Demonstration of High Quality Fuel Fabrication Process

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John Saurwein
Senior Staff Engineer
General Atomics

GENERAL ATOMICS

Outline

- Fuel description and requirements
- Fuel fabrication processes
  - Kernels
  - Coated particles
  - Compacts
  - Quality Control
- Fuel fabrication data needs
- Planned fuel technology development

Extensive Coated Particle Fuel Fabrication Technology is Available

- ~40 years of international coated particle fuel development
  - US, United Kingdom, Germany, Japan, China, Russia
- TRISO fuel has been fabricated on an industrial scale
  - >45,000 kg of heavy metal in coated particle fuel used in 8 reactors
- Coated particles meeting stringent GT-MHR quality requirements fabricated in production size equipment in US and Germany

. . . but some fuel technology development needed for GT-MHR fuel

COATED PARTICLE FUEL USED IN EIGHT REACTORS

Reactor	Country	Year	Thermal Power (MW)
Dragon	Great Britain	1964-77	30
Peach Bottom	U.S.	1966-74	115
UHTREX	U.S.	1967-70	3
AVR	Germany	1966-89	46
Fort St. Vrain (FSV)	U.S.	1967-89	840
Thorium High Temperature Reactor (THTR)	Germany	1983-89	750
High Temperature Engineering Test Reactor (HTTR)	Japan	1998-	30
HTR-10	China	2002	10
... Coated particle fuel with >45,000 kg heavy metal produced for these reactors			

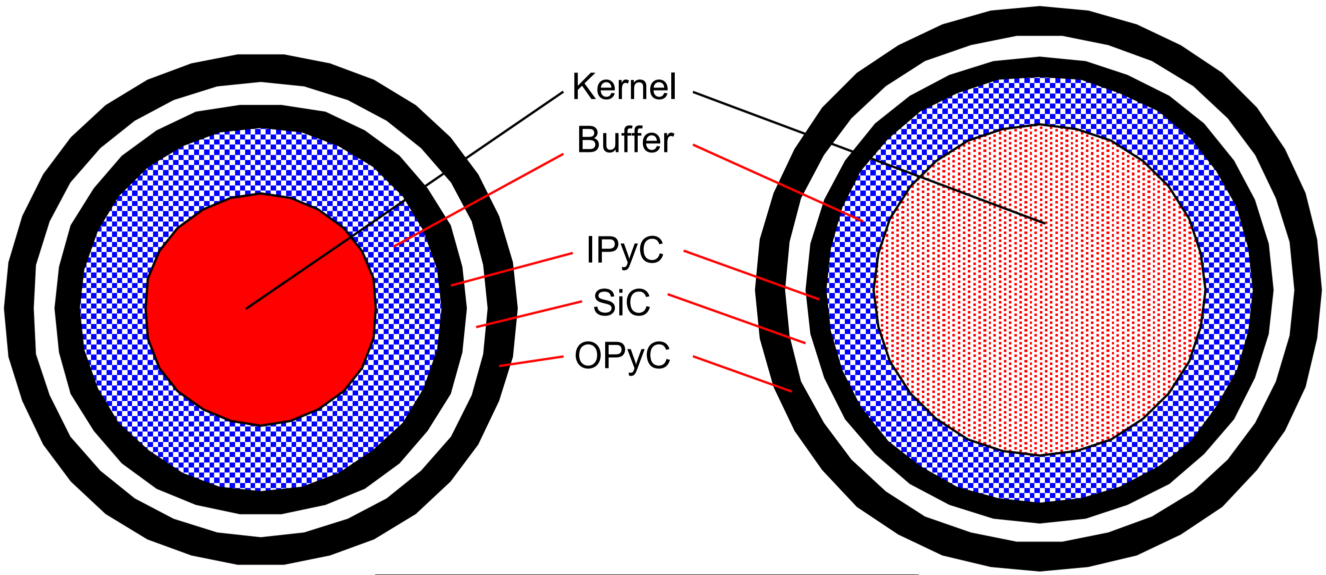
Major Objectives of Fuel Technology Development

- Finalize process and product specifications
- Scale up and improve fuel fabrication equipment
- Provide a statistically significant demonstration of GT-MHR fuel
  - Fuel manufacturing processes and Quality Control methods ensure production of fuel meeting specification requirements
  - Fuel meets GT-MHR performance requirements under normal operation and accident conditions
  - Validated methods are available to accurately predict fuel performance

GT-MHR Core Design Includes Fissile and Fertile Fuel

Fissile Particle
19.9% enriched UCO
770 microns diam.

Fertile Particle
Natural UO_2 or UCO
850 microns diam.



