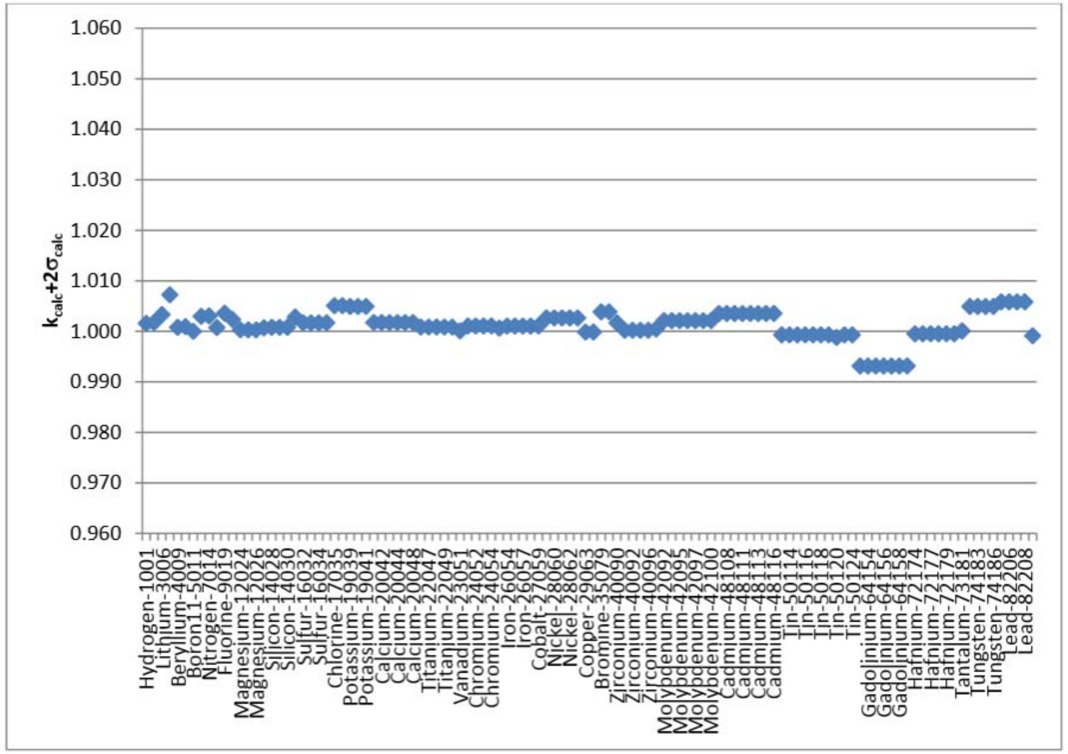


Consolidated Nuclide Plots

Bubble Plot Showing k_{eff} Results by Nuclide



Average K_{eff} by Nuclide



Based on trending and these plots elements such as lithium, Gadolinium, Hafnium, and Tantalum are excluded from the AoA.

Validation: Benchmark Clusters

- Clusters: The benchmark data were reviewed to ensure that no subset existed that would represent a systematic tendency to under predict k_{eff}.

- Data were plotted by cluster groups:
  - Calculation type (infinite homogeneous, lattice cell, and multiregion)
  - Laboratory (e.g. ORNL, LANL, Valduc, Kurchatov Institute, etc.)
  - Uranium chemical form (e.g. uranium oxide, uranyl nitrate, etc.)
  - Primary system geometry (e.g. sphere, cuboid, cylindrical tank, etc.)

- No adverse clustering was identified.

Table 13 Geometry Data

Geometry	Average k_{calc}	Average k_{bench}
Cylinder Tank	1.0013	1.0000
Cuboid Tank	1.0021	0.9994
Sphere Tank	0.9970	1.0001
Annular Tank	0.9981	0.9970
Cuboid	1.0045	0.9996
Cylinder	1.0009	1.0001
Sphere	1.0049	1.0000
Cylinder Plates	1.0050	1.0005
Mixed/Complex Geometries	1.0019	0.9994

