TRISO-X Fuel Fabrication Facility Overview

Introductory Meeting with the NRC

Dr. Peter Pappano
Vice President Fuel Production

Rockville, MD
August 24, 2018

Presentation Overview

Meeting Objectives

- Provide overview of X-energy
- Introduce NRC staff to TRISO-X Fuel Fabrication Facility (FFF)
- Provide overview of our plans to prepare and submit a license application

TRISO-X Fabrication Processes

- High Assay Low Enriched Uranium (HALEU), Uranium Oxide-Carbide (i.e., UCO) Kernel, TRIstructural-ISOtropic (TRISO), Pebble, Characterization and Quality Control (QC)
- Process improvements

Facility Design

- Transition to commercial design
- Conceptual layout

Plans for License Application

- 10 CFR Part 70
- Other regulations and guidance as applicable
- Preliminary license application schedule

Overview and History of X-energy

X-energy is reimagining nuclear's role in solving tomorrow's energy challenges

- X-energy founded in 2009 by Kam Ghaffarian to address the world's most serious energy challenges and make a lasting contribution to clean energy technology
- X-energy leverages expertise from SGT, Inc. the 2nd largest engineering services contractor to the National Aeronautics and Space Administration
- Dr. Ghaffarian has committed ~$38.5M since X-energy inception to date
- Secured two Department of Energy (DOE), Office of Nuclear Energy Cooperative Agreements
  - Advanced Reactor Concept (ARC)15: Xe-100 Pebble Bed Small Modular Reactor: Solving Critical Challenges to Enable the Xe-100 Pebble Bed Advanced Reactor Concept ($53M total project)
  - Industry Funding Opportunity Announcement (iFOA)18: Design and License Application Development for TRISO-X: A Cross-Cutting, High Assay Low Enriched Uranium (HALEU) Fuel Fabrication Facility ($38M total project)

Dr. Kam Ghaffarian
Founder/CEO

Two DOE Cooperative Agreements Support TRISO-X

ARC15

Task 3 Fuel Development

Pebble Bed Fuel Development

- Kernel production
- TRISO particle coating
- Matrix production
- Overcoating
- Pebble pressing
- Characterization
- Pilot scale fuel line development

Production Facility and Supply

- Fuel facility site study
- Nuc. Criticality safety
- HALEU supply eval.
- Transport package eval.
- Conceptual layout of production line