Layer	Fissile	Fertile
Kernel Diam	350	500
Buffer thick	100	65
IPyC thick	35	35
SiC thick	35	35
OPyC thick	40	40

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UCO Provides Superior Fuel Performance at High Burnup

- When UO_2 is fissioned
  - ~85% of liberated oxygen is absorbed by fission products
  - Excess oxygen combines with carbon to form CO and CO_2
  - Reaction of oxygen with carbon drives kernel migration
  - CO/CO_2 causes high internal pressure
- UCO is UO_2 with ~ 15% UC_2 added
  - Excess liberated oxygen reacts with UC_2 to form UO_2
  - Kernel migration suppressed
  - Internal gas pressure reduced
  - Fission products still immobilized as oxides

Summary of GT-MHR Fuel Requirements

	$P \geq 50\%$	$P \geq 95\%$
As-Manufactured Fuel Quality		
Heavy metal contamination fraction	$\leq 1.0 \times 10^{-5}$	$\leq 2.0 \times 10^{-5}$
Missing buffer fraction	$\leq 1.0 \times 10^{-5}$	$\leq 2.0 \times 10^{-5}$
SiC coating defection fraction	$\leq 5.0 \times 10^{-5}$	$\leq 1.0 \times 10^{-4}$
In-Service Performance		
Failure fraction (normal operation)	$\leq 5.0 \times 10^{-5}$	$\leq 2.0 \times 10^{-4}$
Incremental failure during accident	$\leq 1.5 \times 10^{-4}$	$\leq 6.0 \times 10^{-4}$

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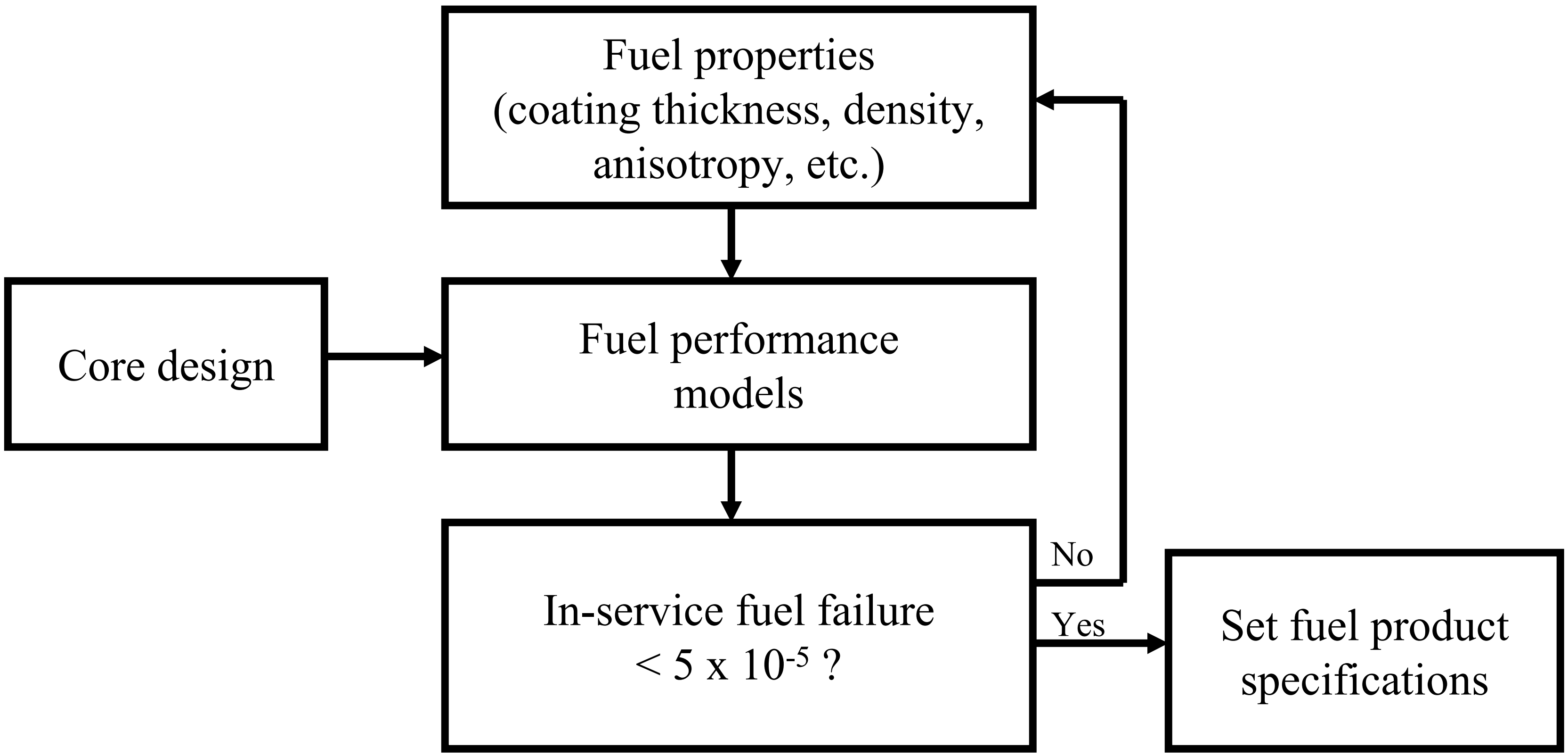
Fuel Properties are Also Specified to Prevent In-Service Fuel Failure

