NC STATE UNIVERSITY

Overview and Introduction

NE 533: Nuclear Fuel Performance

Spring 2025

Dr. Benjamin Beeler

OVERVIEW

Access to Course Resources

- Everything will be hosted on Moodle, classes conducted in-person and via Zoom
- To access Moodle courses, log on to WolfWare with your Unity ID and password
- Lecture recordings will be available via Panopto
- Lecture PDFs will be uploaded to Moodle after each class
- Office hours will be held in my office on Wednesdays 9-10 am
- Additional office hours (in person or virtual) can be scheduled via email
- I encourage all to reach out to me with any questions or concerns
- Have invited everyone to a Slack channel for ease of communication

Syllabus

Course Overview

In this course we will study the basic role of fuel in reactor operation and understand how the fuel impacts heat generation and transport to the coolant. The course will begin with an overview of different fuels and the fabrication processes required to construct nuclear fuel. This will include various fuel types and geometries, with a focus on light water reactor fuel and cladding. Thermal transport, mechanics, and thermomechanics affecting fuel behavior will be introduced, and methods to solve the governing equations numerically and analytically will be developed. Subsequently, changes in the fuel and cladding material that degrade the performance of the fuel will be examined. Finally, the knowledge gained throughout the course will be utilized to conduct fuel performance simulations with MOOSE.

Learning Outcomes

By the end of this course, the student should be able to:

1. Summarize the basics of fuel fabrication
2. Evaluate traditional and alternative nuclear fuel types and their application
3. Determine the rate at which heat is transported to the coolant from the fuel
4. Determine the stress state within both the fuel and the cladding
5. Describe the most important microstructural changes that take place in the fuel and cladding and how they impact fuel performance
6. Critically analyze existing literature in fuel performance modeling
7. Use an existing fuel performance code

Topical Outline

- Module 1: Fuels, Systems, Heat Conduction Equation, and Numerical Discretization
- Module 2: Mechanics, Thermomechanics, and Intro to MOOSE
- Module 3: Fission Products, Swelling, and Pellet Cladding Interactions
- Module 4: Corrosion, Accidents, and Advanced Fuels

Modules contain 4-5 lectures, with an exam at the end of the module

Graded Exercises

- Four exams (64%)
- One paper presentation project (16%)
- One MOOSE-based project (in three parts) (20%)

Please note: the course schedule is subject to change.

Exams, Projects, Grading

- Using the standard NCSU +/- grading system
- Four exams will be conducted closed book (with cheat sheet) and held during normal class hours
- Will work with distance students to schedule exams
- Will do problem session lecture prior to exam periods
- Project presentations will be via PPT and conducted during normal class hours
- No final exam

Paper Project

- Will assign a paper related to the course
- Will deliver a 15-minute presentation providing a critical review of the paper
- This is basically a mini QE Part 1, without the report
- If you have a topic that you want the paper to address, I will do my best to accommodate that
- Will occur around the midpoint of the semester
- Accounts for 16% of your grade

MOOSE Project

- Computational project will be via MOOSE, where code (inputs/outputs) will be submitted in addition to a writeup
- Project is split into 3 parts, each with a submission
- The submissions are building upon each other
  - Submission 1 = Part 1; Submission 2 = Part 1+ Part 2; Submission 3 = All three parts
  - Grading is performed on the entirety of each submission
  - Thus, you need to fix mistakes made in Part 1 for subsequent submissions
  - MOOSE project is 20% of your grade, with Submission 1 = 5%; Submission 2 = 5%; Submission 3 = 10%
- I am being this granular because some of this has been unclear previously

Feedback

- No course is static, and I need your feedback to modify/update the course to meet the needs of the students
- I will be reaching out for feedback periodically throughout the semester
- Completion of feedback will gain extra credit (+5) on exams