iFOA18

Task 4 License Application Development

Safety Program Description

- Design
- ISA
- Management Measures

Security Plan

- Physical security
- Cyber security

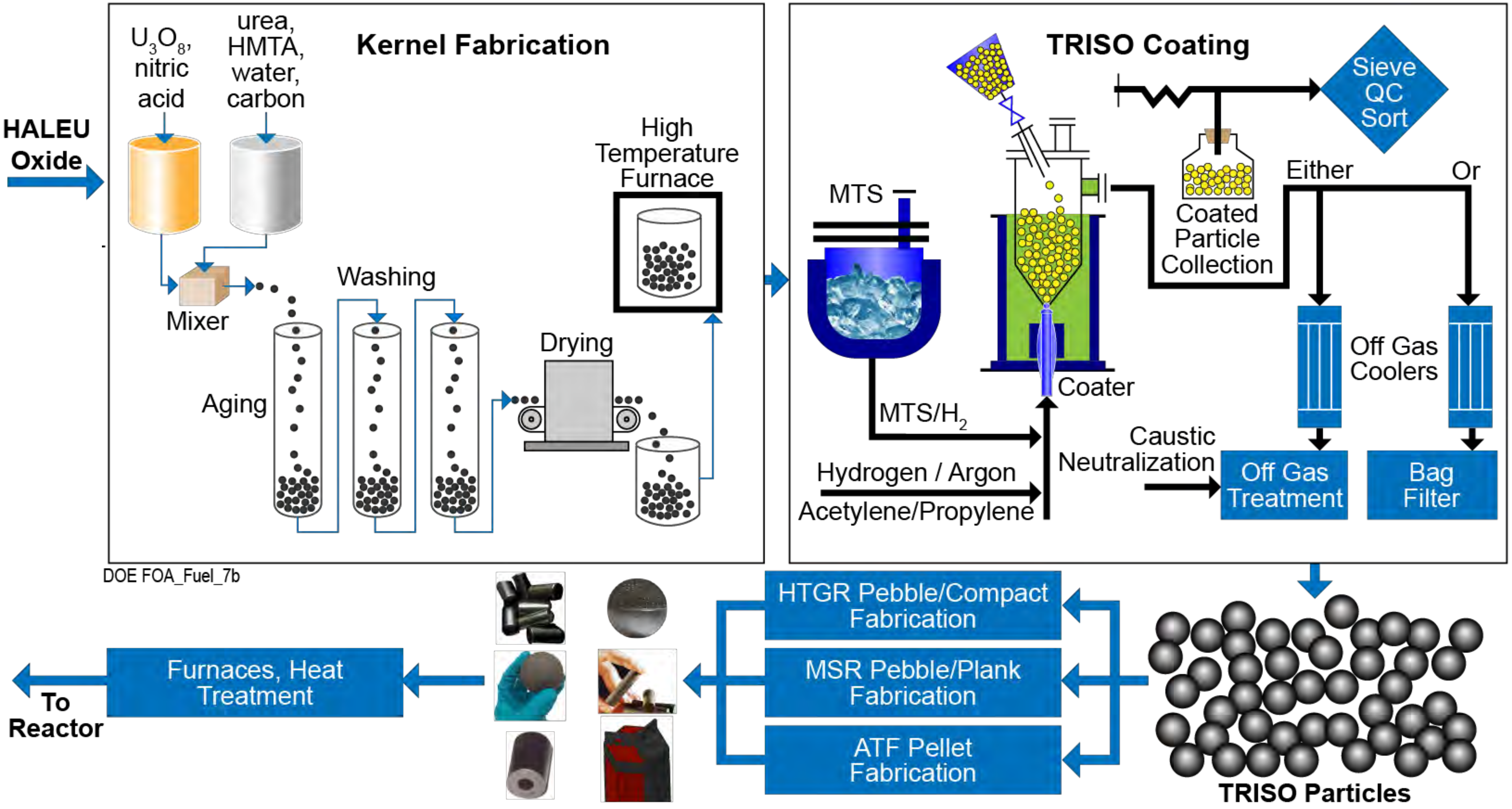
Production Facility and Supply

- Site characteristics
- Effluents
- Impacts

Emergency Plan

- Emergency action levels
- Emergency planning

TRISO-X: A Crosscutting Facility for Advanced Reactors (ARs) & Current Fleet



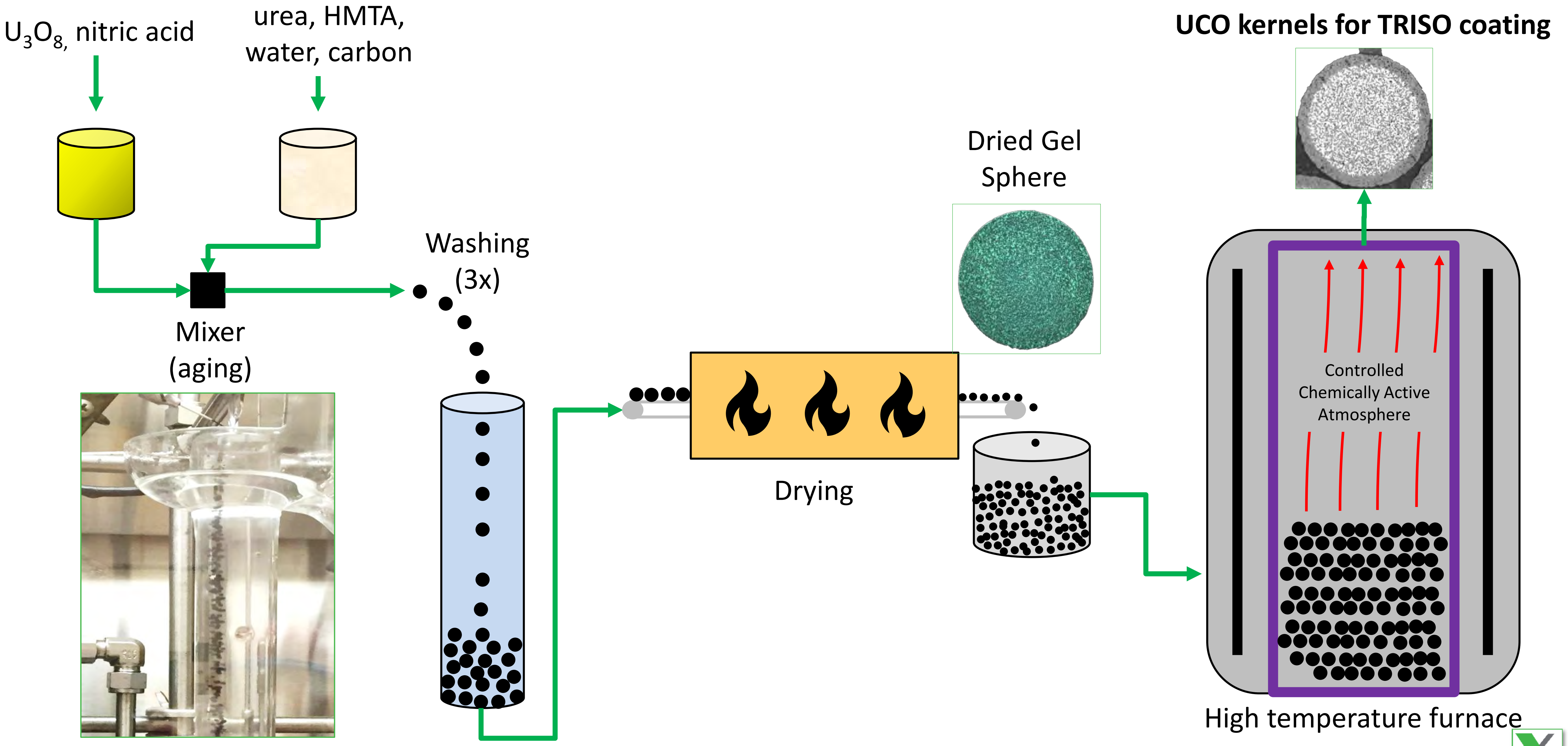
Key TRISO-X Fabrication Processes

- Kernel fabrication
- Particle coating (TRISO)
- Pebble fuel element pressing
  - Matrix production
  - Overcoating
  - Fuel core pressing
  - Fuel free zone pressing
  - lathing
- Characterization

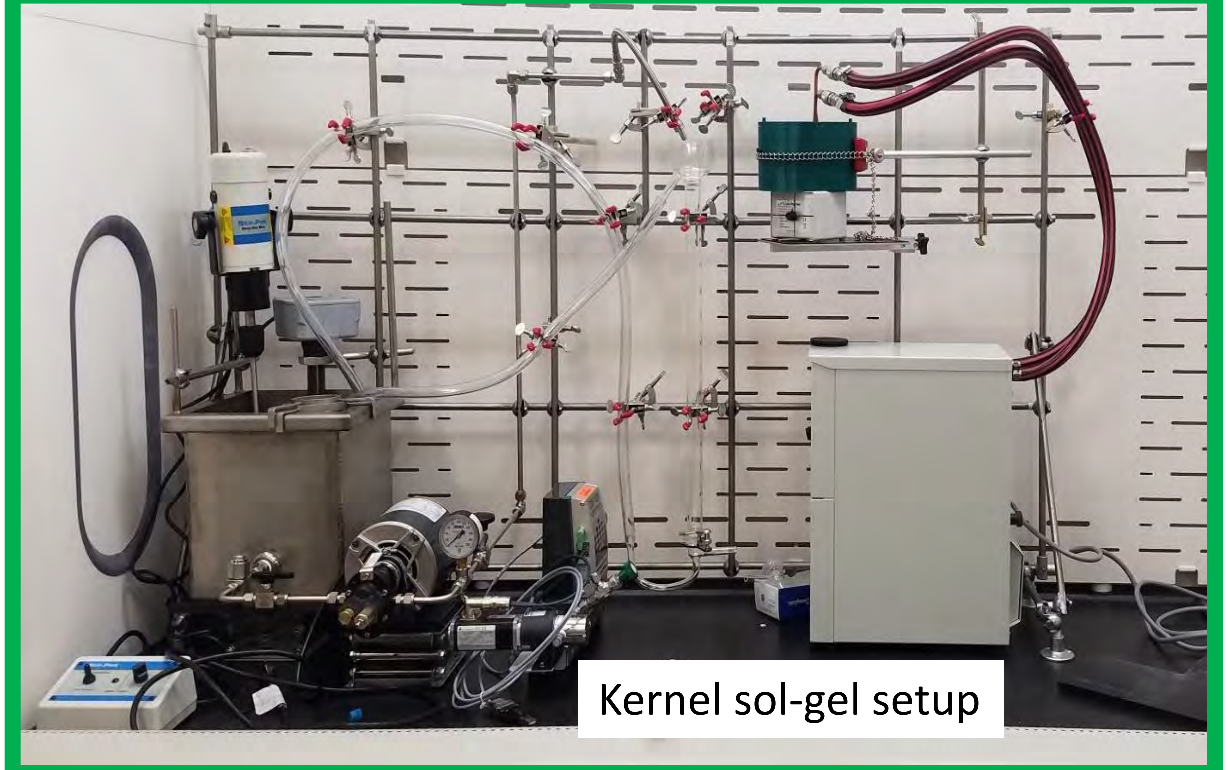
The TRISO-X fuel fabrication facility will produce fuel elements ranging from natural uranium to 19.75% enriched. The TRISO-X facility will be Category II as defined in 10 CFR Part 70.

Note: The initial license application will cover pebble fuel element fabrication, any additional fuel forms would be addressed by license amendment requests.