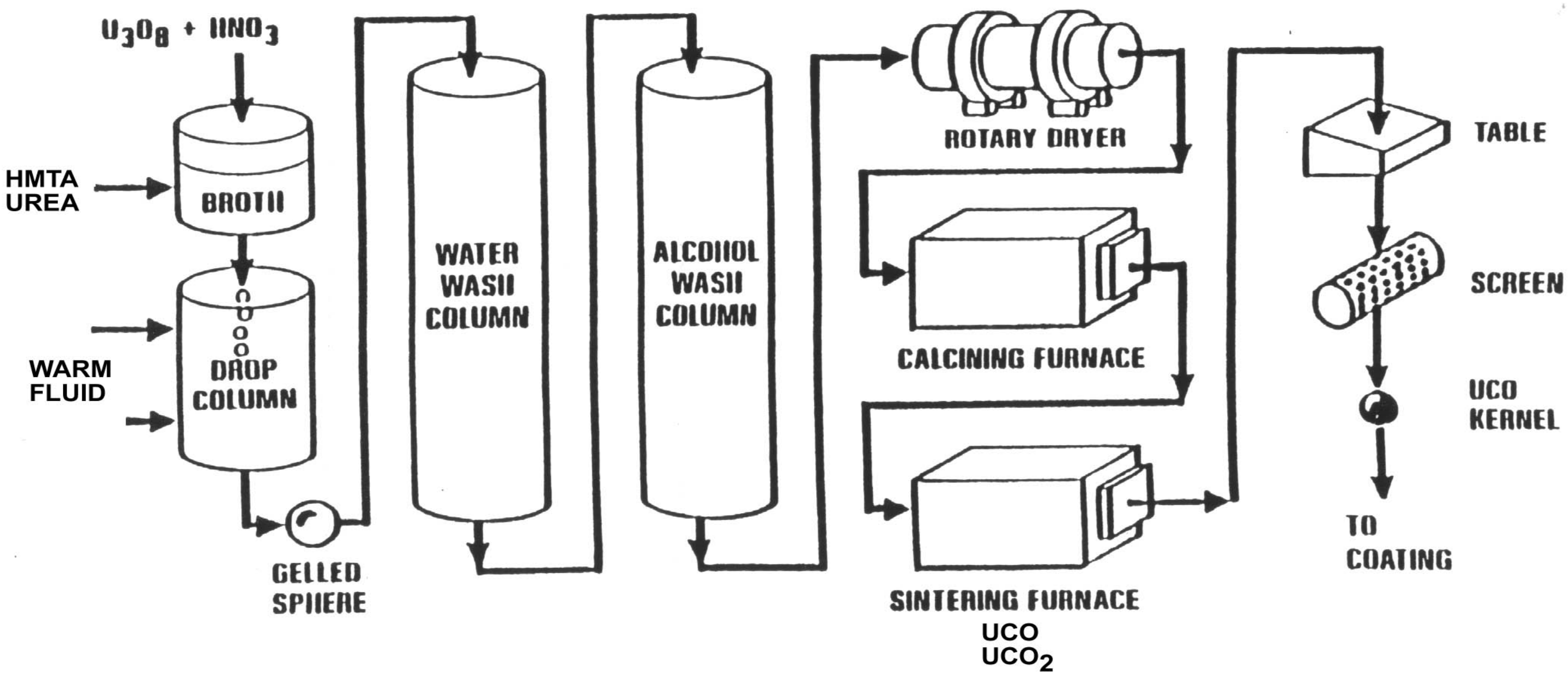


Fuel performance models establish link between in-service fuel failure and measurable fuel properties

Product Specifications and Process Specifications Control Fuel Quality

- Product specifications define property requirements for as-manufactured fuel
- Process specifications define how fuel is to be made
  - Raw material specifications
  - Equipment specifications
  - Process conditions
- Reactor designer uses both product specifications and process specifications to control fuel quality
  - Kernels and compacts - product specifications
  - Coated particles - product and process specifications