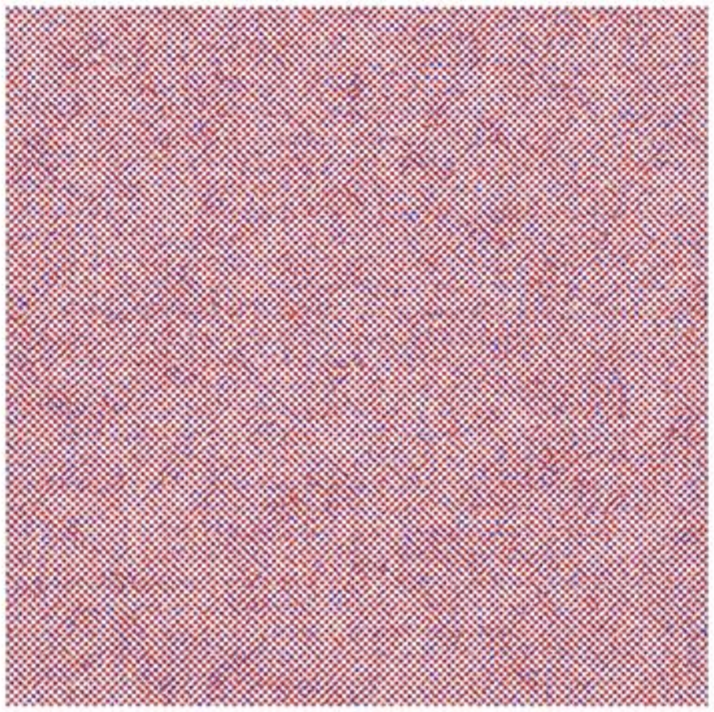
Miscellaneous

- My exams are known to be time-consuming but not hard, so be familiar with the material and don’t overly rely on your cheat sheet
- My slides are generally information-dense, so if I am going too fast, stop me
- Always ask questions, I don’t know if you aren’t getting it unless you tell me
- I want to help you succeed in this class, so get help if you need it

- Finally, I have two speech impediments and a southern accent
- I stutter and will struggle through some lectures; bear with me and ask me to repeat something if it is unintelligible

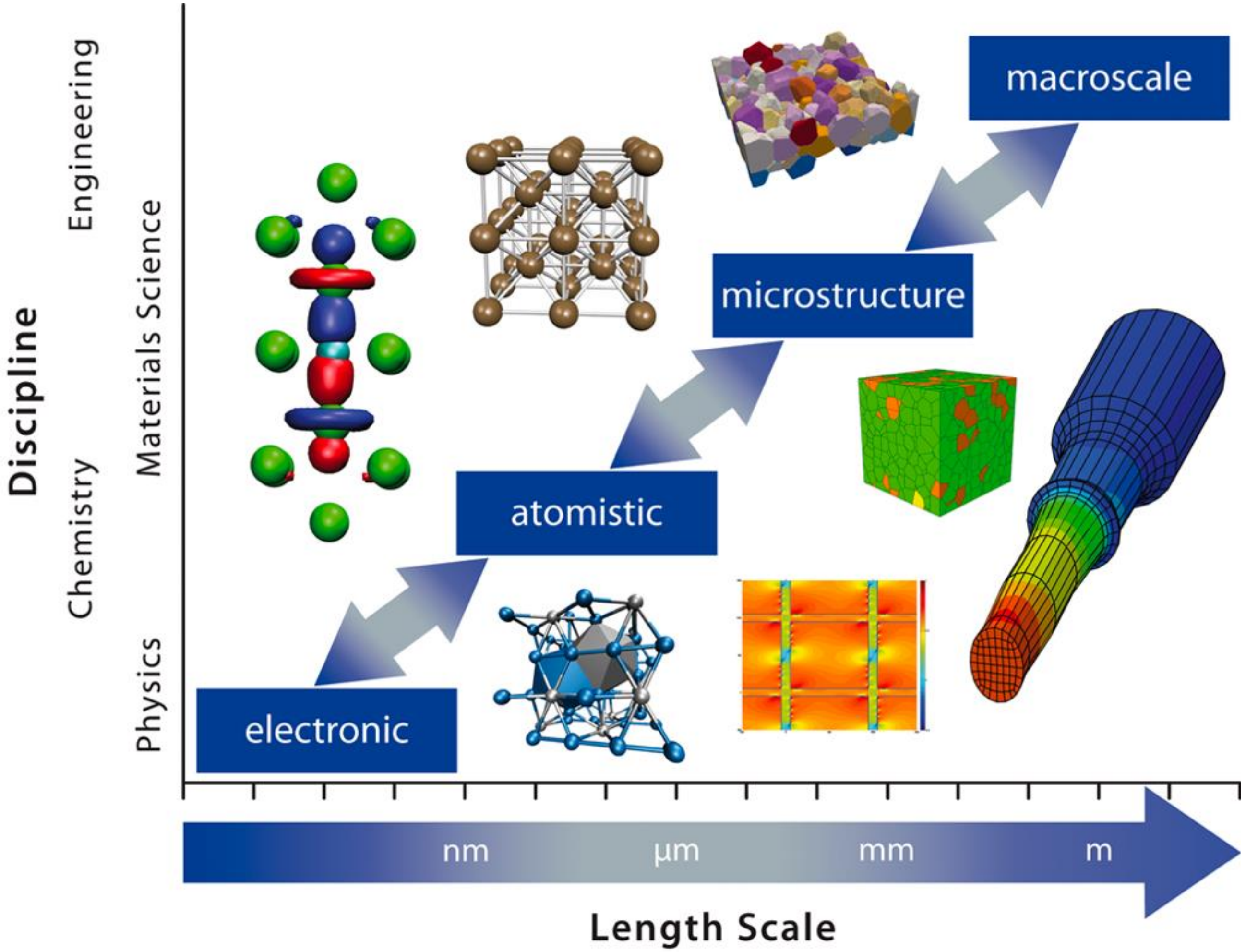
Brief Bio/Background

- Computational Nuclear Materials Scientist
- Expertise in advanced nuclear fuels
- Ph.D. in Nuclear Engineering from Georgia Tech
- Previously a staff scientist at Idaho National Laboratory in Fuel Modeling and Simulation Group
- Atomistic simulations: density functional theory and molecular dynamics