Kernel Fabrication Overview



TRISO-X Equipment in Pilot Facility



Kernel sol-gel setup

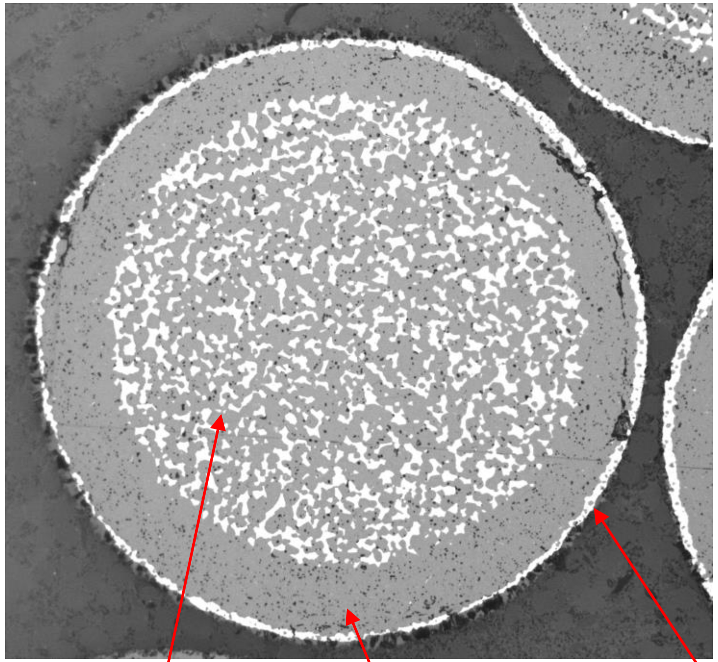
Kernel drying furnace

Distillation column

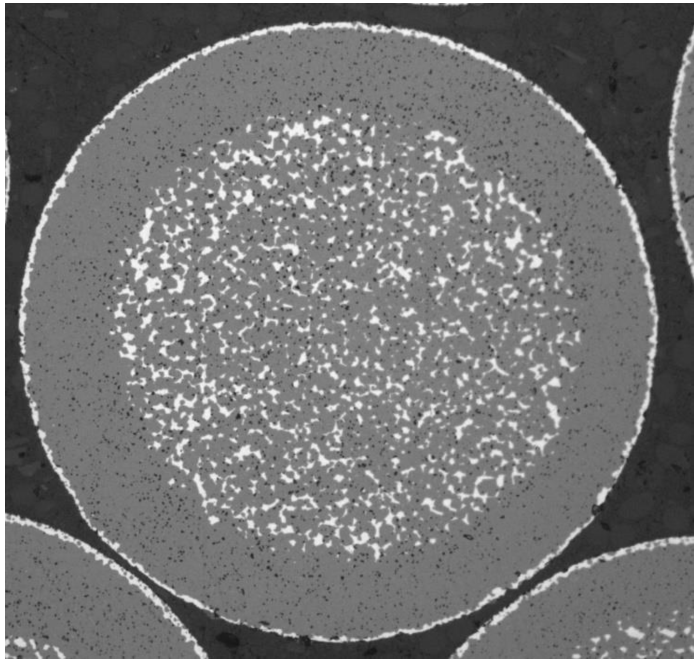
Conversion furnace

Optimized UCO Kernel Chemistry

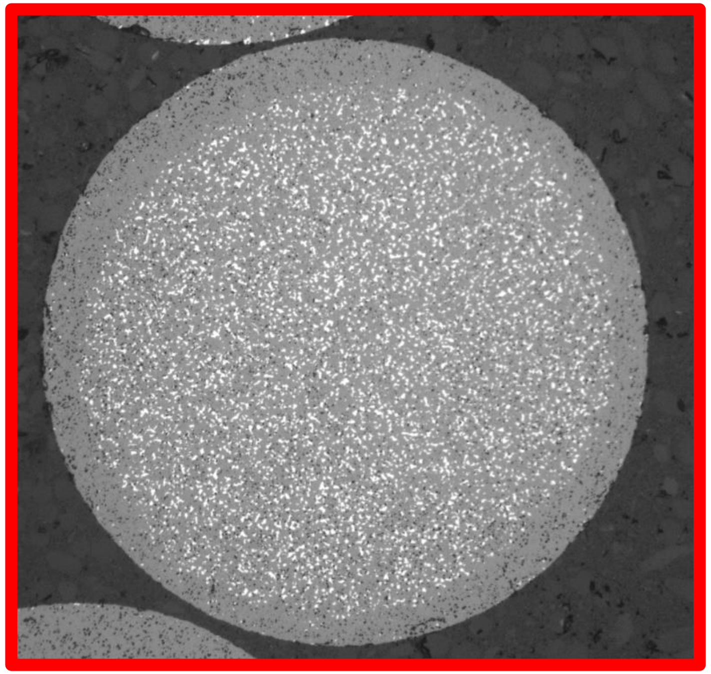
UO_2 / UC_2 Ratio 1



UO_2 / UC_2 Ratio 2



UO_2 / UC_2 Ratio 2 Optimized

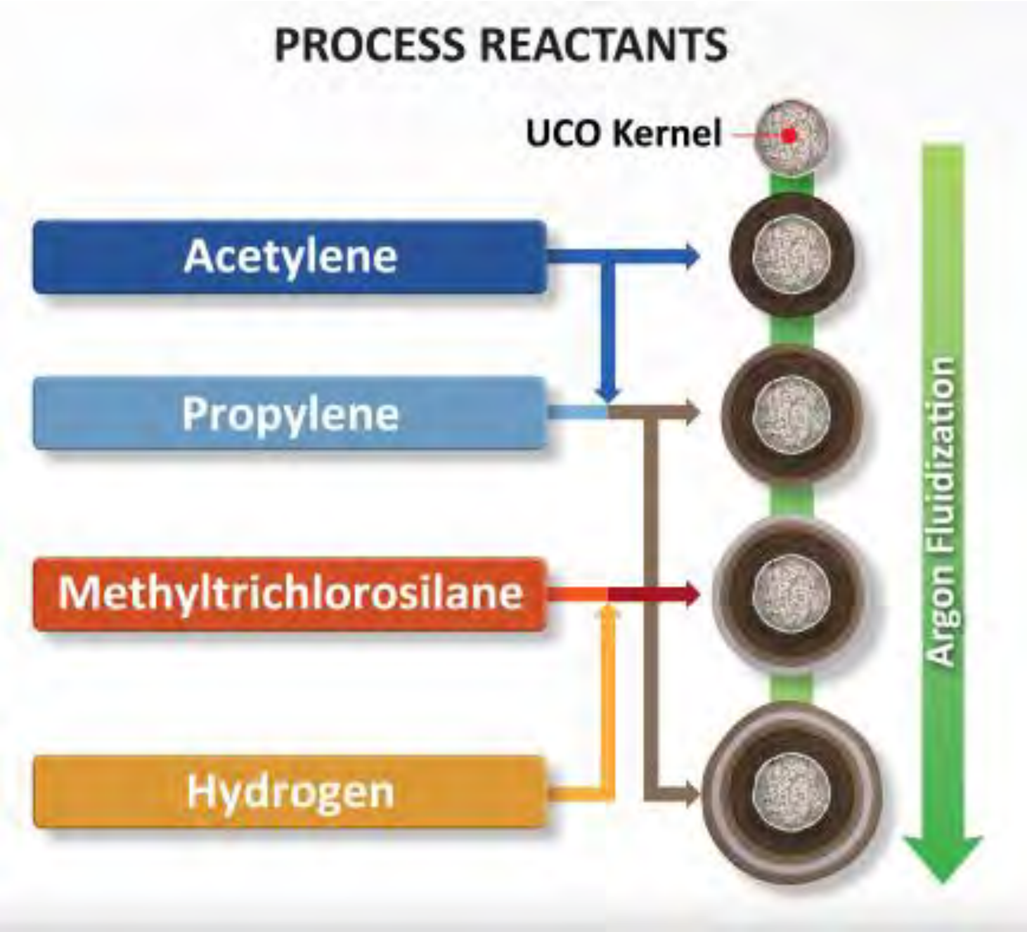


Two phase region   Oxide rind   Carbide skin

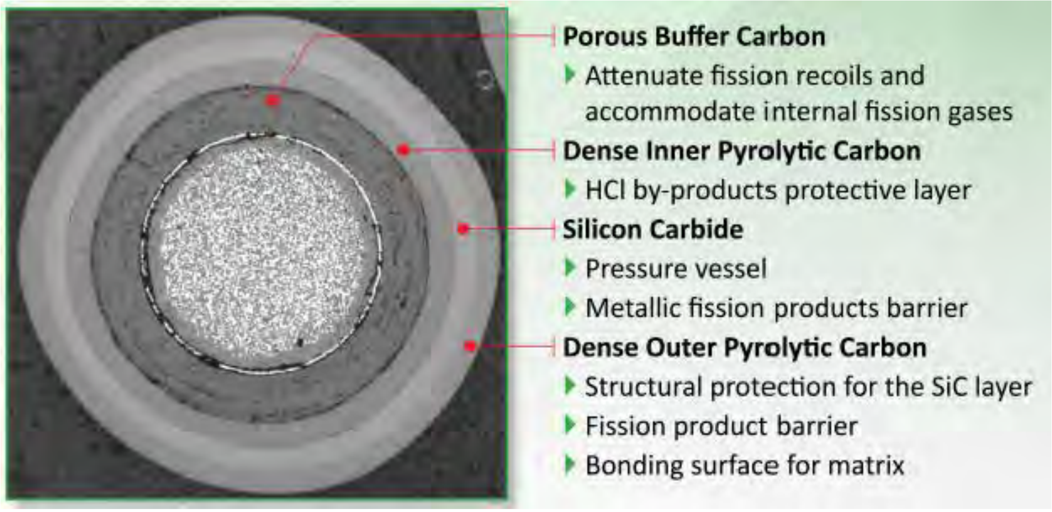
1st of its kind
-highly dispersed UC_2 phase w/o carbide skin