UCO Fuel Kernels Formed by Gelation Process



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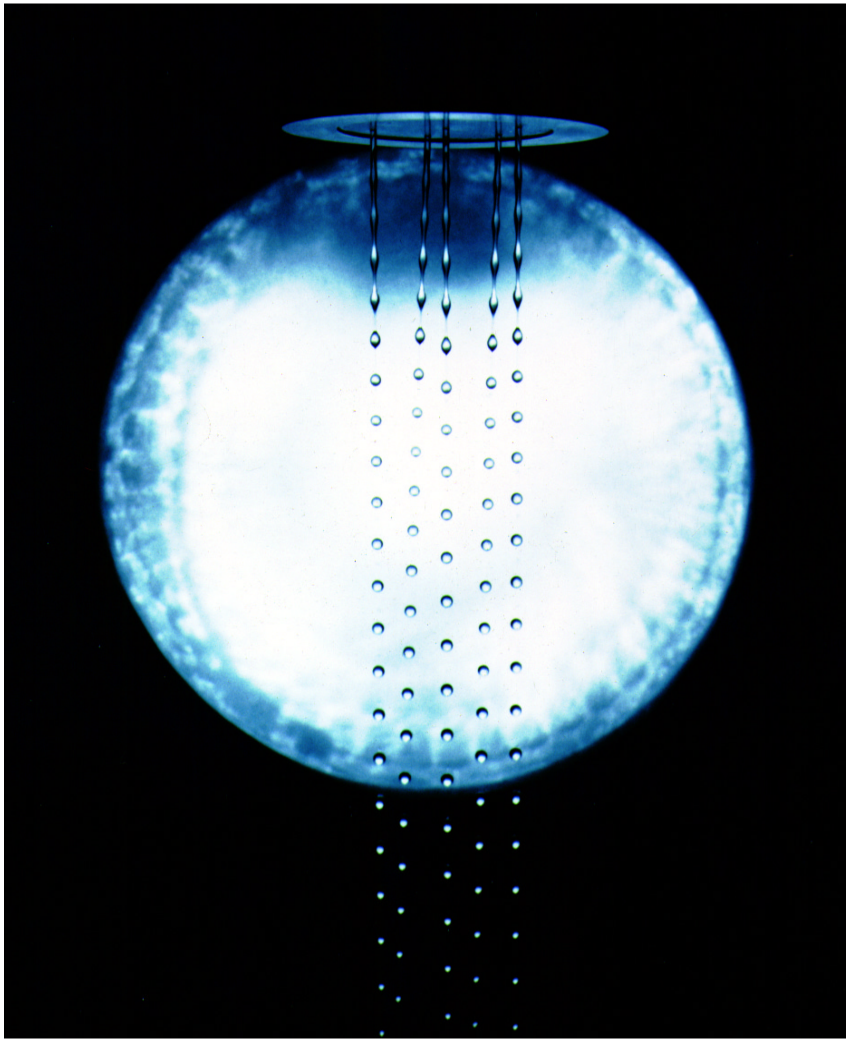
Broth is Pumped Through Vibrating Nozzles to Form Spherical Droplets



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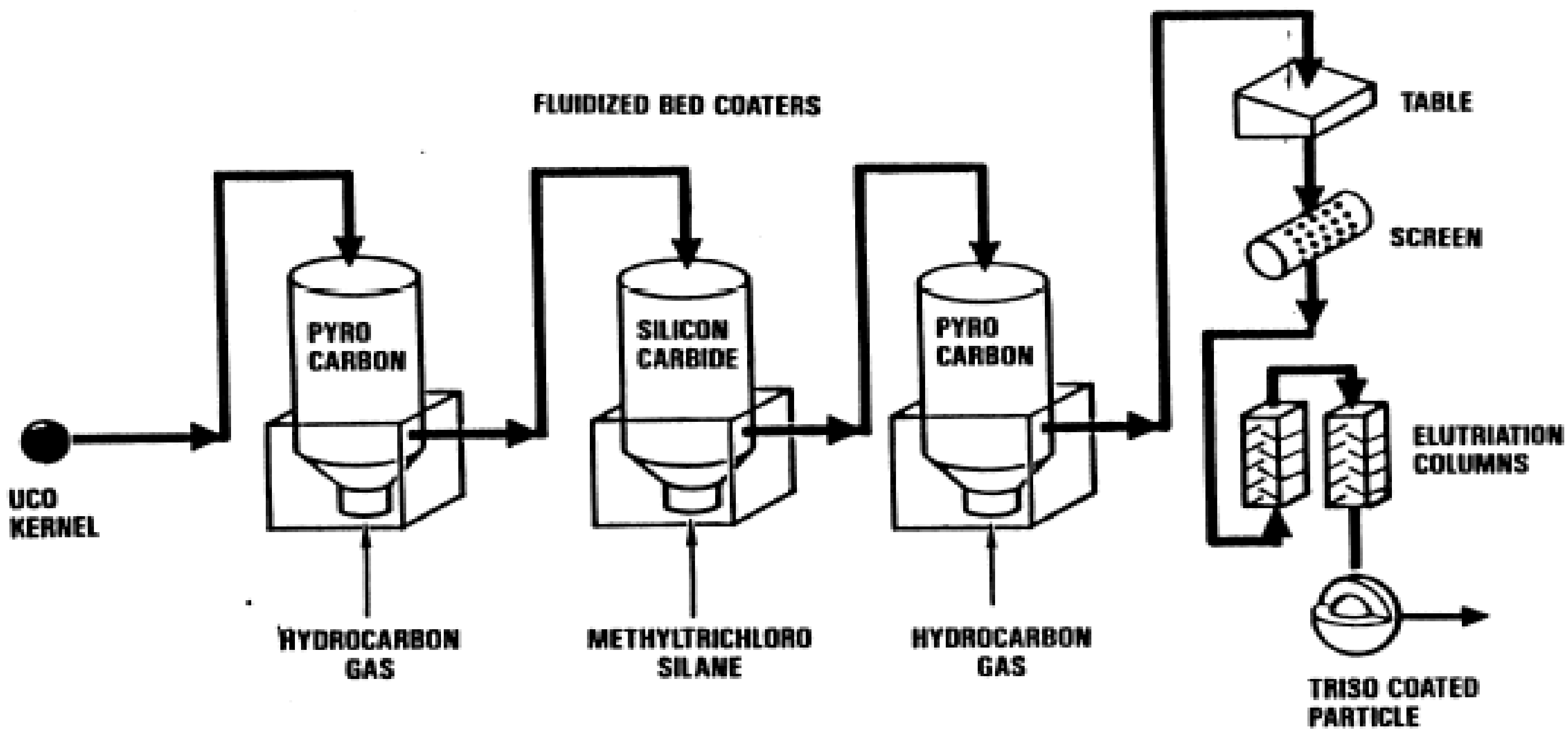
Key Kernel Properties