My viewpoint/approach

- Scientifically informed engineering is a multiscale problem
- Critical phenomena need to be identified from the macroscale, and informed from the lower length scales
- Perform good science, sometimes for science's sake, but often to address a key engineering problem or need

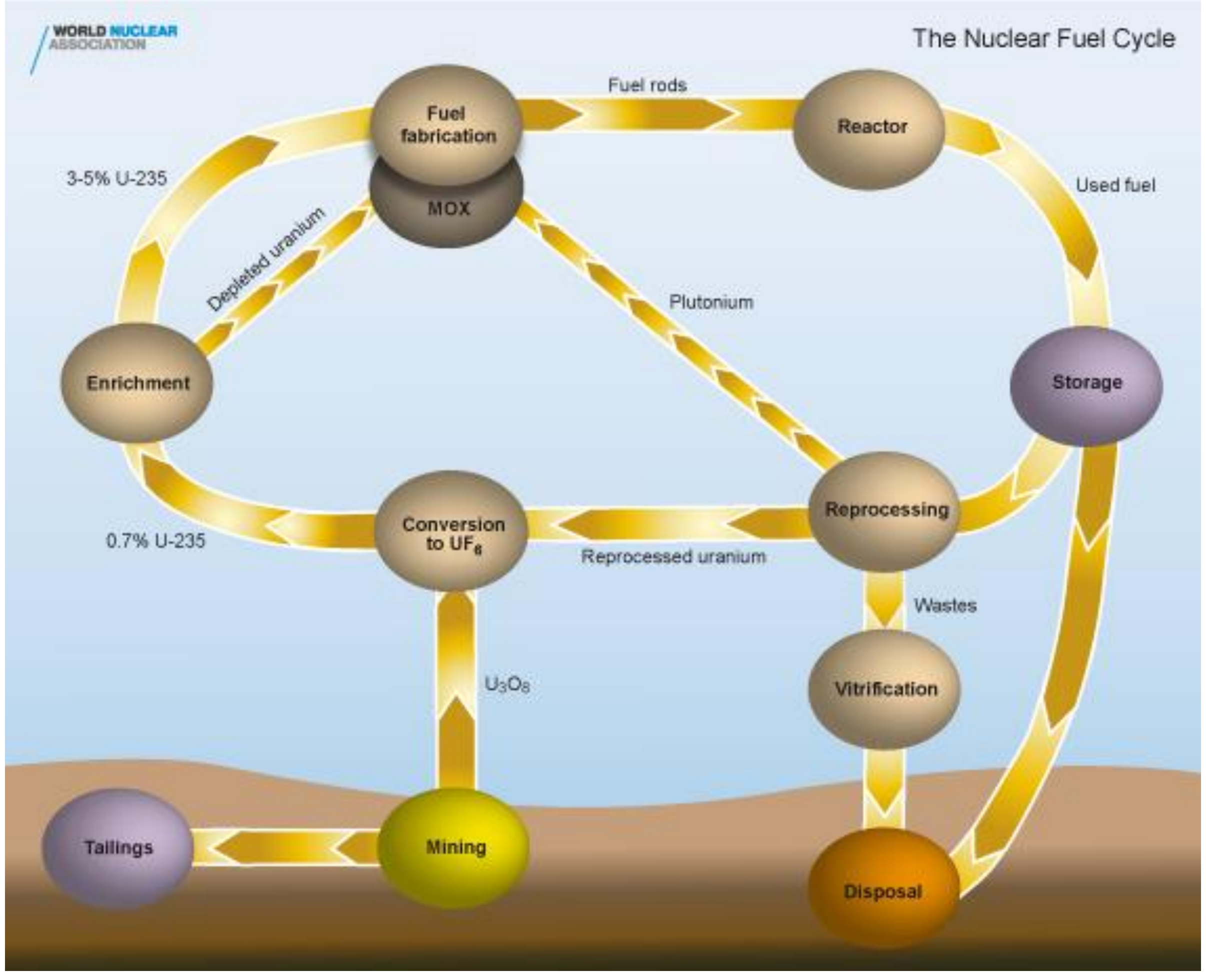


TELL ME ABOUT YOURSELF

- Name, including how to pronounce it ‘properly’
- Where you’re from
- PhD/Masters/ABM
- Advisor and research topic (if applicable)
- Anything else???