Determination of minimum amount Carbon to reap benefit of UCO mixture

TRISO Coating



TRISO-X coater, located In Pilot Facility At ORNL

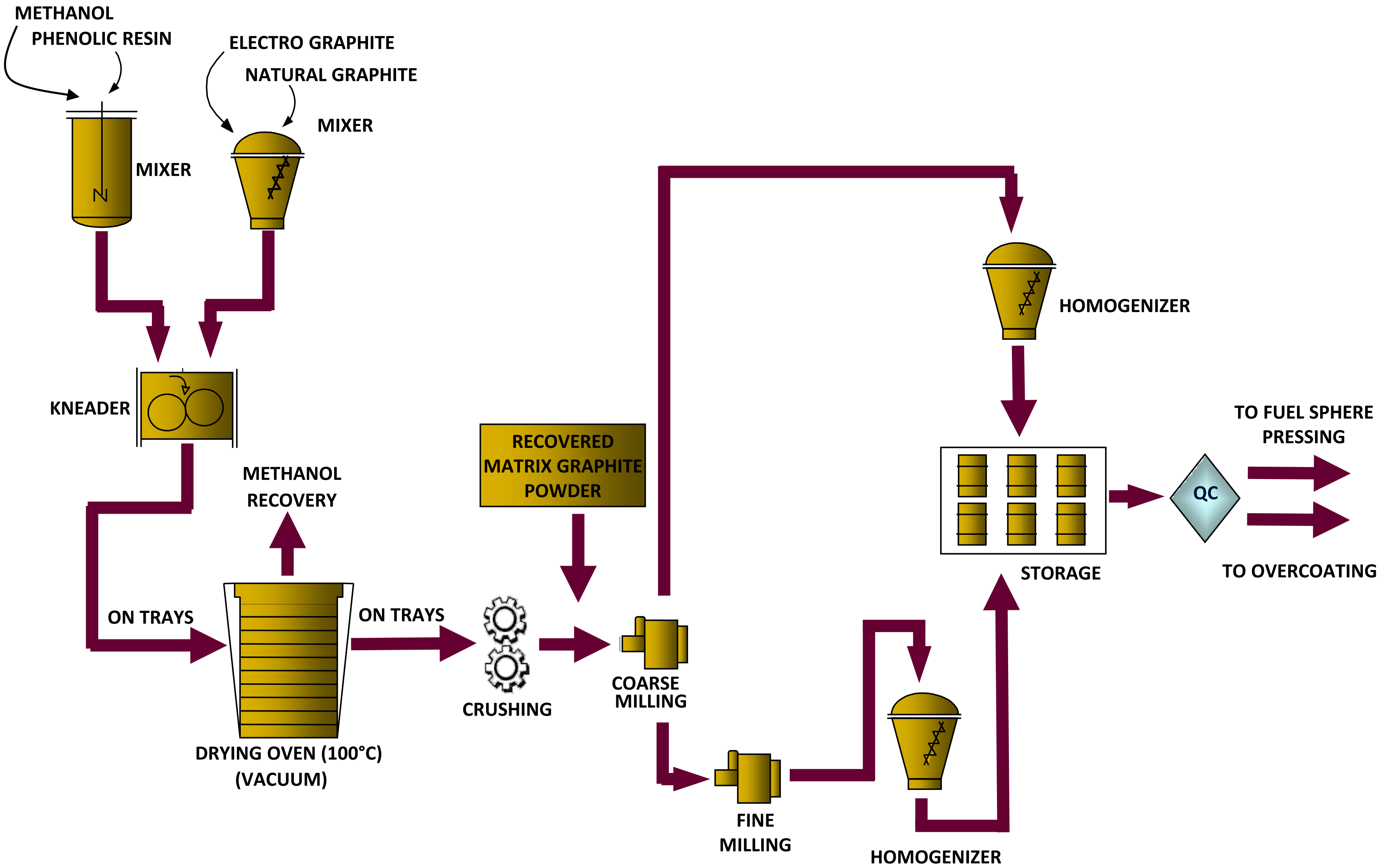


Description and function of each TRISO layer

Pebble Pressing

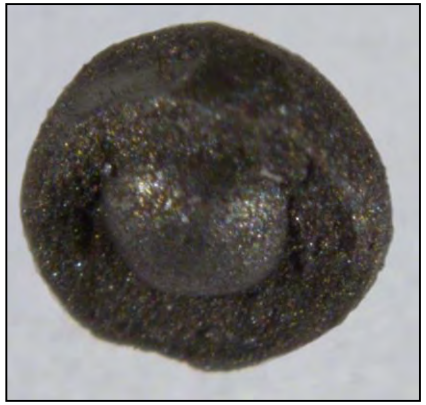
- Pebble pressing consists of the following steps:
  - Graphite matrix production
  - Overcoating
  - Fuel core press
  - Fuel free zone press
  - Lathing
  - Carbonization
  - Heat-treatment
- Other fuel elements, such as cylindrical compacts, require one press in a warmed die, and no lathing

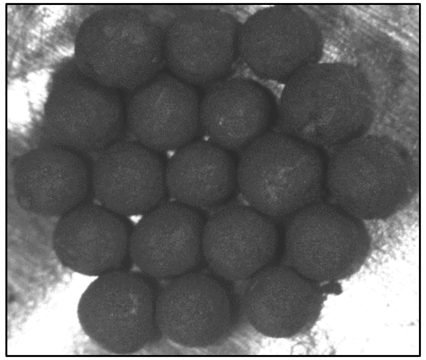
Graphite Matrix Production

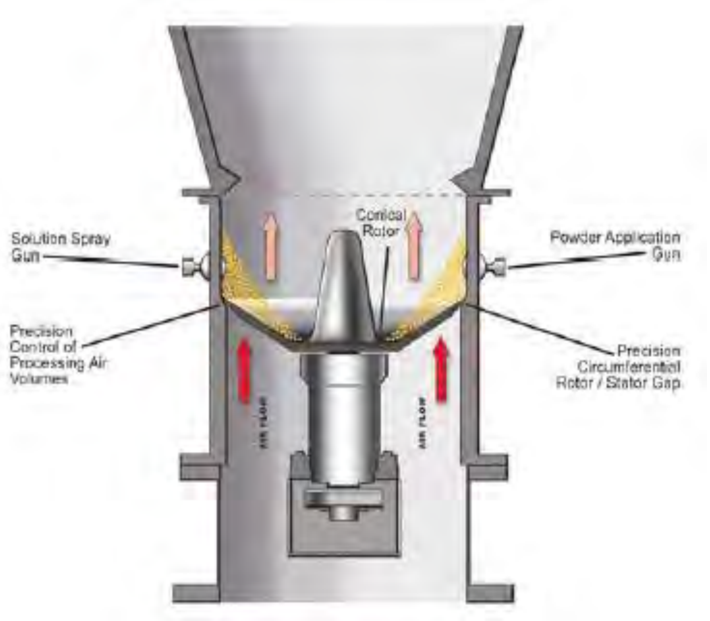


Overcoating

- The "overcoating" is a layer of graphite matrix that surrounds the TRISO particles
  - The uncoated TRISO roll in the conical rotor system
  - The TRISO are semi fluidized
  - Liquid and powder are sprayed into the bed of particles
  - The particles slowly collect material until they are the desired diameter
- This layer of matrix separates the particles from each other during the pressing operation
- The thickness of the overcoating layer can be used to control the particle spacing
- A conical Flo-Coater has been selected, tested, and installed at ORNL
- Working towards finely-controlled, consistent overcoating thickness