Property	QC Method
Density	Pycnometry
Diameter	Particle size analyzer
C/U and O/U	Combustion and wet chemistry Metallography/image analysis
Impurities	Spectrographic methods and wet chemistry

TRISO Coating Process



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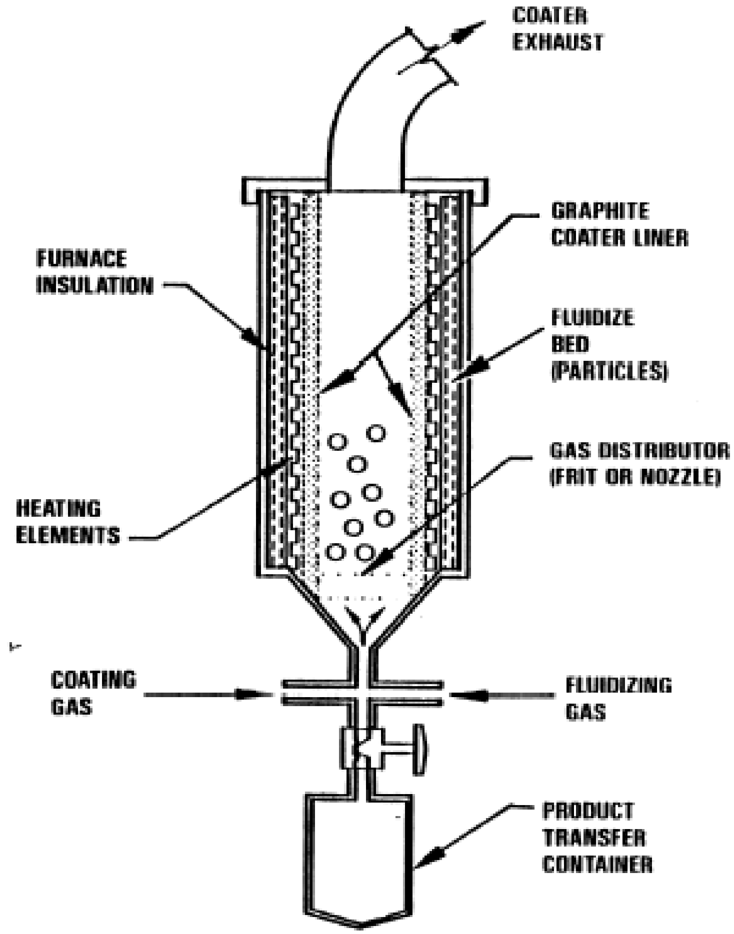
Coating Layers Deposited by CVD in a Fluidized Bed Coater

Key Coating Process Parameters

- Coater Diameter
- Batch Size
- Bed Surface Area
- Gas Distributor Configuration
- Gas Concentrations
- Gas Fluidization Velocity
- Coating Temperature
- Coating Rate



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Key Buffer Layer Properties

Property	QC Method
Thickness	Radiography
Density	Mercury pycnometry and carbon content analysis (LECO)
Missing layer	Radiography