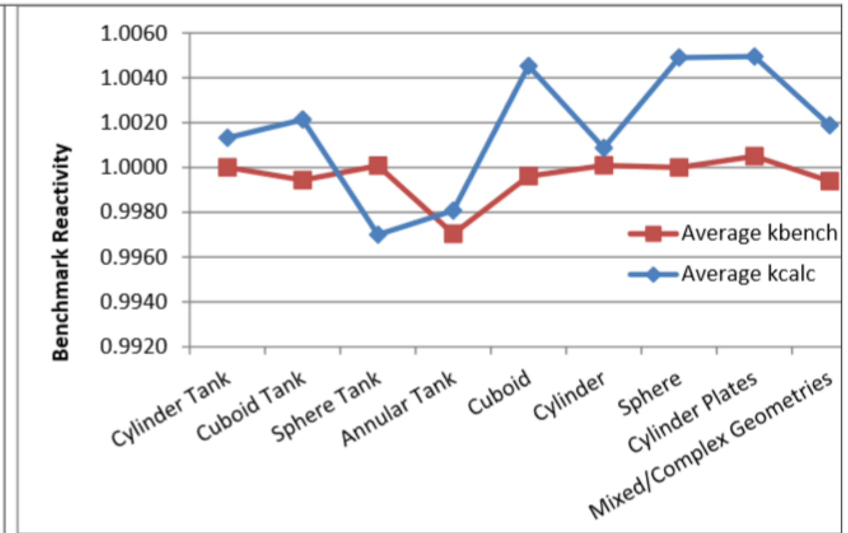


Figure 30 Average Reactivity Vs Driver Geometry for Calculation and

USL Determined by subsets

- Establish a single conservative USL for TRISO-X FFF analyses; however, that single USL is based on the lowest USL determined by diverse means and for various subsets of benchmark results.

- USL determined by diverse methods:
  - Normal statistics via Confidence Limit
  - Normal statistics via Lower Tolerance Limit
  - Non-parametric Rank and Percentile
  - Evaluation of 500 randomized groups of benchmarks
  - Evaluation of USL based on the lowest 100 benchmarks

- USL determined for the complete set and for several logical subsets to ensure non-conservative bias by group is not masked/hidden.

Single USL based on USL of Subsets

- USL was determined to be 0.95216.
- $k_{eff}+2\sigma$ must be less than 0.95216 to ensure subcriticality.
- USL is the lowest calculated result from the following subsets:

All Benchmarks (948)	H/X=0 (124)	TFF > 0.9 (377)	Latticecell (393)	USL for 500 Random groups of 100 benchmarks
LEU & HALEU (498)	H/X >0 up to 100 (201)	0.1 < TFF < 0.9 (515)	Infinite Homogeneous (380)	Lowest 100 cases
IEU (163)	H/X>100 (623)	TFF < 0.1 (56)	Multiregion (175)	
HEU (287)				

Area of Applicability

- Enrichment: 0 wt.% ^{235}U to 100 wt.% ^{235}U
- Moderation: Any H/^{235}U, any C/^{235}U
- Spectra: Each group in EPI range (0.8 eV to 10eV) shall be less than 5%
- SCALE 6.2.3 (CSAS5 module) with KENO V.a and v7-252 cross-sections
  - Infinite homogeneous
  - Latticecell
  - Multi-region
- Basic material forms of uranium
  - Uranium oxide
  - Uranium tetrafluoride
  - Uranium metal
  - Uranyl nitrate
  - Uranyl fluoride
  - Uranium in combination with the non-uranium materials included in the AoA.
- Any nuclide separate or included in materials of the Standard Composition Library from the table on the following page.

Nuclides of the AoA

Hydrogen-1001
Deuterium-1002
Lithium-3006
Lithium-3007
Beryllium-4009
Boron10-5010
Boron11-5011
Carbon-6012
Nitrogen-7014
Oxygen-8016
Fluorine-9019
Sodium-11023
Magnesium-12024
Magnesium-12025
Magnesium-12026
Aluminum-13027
Silicon-14028
Silicon-14029
Silicon-14030
Phophorus-15031
Sulfur-16032
Sulfur-16033
Sulfur-16034
Sulfur-16036
Chlorine-17035
Chlorine-17037
Potassium-19039
Potassium-19040
Potassium-19041

Calcium-20040
Calcium-20042
Calcium-20043
Calcium-20044
Calcium-20046
Calcium-20048
Titanium-22046
Titanium-22047
Titanium-22048
Titanium-22049
Titanium-22050
Chromium-24050
Chromium-24052
Chromium-24053
Chromium-24054
Manganese-25055
Iron-26054
Iron-26056
Iron-26057
Iron-26058
Cobalt-27059
Nickel-28058
Nickel-28060
Nickel-28061
Nickel-28062
Nickel-28064
Copper-29063
Copper-29065

Bromine-35079
Bromine-35081
Zirconium-40090
Zirconium-40091
Zirconium-40092
Zirconium-40094
Zirconium-40096
Molybdenum-42092
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Cadmium-48113
Cadmium-48114
Cadmium-48116
Tungsten-74182
Tungsten-74183
Tungsten-74184
Tungsten-74186
Lead-82204
Lead-82206
Lead-82207