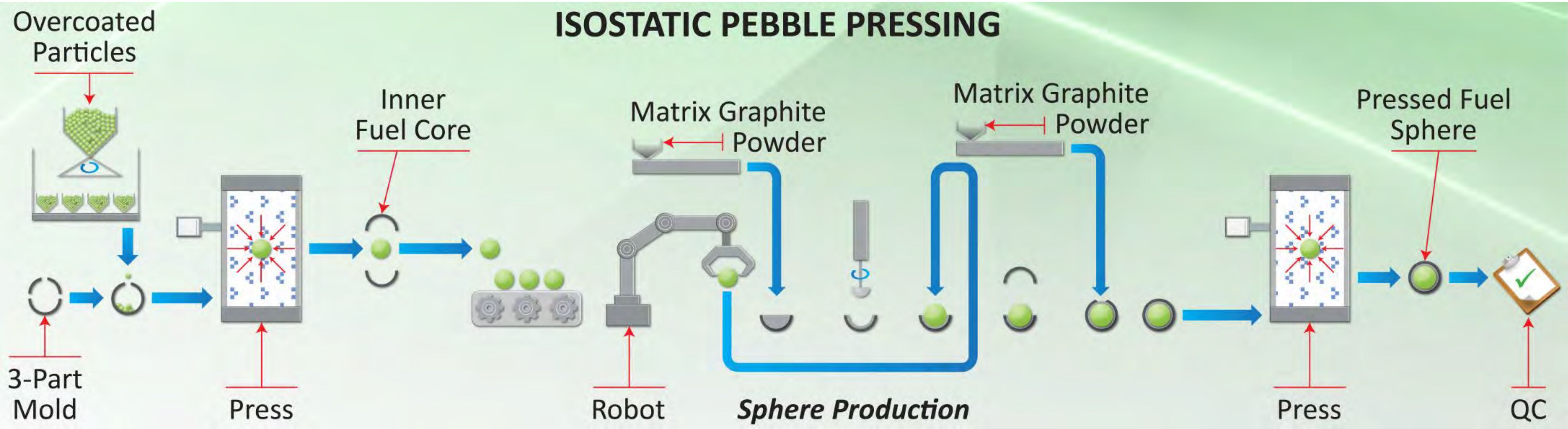



Overcoated particles



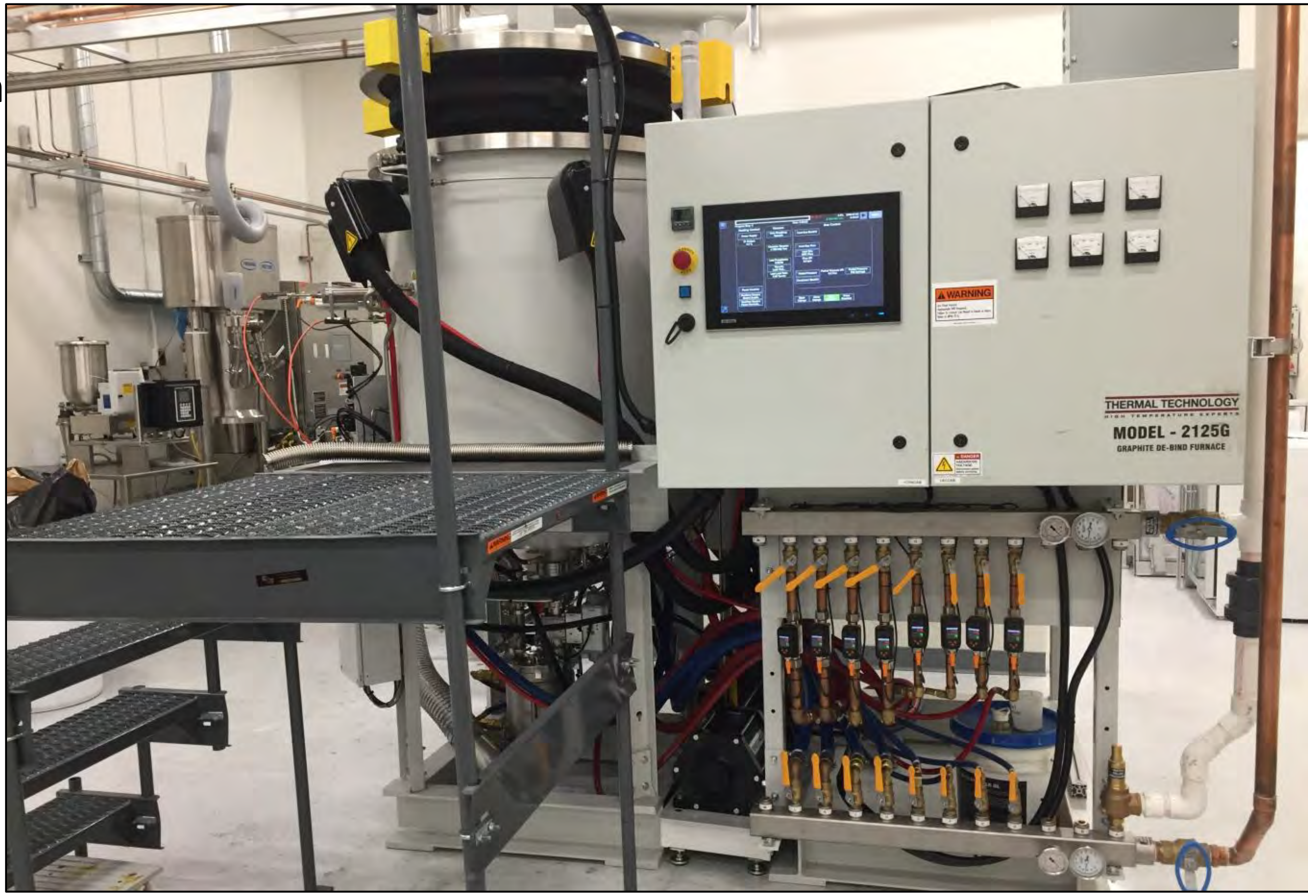
Cross section view of flow coater rotor

Pebble Pressing



Pebble Carbonization and Heat-treatment

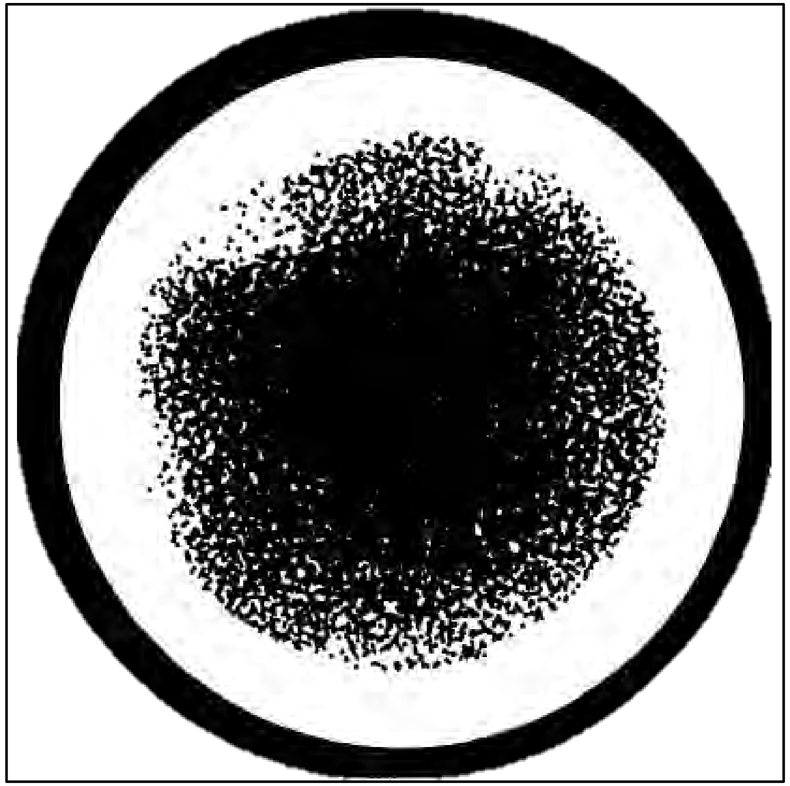
- Two stage heat treatment
  - Carbonization (up to 1000°C) in flowing argon
  - High temperature portion (up to 1950°C) in low vacuum
- Heat treatment plan development
  - Variables include:
    - Temperature ramp rates
    - Hold times
    - Maximum temperatures
  - Measured results:
    - Density
    - Dimensional change
    - Compressive strength
- Large furnace installed in Pilot Facility (~200 pebbles)
  - 2000 °C
  - Vacuum
  - Partial pressure
  - Flowing gas