Key IPyC Coating Properties

Property	QC Method
Thickness	Radiography
Density	Liquid gradient column
Anisotropy	Optical (BAFo)
Microstructure	Calculate coating rate and verify process conditions (temperature, coating gas ratio)
Permeability	Fuel dispersion

Key SiC Coating Properties

Property	QC Method
Thickness	Radiography
Density	Liquid gradient column
Microstructure	Calculate coating rate and verify process conditions (temperature, MTS/H_2)
Spatial defects	Burn/leach

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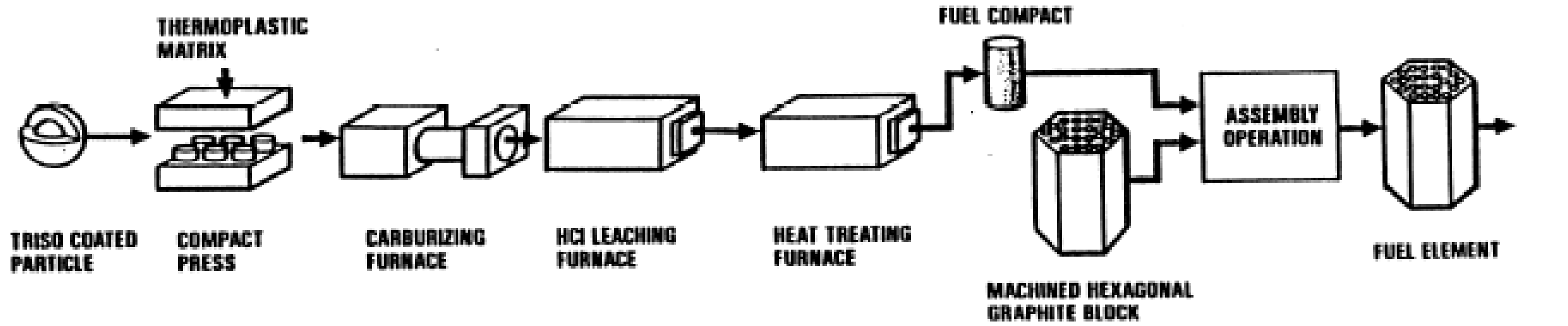
Key OPyC Coating Properties

Property	QC Method
Thickness	Radiography
Density (bulk)	Coating weight and pycnometry
Anisotropy	Optical (BAFo)
Microstructure	Calculate coating rate and verify process conditions (temperature, coating gas ratio)
Missing or defective layer	Optical microscopy
Surface connected porosity	Mercury porosimetry

Fuel Compact Fabrication Process



Key Fuel Compact Properties

Property	QC Method
Integrity	Visual inspection
Dimensions	Air gauge, ring gauge
U content	Wet chemistry
U homogeneity	Gamma spectroscopy
Defective SiC	Burn leach
U contamination	HCl leaching
Fuel dispersion	Radiography
Impurities	Spectrographic methods and wet chemistry

Quality Control

- QC verifies processes are in control and high-quality fuel has been produced
- Statistical process control
  - Monitor process conditions
  - Monitor key product characteristics
  - Timely feedback of information to process line
  - Early identification of process problems
- Product acceptance testing
  - Verify product characteristics meet specification requirements with 95% confidence

QC Acceptance Testing Based on Statistical Sampling and Analysis

- **QC approach**
  - Collect representative sample
  - Measure property of interest
  - Perform statistical tests to determine acceptability of population based on sample results
- **Proven methods**
  - Used in Fort St Vrain fuel manufacturing
  - Independently verified by INEEL during NP-MHTGR Program
  - Same approach used by Germans, Japanese, Russians

Fuel Process DDNs

DDN No.	DDN Title
C.07.01.01	UCO Kernel Process Development
C.07.01.02	Fuel Particle Coating Process Development
C.07.01.03	Fuel Compact Fabrication Process Development
C.07.01.04	Quality Control Test Technique Development
C.07.01.05	Fuel Product Recovery Development

UCO Kernel Process Development (DDN C.07.01.01)

- **OBJECTIVE**
  - Demonstrate that 350-μm and 500-μm UCO kernels manufactured in full size equipment meet fuel quality and fuel performance requirements
- **EXISTING DATA BASE**
  - Internal gelation selected over external gelation as reference process
  - 195-μm diameter UCO kernels fabricated in kilogram quantities by internal gelation for NP-MHTGR Program
  - 350-μm diameter UCO kernels fabricated in small quantities by internal gelation for DOE GT-MHR Program (1994)

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UCO Kernel Process Development (DDN C.07.01.01) (Cont.)