INTRODUCTION

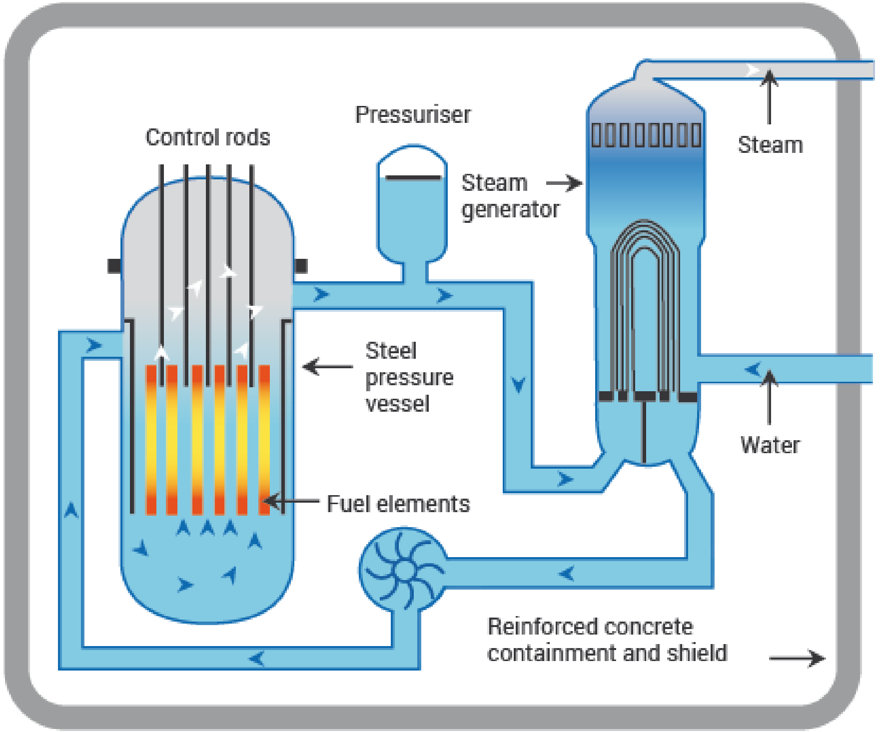
Complete nuclear fuel cycle



Emphasis on In-Reactor Behavior of Fuel

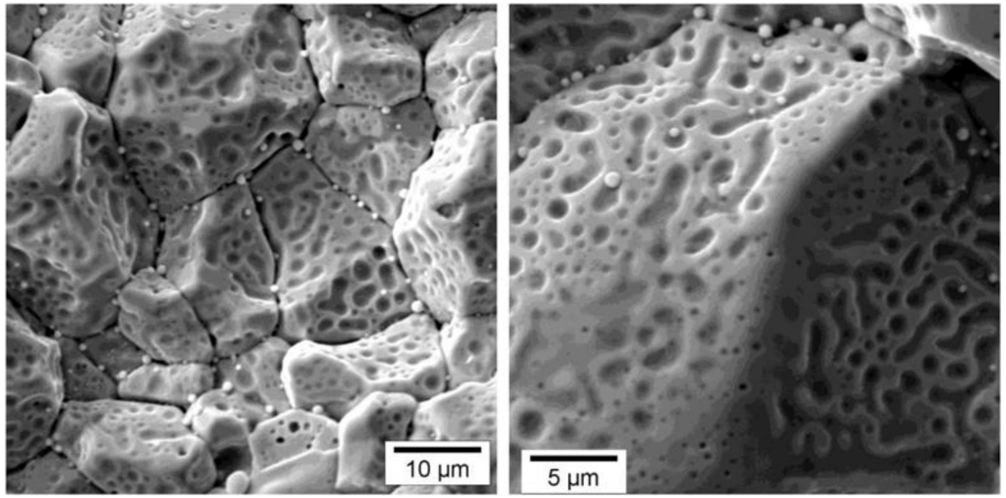
- The full reactor system is complex and substantial, and there are separate NE courses covering this area
- Although the fuel is a relatively small part of a reactor system, it determines thermal power, which drives electric power generation
- The performance of the fuel is measured by:
  - How much heat is delivered to the coolant
  - The length of time it operates without any problems
  - How well it performs during an accident

A Pressurized Water Reactor (PWR)