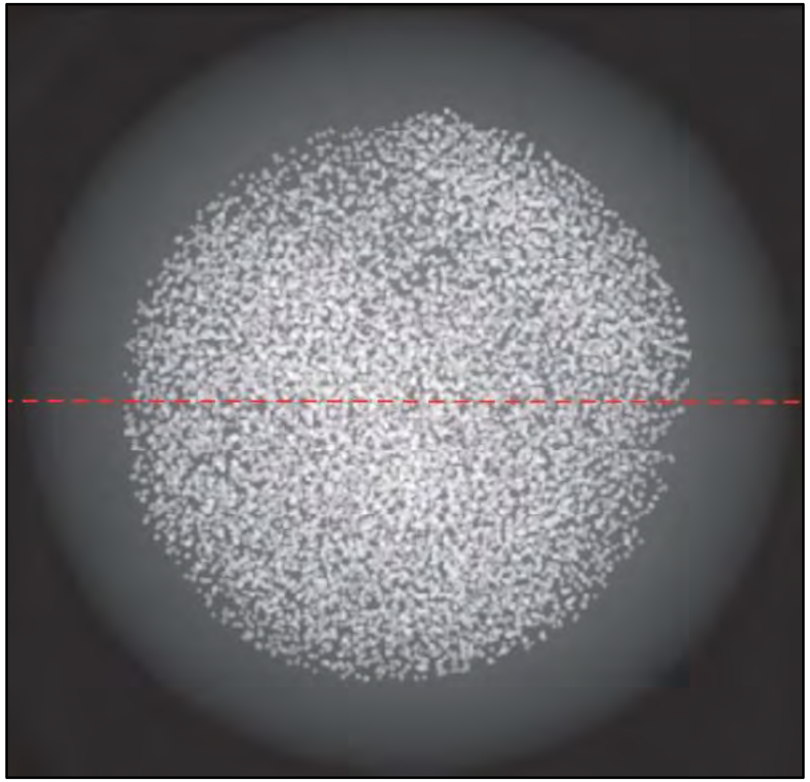
Carbonization and HT Furnace

Superior Particle Spacing and Homogeneity

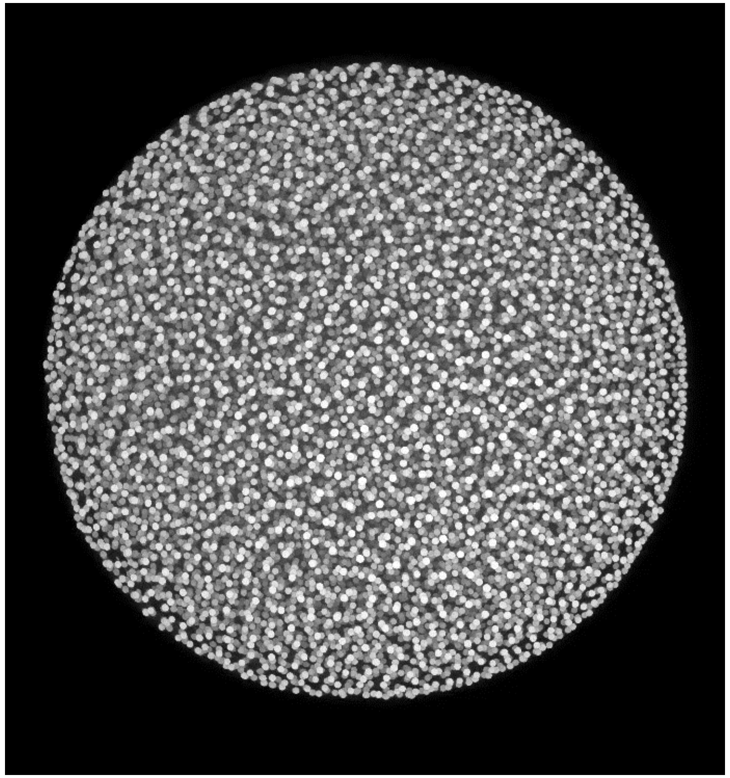
- German 2D radiography vs Chinese 3D tomography vs TRISO-X 3D tomography
- Increased homogeneity
- Increased fuel core sphericity