Lead-82207
Lead-82208
Uranium-92234
Uranium-92235
Uranium-92236
Uranium-92238

Calculational Methods

Shielding Validation

- Performed rigorous validation of MNCP6.2 for shielding applications using cross-section sets ENDF/B-VII.1 neutron and MCPLIB84 photo-atomic library based on ENDF/B-VI.8
- MCNP6.2 needed to support following types of calculations:
  - Detection of the minimum accident of concern: Total photon dose (prompt gamma plus secondary gamma) observed at detectors based on the minimum accident of concern.
  - CAAS radiation tolerance: Total dose neutron plus gamma at secondary detector locations with detector burnout occurring at the nearest location to the event.
  - Emergency planning: Total dose at the site boundary, and distance to the 12-rad dose boundary, for neutron plus gamma based on the design basis yield and worst-case energy spectrum.
- Validation established conservative estimation of bias and bias uncertainty applying methods adopted from ANSI/ANS-8.24 (2017)

Integrated Safety Analysis

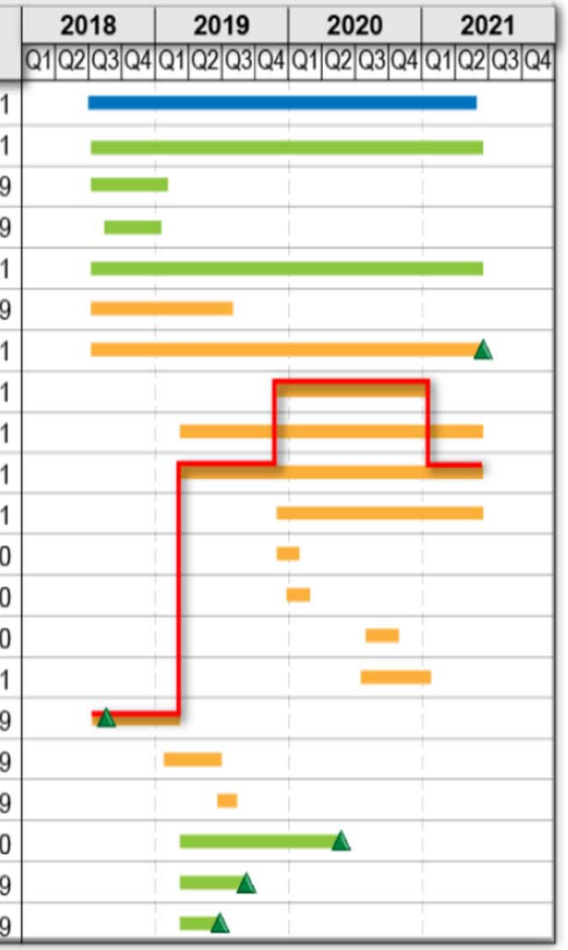
ISA Status

- The Integrated Safety Analysis is scheduled to start in Q4 2019.
- ISA methodology will be addressed in separate NRC pre-application meeting.

Criticality Hazards & ISA

- Criticality will be addressed in the ISA.
- Primary means of criticality protection at the TRISO-X FFF will be **PREVENTION**.
- PNCSEs and NCSEs will utilized to support the ISA development.
  - Identify criticality scenarios
  - Identify controls to be considered as IROFS

Activity Name	Start	End
400 - Facility License Application Development	07-01-18	06-30-21
Regulatory Engineering Management	07-01-18	06-18-21
Regulatory Strategy Development	07-01-18	02-01-19
Pre-application NRC Engagement	07-01-18	01-18-19
Safety Program Description (SPD)	07-02-18	06-18-21
Ch. 1 - General Information	07-02-18	07-22-19
Ch. 2 - Organization and Administration	07-02-18	06-18-21
Ch. 3 - Integrated Safety Analysis and Summary	11-12-19	01-28-21
Ch. 4 - Radiation Protection	03-05-19	06-18-21
Ch. 5 - Nuclear Criticality Safety	03-05-19	06-18-21
Ch. 6 - Chemical Process Safety	11-12-19	06-18-21
Ch. 7 - Fire Safety	11-12-19	01-13-20
Ch. 8 - Emergency Management	12-31-19	02-19-20
Ch. 9 - Environmental Protection	08-04-20	10-19-20
Ch. 10 - Decommissioning	07-21-20	01-28-21
Ch. 11 - Management Measures	07-02-18	03-04-19
Ch. 12 - Material Control and Accounting	01-22-19	07-01-19
Ch. 13 - Physical Protection	06-27-19	08-07-19
Environmental Report	03-05-19	05-25-20
Security Plan	03-05-19	08-05-19
Emergency Plan	03-05-19	07-22-19



Legend: Level 1 Level 2 Level 3 Critical Path Deliverables Milestones FOA_003v3

Wrap Up

Review of Meeting Objectives

- Provide overview of criticality safety activities related to TRISO-X fuel fabrication facility license application
- Enhance communication and minimize regulatory risk in overall NCS program development and implementation
  - Pre-application meeting
  - Future communications

Questions/Open Forum