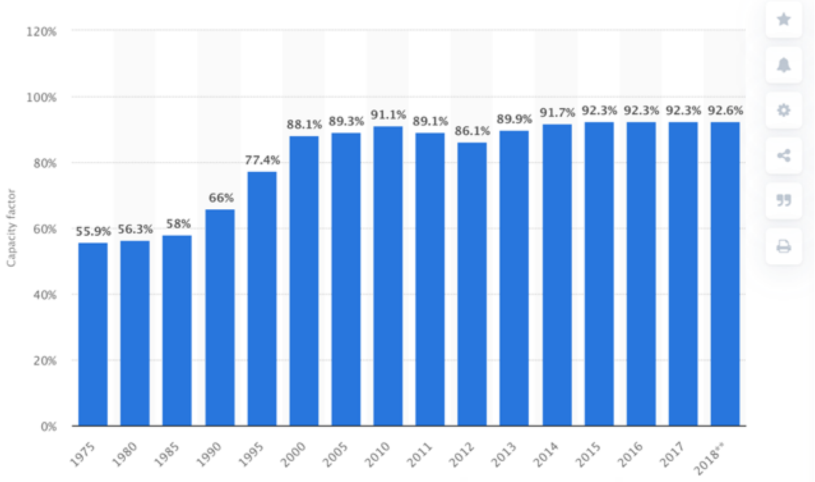
How much heat is delivered to the coolant?

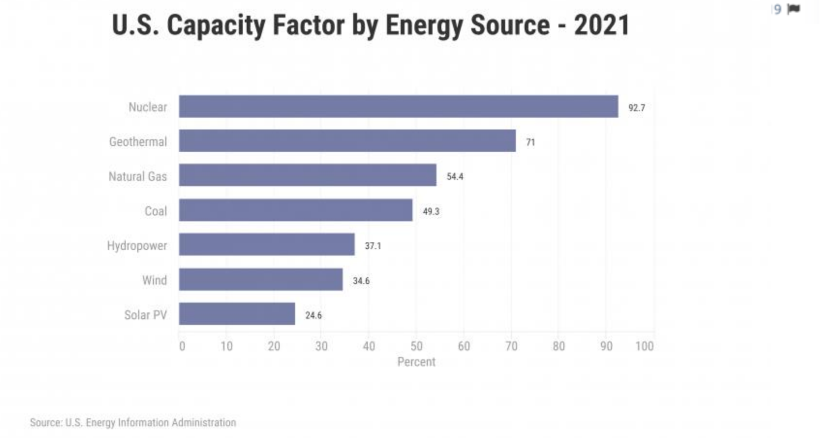
- Heat generated by fuel
- Heat transport is related to thermal conductivity
- In single crystal, pristine materials, thermal conductivity is reasonably straightforward
- In dynamic, radiation environments, thermal conductivity degrades, fission gas bubbles form, grain boundaries are generated and destroyed, changing geometries, evolving chemical compositions, etc.
- How does thermal conductivity vary?



The length of time fuel operates without any problems

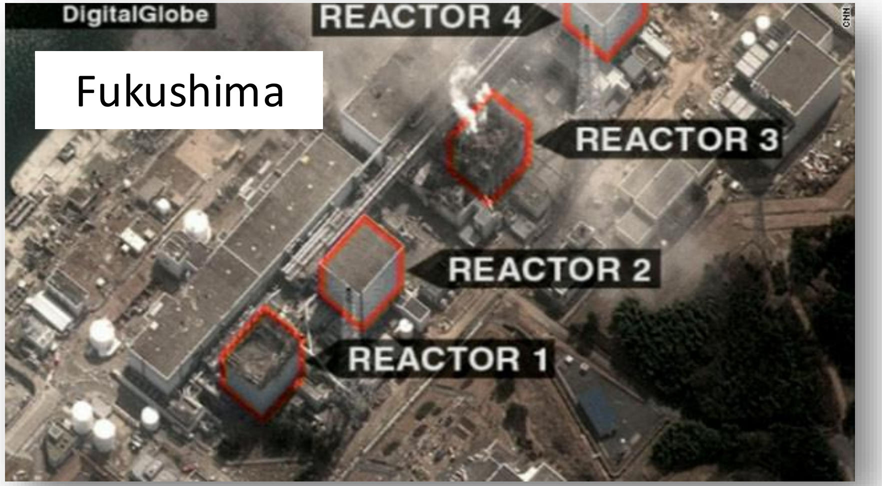
- There are 94 operating nuclear reactors in the US, producing ~20% of the electricity
- The net capacity factor is the ratio of an actual electrical energy output to the maximum possible electrical energy output over a period of time
- Nuclear reactor capacity factor is ~92% over the past decade
- The ability to maintain a high capacity factor, largely by limiting shutdown time, is key in making nuclear power economical
- Fuel is the primary component forcing reactor downtime