German radiograph

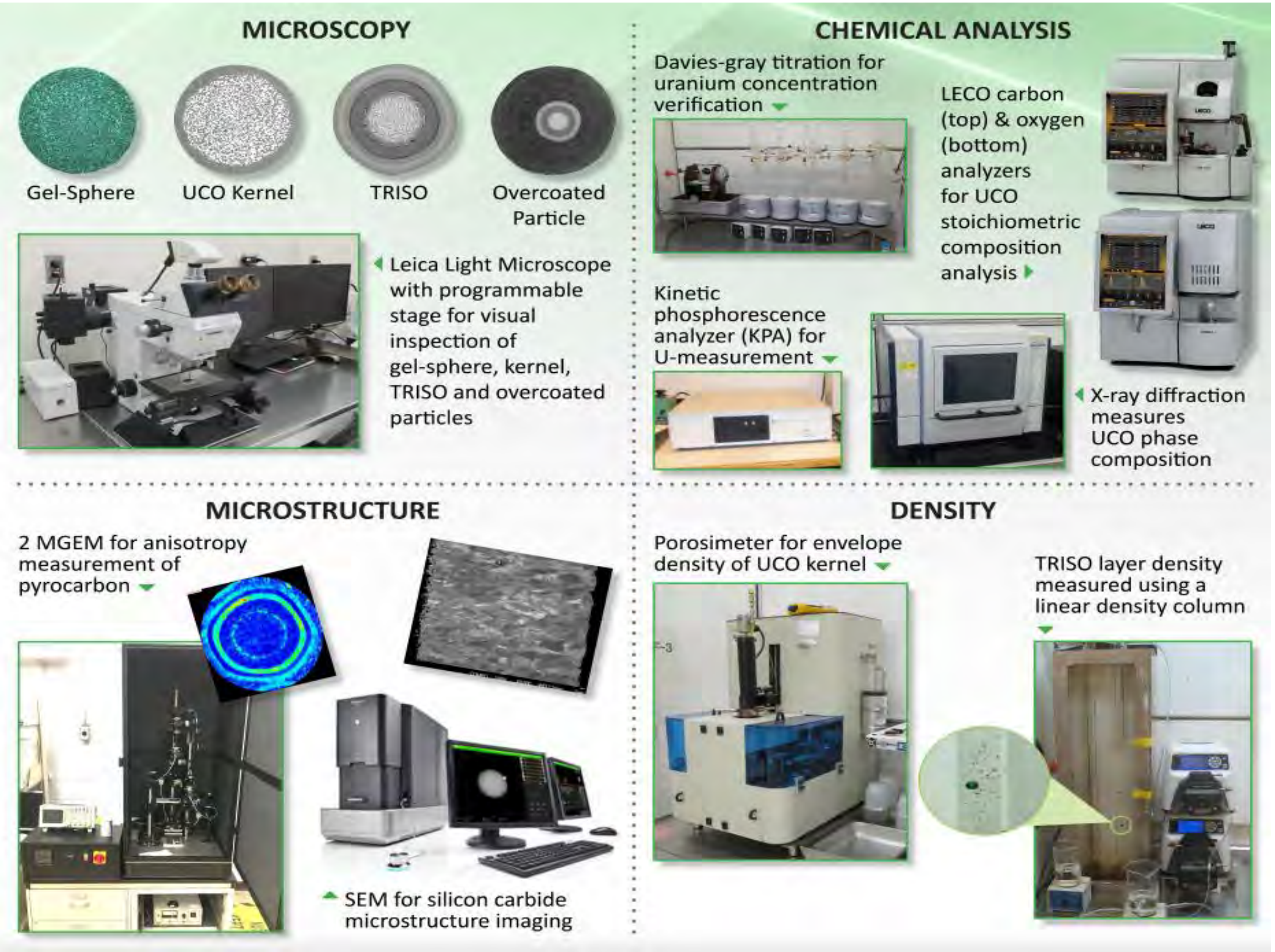


Chinese radiograph



XE tomography scan

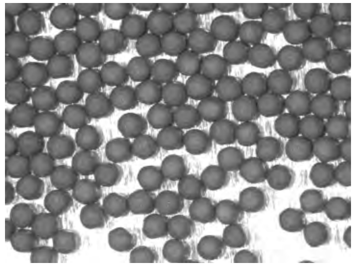
Characterization and Quality Control



Note: Some equipment owned by ORNL will be reproduced in TRISO-X FFF Equipment performance proven in pilot plant

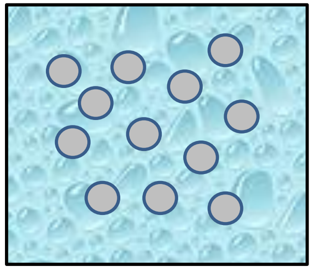
Characterization and Quality Control

Burn-Leach to Confirm Layer Integrity



TRISO particles

C-digestion
(removes OPyC)

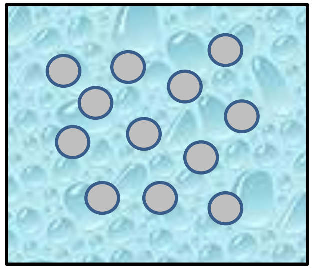


SiC layer particles soak in acid

Acid tested for uranium

#1 Initial defect fraction determination

C-digestion
(removes matrix, OPyC)



SiC layer particles soak in acid

Acid tested for uranium

#2 defect fraction after pressing

The goal of the pebble fabrication process is to avoid damaging particles, evidenced when #1 defect fraction = #2 defect fraction

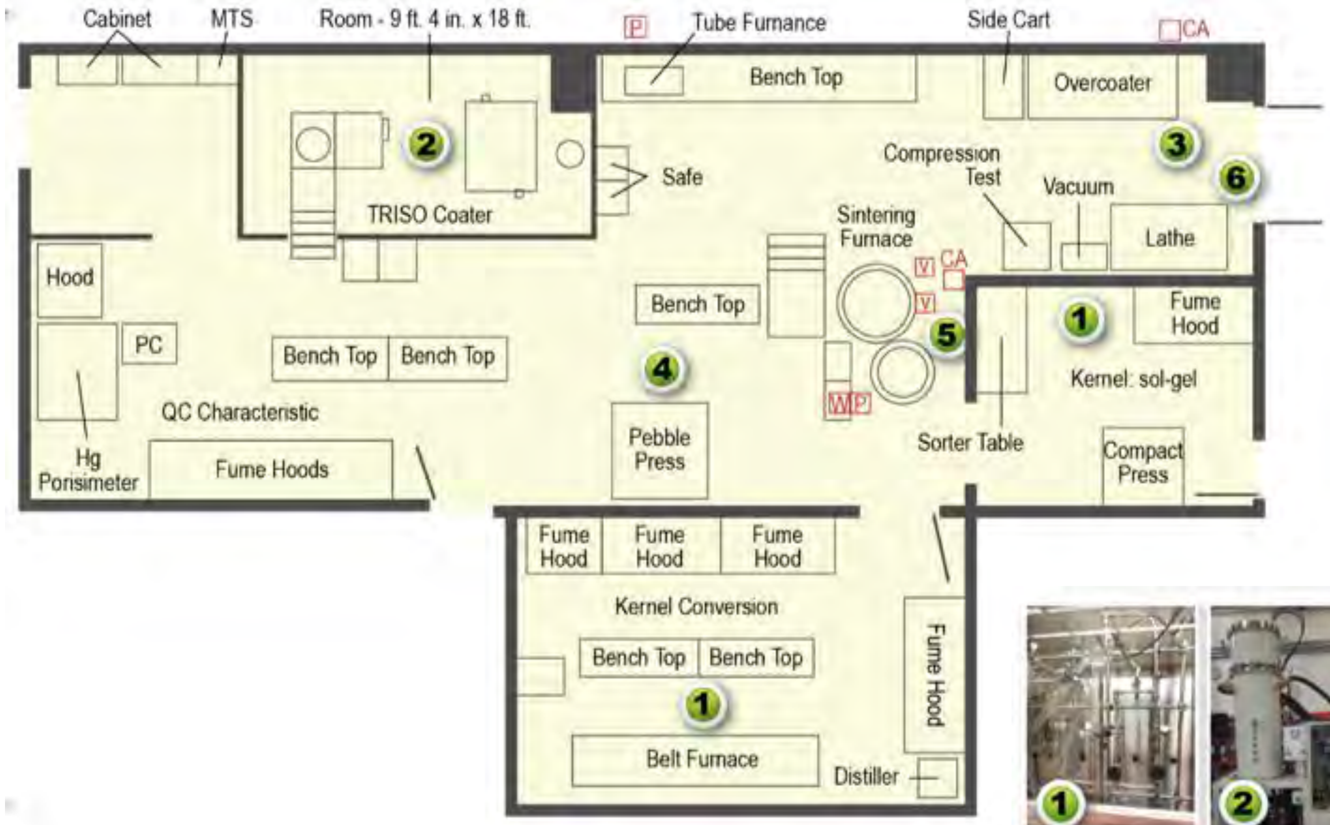
Process Improvements

Process	Improvements over historical methods
Kernel fabrication	• Identification of "ideal" carbon content • Novel droplet formation manifold • In-line droplet characterization • Waste reduction with organic de-greasers • Optimized pH for internal gelation
TRISO coating	• Improved loading/unloading to minimize particle damage • Novel gas-injector inlet design • Optimized graphite internal geometry for yield and waste minimization • Novel top furnace design to ensure proper fluidization
Fuel element pressing	• Optimized overcoating technique for yield and reduced run time • Improved pressing technique to minimize lathing requirements • Improved pressing method leading to uniform distribution of particles • Elimination of loading/mixing steps in pebble pressing process • Combined carbonization/heat treatment step to reduce run time
Characterization & QC	• Use of modern materials science techniques for product visualization • Intelligent design through insitu monitoring of fabrication processes • Reduced development time through rapid prototyping • Faster method for determining particle defect fraction

Bottom line: These improvements result in better particle layer integrity and performance compared to previous programs