- ADDITIONAL DATA NEEDED
  - Process specifications for 350-μm and 500-μm UCO kernels
  - Sensitivity of product properties to process variables
  - Demonstration of capability to fabricate kernels meeting quality and yield requirements in full size equipment
  - Manufacturing cost data
- PLANNED TECHNOLOGY PROGRAM
  - Conduct process development to establish process specifications for 350-μm and 500-μm UCO kernels
  - Fabricate kernels for coating process development and irradiation test fuel
  - Design, build, and operate full-size equipment
  - Fabricate kernels for proof test fuel

Fuel Particle Coating Process Development (DDN C.07.01.02)

- OBJECTIVE
  - Demonstrate that TRISO coated particles fabricated in a production size coater meet fuel quality and fuel performance requirements
- EXISTING DATA BASE
  - TRISO coated particles mass produced for Fort St. Vrain
  - As manufactured SiC defect fraction of $<5 \times 10^{-5}$ achieved in TRISO-coated UCO in production size coater at GA, but fuel exhibited poor irradiation performance
  - Large quantities of TRISO-coated UO_2 (and some UCO) meeting as-manufactured quality and fuel performance requirement fabricated in Germany

Fluidized Bed Coater Used in Fort St. Vrain Fuel Manufacturing

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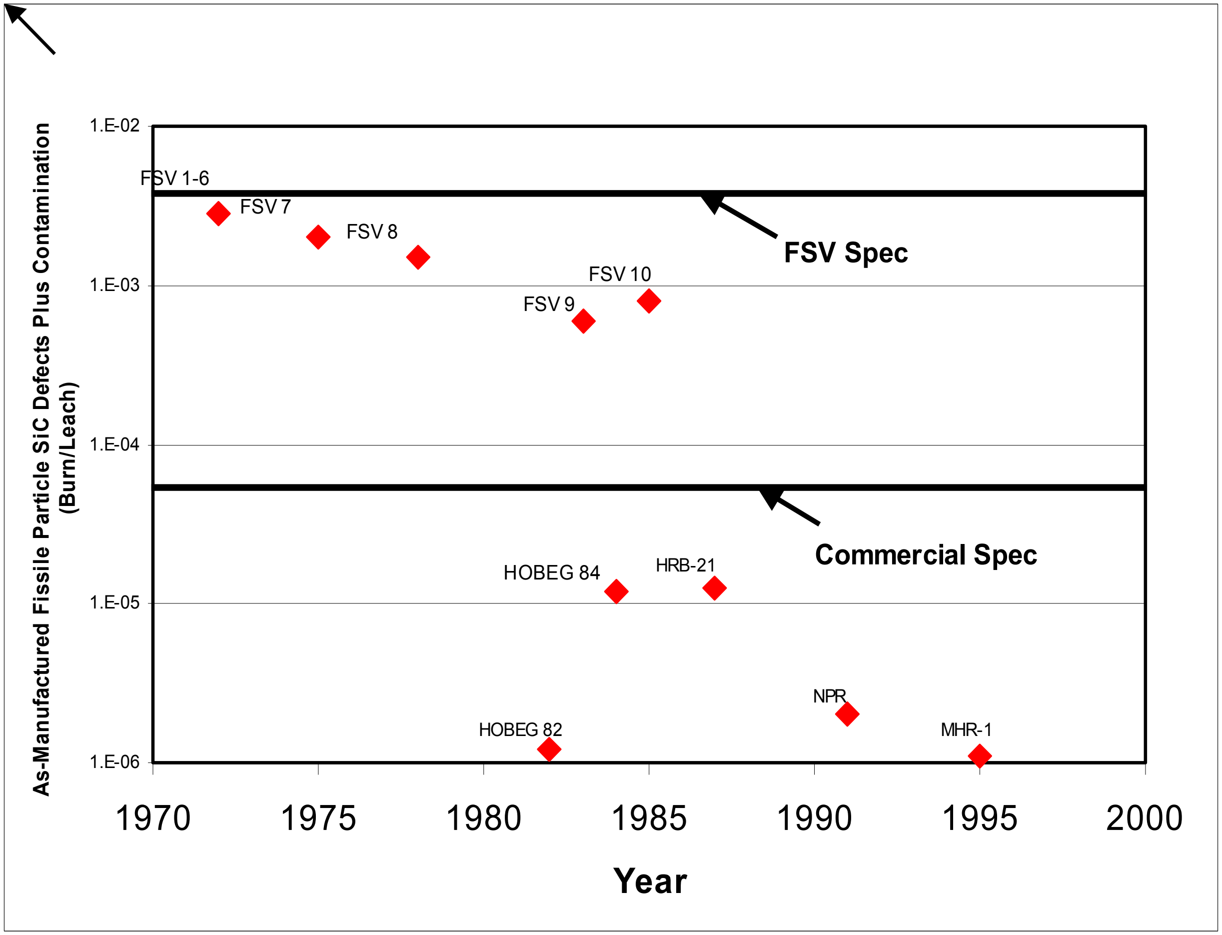
Fuel Particle Coating Process Development (DDN C.07.01.02) (Cont.)