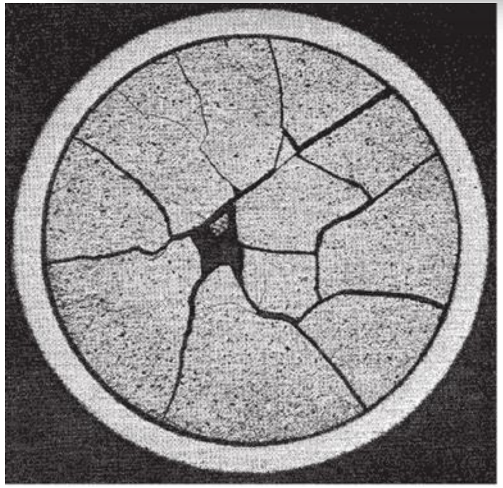


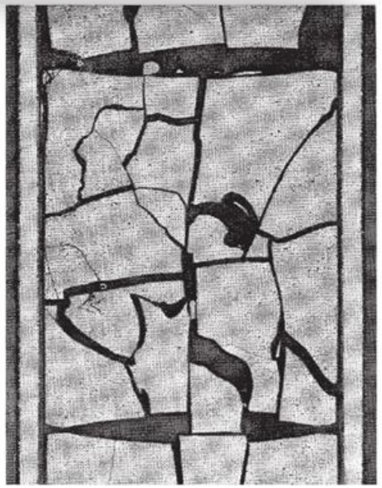


Fuel behavior during accidents

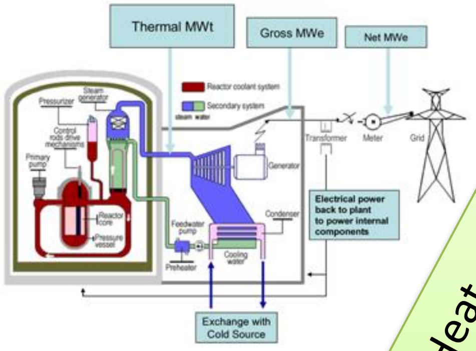
- In addition to normal operating conditions, the behavior of the fuel during accidents is of critical importance
- Predictable, and hopefully stable, behavior is desired during a variety of accident scenarios
- Even low impact accidents are detrimental to public opinion surrounding nuclear energy







All of these factors together represent what we call "fuel performance"