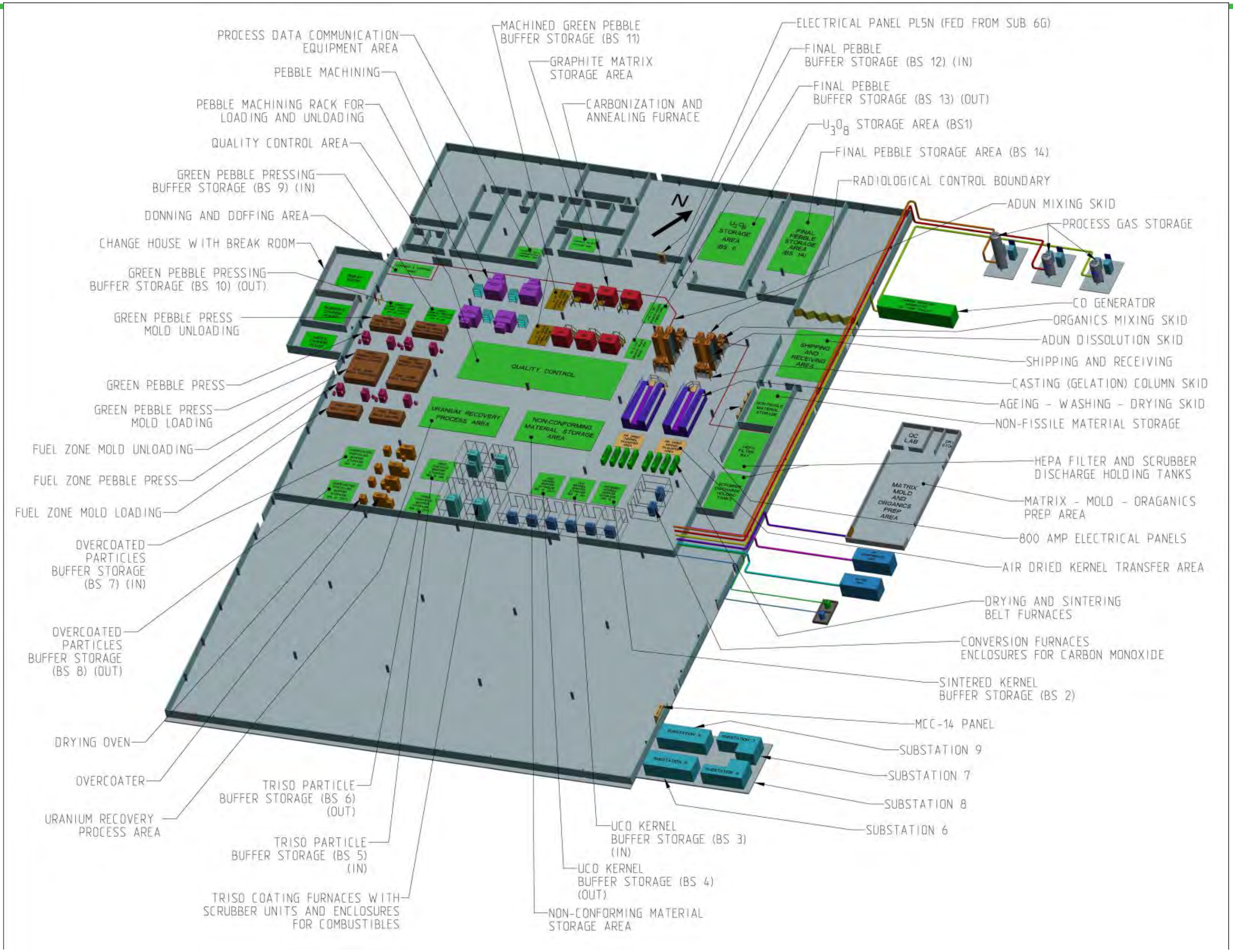
Pilot to Commercial Transition

TRISO-X Pilot Facility (Building 4508, ORNL)



-The equipment in the TRISO-X Pilot Facility will be transferred/replicated in the TRISO-X FFF
-No further upscaling of the equipment capabilities is necessary
- The production line will be replicated in the commercial to achieve reactor production demand

Conceptual Layout:
Isometric of TRISO-X Fuel Fabrication Facility



Key Facility Areas

- U_3O_8 receipt/storage
- Kernel production
- TRISO particle production
- Fuel form production
- QC
- Characterization/testing
- Fuel form storage
- R & D
- Engineering support
- Raw material storage
- Management offices
- Uranium recovery

Plans for License Application

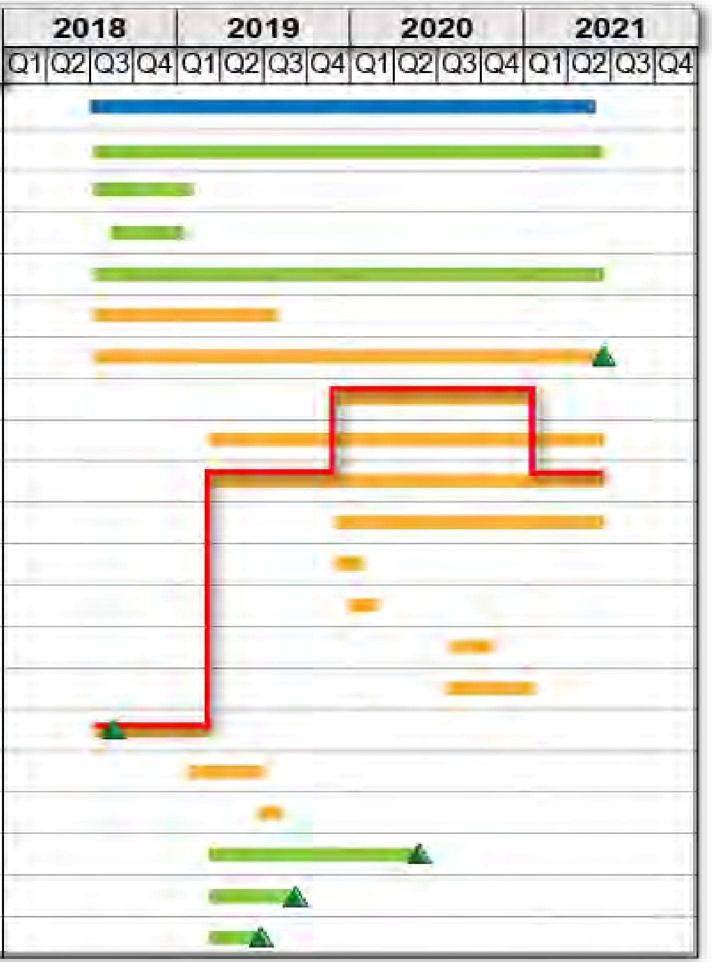
- License application being prepared in compliance with 10 CFR Part 70, "Domestic Licensing of Special Nuclear Material," 10 CFR Part 51, "Environmental Protection Regulations for Domestic Licensing and Related Regulatory Function," and other applicable regulations
- Preparation of the license application will follow the guidance in NUREG-1520, "Standard Review Plan for Fuel Cycle Facilities License Application," and other applicable NRC guidance
- The initial Regulatory Engagement Plan was submitted on August 8, 2018
  - Follow on pre-application meetings over the next six months to include:
    - Nuclear criticality safety
    - Material control and accountability
    - Security plan considerations
    - Integrated safety analysis

  These topics were selected based on the complexity and first-of-a-kind nature of the subjects

  Organizations supporting the preparation of the license application:
  X-energy – manufacturing process, design, equipment selection, license application development
  Centrus – facility design, industrial automation
  Sargent & Lundy – Site selection and characterization
  Paschal Solutions – nuclear criticality safety analyses

Plans for License Application (cont')

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

TRISO-X Fuel Fabrication Facility License Application Submitted to NRC: First Quarter 2021

Reference Acronym List

ADUN	Acid Deficient Uranyl-Nitrate
ANSI	American National Standards Institute
ASME	American Society of Mechanical Engineers
ATF	Accident Tolerant Fuel
CAT	Category
CVD	Chemical Vapor Deposition
DOE	Department of Energy
EPlan	Emergency Plan
ER	Environmental Report
FOAK	First-Of-A-Kind
HALEU	High Assay, Low Enriched Uranium
HALEU-O	High Assay, Low Enriched Uranium Oxide
HTGR	High-Temperature Gas-cooled Reactor
ISA	Integrated Safety Analysis
IPyC	Inner Pyrolytic Carbon
LWR	Light Water Reactor
NEI	Nuclear Energy Institute
NRC	Nuclear Regulatory Commission
OPyC	Outer Pyrolytic Carbon
ORNL	Oak Ridge National Laboratory
QA	Quality Assurance
QAPD	Quality Assurance Program Description
REP	Regulatory Engagement Plan
SPD	Safety Program Description
SiC	Silicon Carbide
Sol-gel	Solution-gelation
TRISO	TRistructural ISOtropic
UCO	Uranium oxide – carbide mixture
X-energy	X-Energy, LLC