- **ADDITIONAL DATA NEEDED**
  - Process specifications for coating UCO kernels
  - Sensitivity of product properties and irradiation performance to process variables
  - Demonstration of capability to fabricate coated particles meeting quality, fuel performance, and yield requirements in full size coater
  - Manufacturing cost data
- **PLANNED TECHNOLOGY PROGRAM**
  - Conduct coating process development to adapt German coating technology to GT-MHR UCO fuel
  - Fabricate coated particles for compact process development and irradiation test fuel
  - Design, build, and operate full-size coater
  - Fabricate coated particles for qualification test and proof test fuel

Fuel Compact Fabrication Process (DDN C.07.01.03)

- **OBJECTIVE**
  - Demonstrate that fuel compacts fabricated with thermosetting matrix in full size equipment meet fuel quality and fuel performance requirements
- **EXISTING DATA BASE**
  - Fuel compacts mass produced for Fort St. Vrain (FSV)
  - Capability to fabricate compacts meeting GT-MHR quality requirements demonstrated in laboratory scale equipment
  - GA compacting process uses a thermoplastic matrix
  - Thermosetting matrix widely used internationally

Coated Particle Fuel Meeting GT-MHR Quality Requirements Has Been Fabricated



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Fuel Compact Fabrication Process (DDN C.07.01.03) (Cont.)

- **ADDITIONAL DATA NEEDED**
  - Process specifications for thermosetting matrix process
  - Sensitivity of product properties to process variables
  - Demonstration of capability to fabricate compacts meeting quality, fuel performance, and yield requirements in full size equipment
  - Manufacturing cost data
- **PLANNED TECHNOLOGY PROGRAM**
  - Conduct process development to establish process specifications for thermosetting matrix based process
  - Fabricate irradiation test fuel
  - Design, build, and operate full-size equipment
  - Fabricate and irradiate proof test fuel

Quality Control Test Technique Development (DDN C.07.01.04)

- OBJECTIVE
  - Develop improved QC methods for GT-MHR fuel manufacturing
- EXISTING DATA BASE
  - Full set of QC methods developed and used for Fort St. Vrain (FSV) fuel manufacturing
  - FSV QC methods for coated particles are basically the same as QC methods used by Germans
  - Fuel fabricated for NPR and GT-MHR irradiation tests satisfied fuel product specifications but exhibited poor irradiation performance

Quality Control Test Technique Development (DDN C.07.01.04) (Cont.)

- ADDITIONAL DATA NEEDED
  - QC methods for enhanced characterization of fuel
    - SiC defects
    - SiC microstructure
    - PyC microstructure
    - C/U and O/U in individual UCO kernels
  - Automated QC methods for mass production of fuel
  - QC costs for large-scale fuel production
- PLANNED TECHNOLOGY PROGRAM
  - Develop new QC methods for enhanced fuel characterization
  - Use new QC methods to improve characterization of irradiation test fuel
  - Develop and qualify automated QC methods
  - Demonstrate automated QC methods in fuel manufacturing plant

Summary of Planned Fuel Fabrication Process Technology Development

- Process Development
  - Establish process conditions for 350-μm and 500-μm UCO kernels
  - Adapt German coating technology to GT-MHR UCO fuel
  - Develop thermosetting matrix compact fabrication process
  - Develop QC methods for enhanced characterization of fuel
  - Fabricate fuel for irradiation testing
  - Adjust processes based on feedback from irradiation testing
- Fuel Qualification
  - Finalize design, build, and install prototypic equipment
  - Establish process specifications
  - Fabricate qualification test fuel

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Summary of Planned Fuel Fabrication Process Technology Development

- **Process Demonstration**
  - Develop and demonstrate improved QC methods for mass production
  - Build plant with automated, full-size equipment
  - Demonstrate process capability
  - Develop process cost data
  - Fabricate and irradiate proof test fuel

Summary

- Product and process specifications control as-manufactured defects and fuel product properties important to irradiation performance
- Extensive coated-particle-fuel fabrication technology available, but some technology development needed for GT-MHR fuel
- DDNs systematically identify data needs and necessary technology development
- Planned fuel fabrication process technology development will satisfy major program objectives
  - Finalize process and product specifications for UCO fuel
  - Scale up and improve fuel fabrication equipment
  - Demonstrate fuel fabrication to specification requirements
  - Provide fuel for irradiation testing to verify fuel performance

Outcome Objectives

- NRC agreement or comment on the adequacy of fuel fabrication DDNs at identifying data needed to satisfy regulatory needs relative to the GT-MHR source term