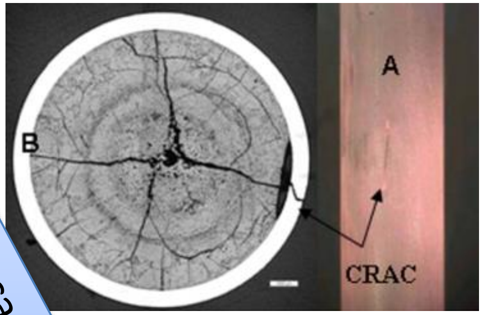


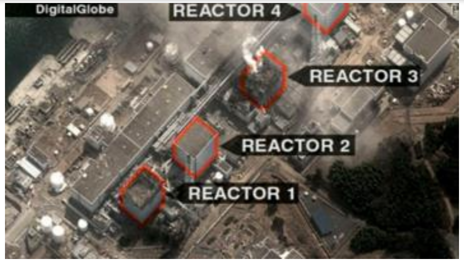
Heat generation

Fuel problems causing unscheduled outages

Fuel Performance

Fuel behavior during an accident



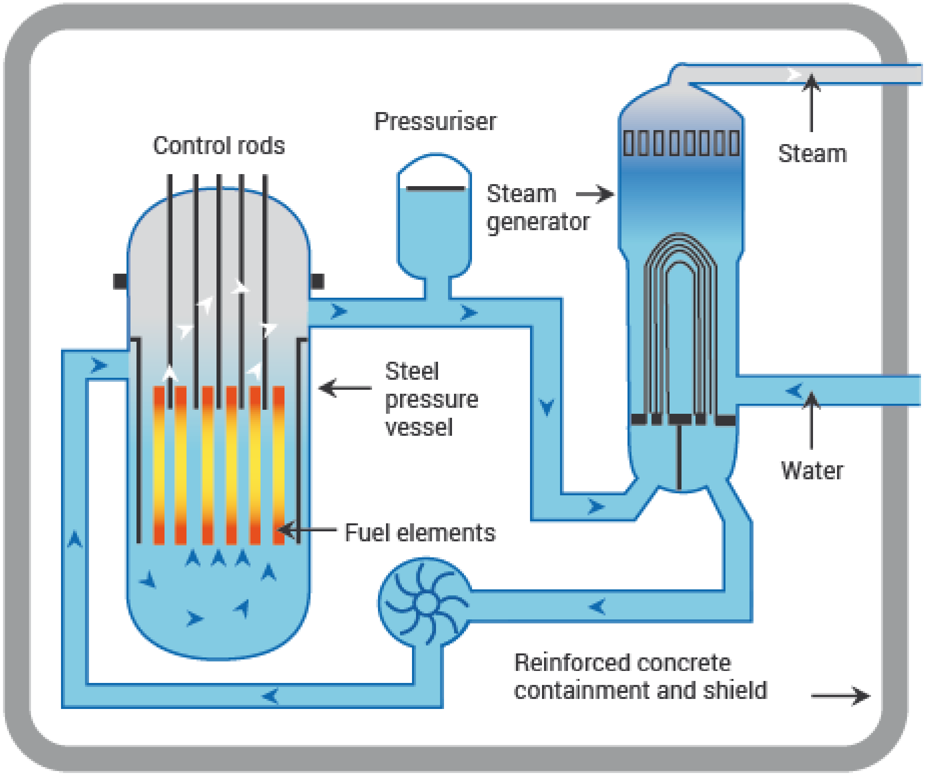


FUEL TYPES

Fuel is the Heat Source

- Fuel functions as a heat source, generating heat that is transferred to a coolant, which transfers heat through external loops, heat exchangers, etc., to run a generator

A Pressurized Water Reactor (PWR)



Fuel is limited to select elements

- A **fissionable nuclide** is capable of undergoing fission (even with a low probability) after capturing a high energy neutron
- A **fissile nuclide** is capable of sustaining a nuclear fission chain reaction with neutrons of any energy
- A **fertile material** is a material that, although not itself fissionable, can be converted into a fissile nuclide by neutron absorption and subsequent nuclei conversions.

- The Ronen **fissile rule** states that for a heavy element with $90 \leq Z \leq 100$, its isotopes with neutrons $(A-Z) = 2 \times Z - N$, where $N = 43 \pm 2$ are fissile (with some exceptions)

Potential fuel candidates

- The heavy elements with $90 \le Z \le 100$
  - Thorium (Th), Protactinium (Pa), Uranium (U), Neptunium (Np), Plutonium (Pu), Americium (Am), Curium (Cm), Berkelium (Bk), Californium (Cf), Einsteinium (Es) and Fermium (Fm)
- Let's apply the fissile rule to U ($2 \times Z - N$)
  - $(A\text{-}Z) = 2Z - (43 \pm 2)$
  - $(A\text{-}Z) = 2 \times 92 - [41, 42, 43, 44, 45] = [143, 142, 141, 140, 139]$ neutrons
  - So, U-231 through U-235 should be fissile

There are only four fissile nuclides that are practical for nuclear fuel

- U-235
  - Naturally occurs in uranium in small amounts (0.7%). Can be enriched
- Pu-239
  - Bred from U-238 by neutron capture

$$^{238}\mathrm{U} + n \xrightarrow{\gamma} {}^{239}\mathrm{U} \xrightarrow{\beta} {}^{239}\mathrm{Np} \xrightarrow{\beta} {}^{239}\mathrm{Pu}$$

- Pu-241
  - Bred from Pu-240 (which comes from Pu-239) by neutron capture

$$^{239}Pu + n \rightarrow {}^{240}Pu + n \rightarrow {}^{241}Pu$$

- U-233
  - Bred from Th-232 by neutron capture

$$^{232}\mathrm{Th} + n \xrightarrow{\gamma} {}^{233}\mathrm{Th} \xrightarrow{\beta} {}^{233}\mathrm{Pa} \xrightarrow{\beta} {}^{233}\mathrm{U}$$

Fuel Considerations

- Safety:
  - Stable and predictable behavior
  - No melting, no phase changes under transients that lead to deleterious behavior
- Uranium density
- Mechanical integrity
- Cladding interactions
- Swelling and fission gas release
- Operating temperatures

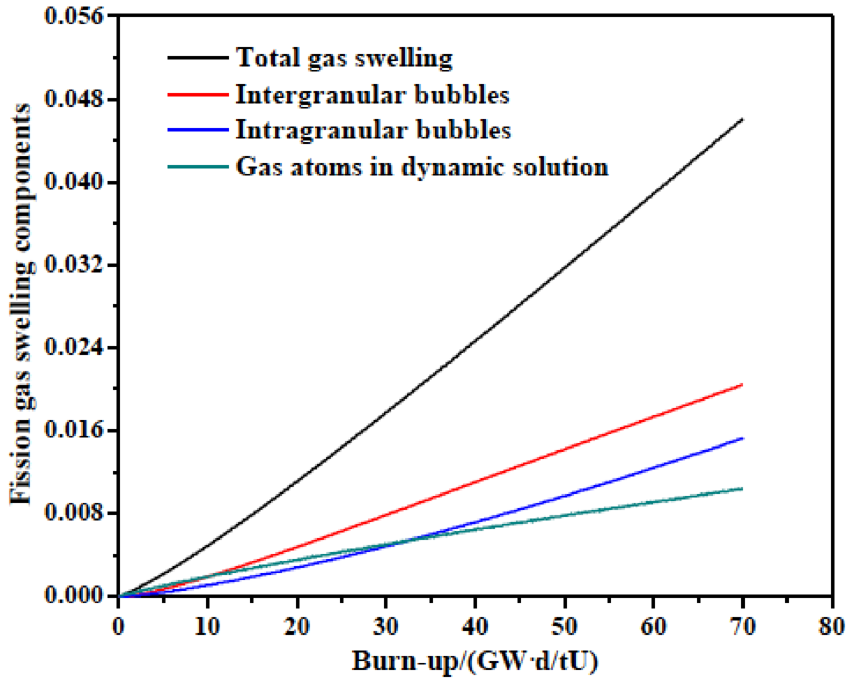
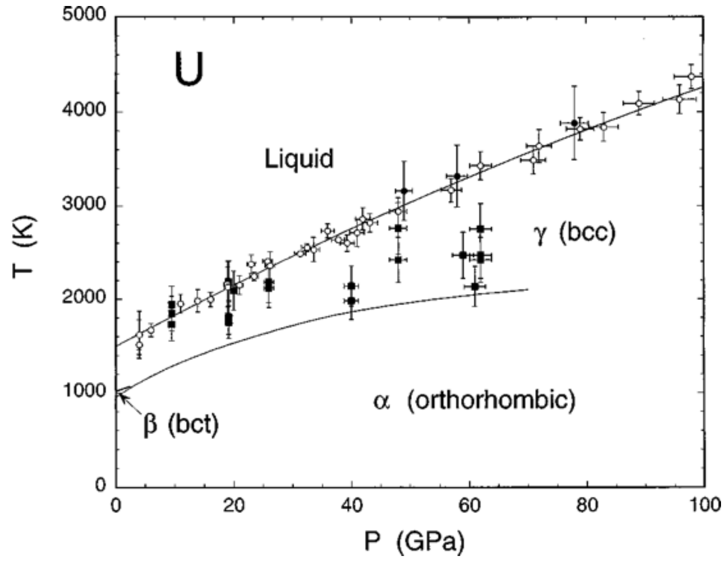
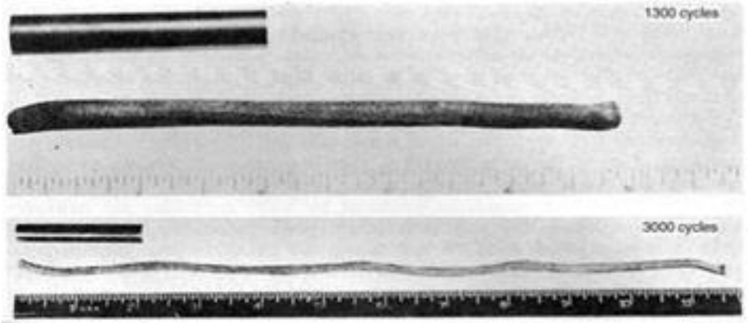


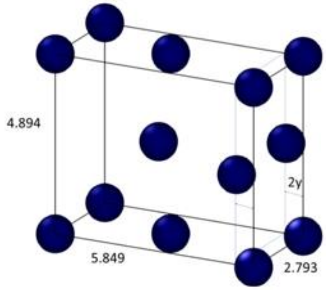
Fig. 4. Variation of swelling rate components of fission gas in UO_2 fuel with the burn-up.

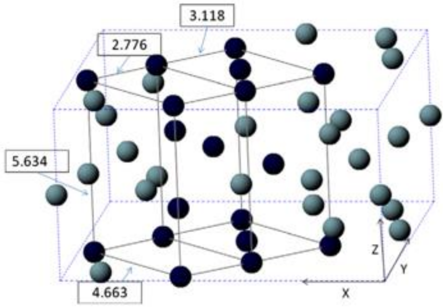
Why not use pure uranium metal?

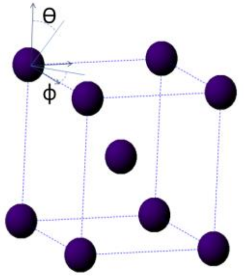
- Pure uranium has three phases
  - α-phase is orthorhombic
  - β-phase is tetragonal
  - γ-phase is body-centered cubic
  - During thermal cycling, pure uranium dramatically swells
  - Alpha U has both anisotropic thermal expansion and anisotropic irradiation growth











Fuel Types and Associated Reactor Types

- UO_2 – Light Water Reactors
  - Mixed oxide (MOX)
  - Accident tolerant/Advanced Technology Fuel (ATF)
- UZr – Sodium Cooled Fast Reactors
- UMo – Research Reactors
- UC/UCO – High Temperature Gas Reactors
- UN – Lead Cooled Fast Reactors
- Other

Uranium Dioxide (UO2)

- Reference fuel for nuclear power industry
- Single phase, fluorite structure
- Fabrication via sintering UO2 powder into pellets
- Water coolant
- Pellets are stacked inside Zircaloy cladding tubes