NC STATE UNIVERSITY

Overview and Introduction

NE 533: Nuclear Fuel Performance

Spring 2023

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
- Office hours will be held in my office on Wednesdays 10-11 am
- Additional virtual office hours can be scheduled via email
- I encourage all to reach out to me with any questions or concerns

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. Use an existing fuel performance code

Topical Outline

- Introduction and Overview
- Fuel types
- Fuel fabrication
- Thermal transport
- Mechanical behavior
- Materials issues in the fuel
- Materials issues in the cladding
- Used fuel disposition
- Overview of fuel performance codes
- Utilization of fuel performance codes

Graded Exercises

- Four exams
- One paper presentation project
- One MOOSE-based project (in three parts)

Exams, Projects, Grading

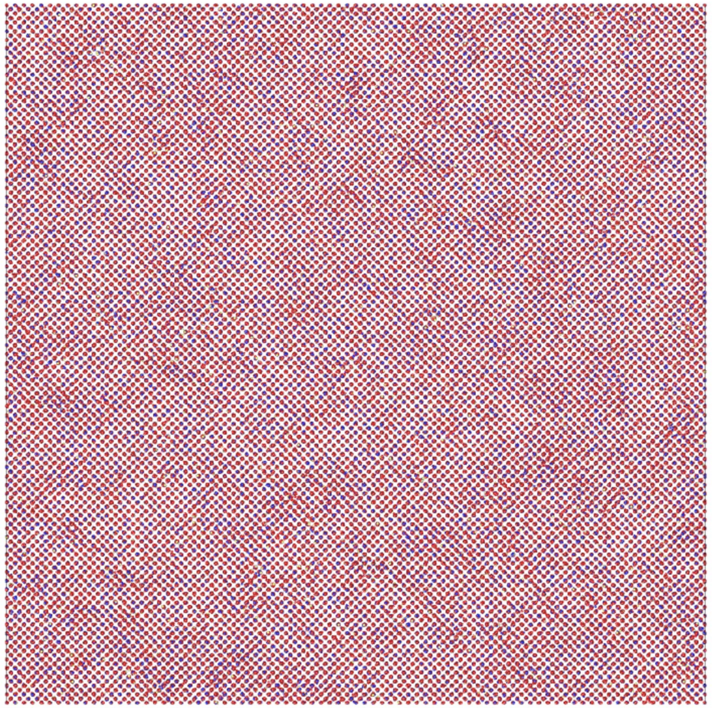
- Using the standard NCSU +/- grading system
- Four exams will be conducted open book, timed, and held during normal class hours
- Will do problem session lecture prior to exam periods
- Project presentations will be via PPT and conducted during normal class hours
- Computational project will be via MOOSE, where code will be submitted in addition to a writeup
- No final exam

Feedback

- This course is still evolving, and I want to make sure that this class is able to meet the needs of the students, provides relevant information, and is taught at a level commensurate with the abilities of the students, and I need your feedback to do that
- I will be reaching out for feedback periodically throughout the semester
- Completion of feedback will gain extra credit on exams
- Fill out the “Tell me about yourself” forum/activity on the Moodle so I can get to know everyone, and you can get to know each other

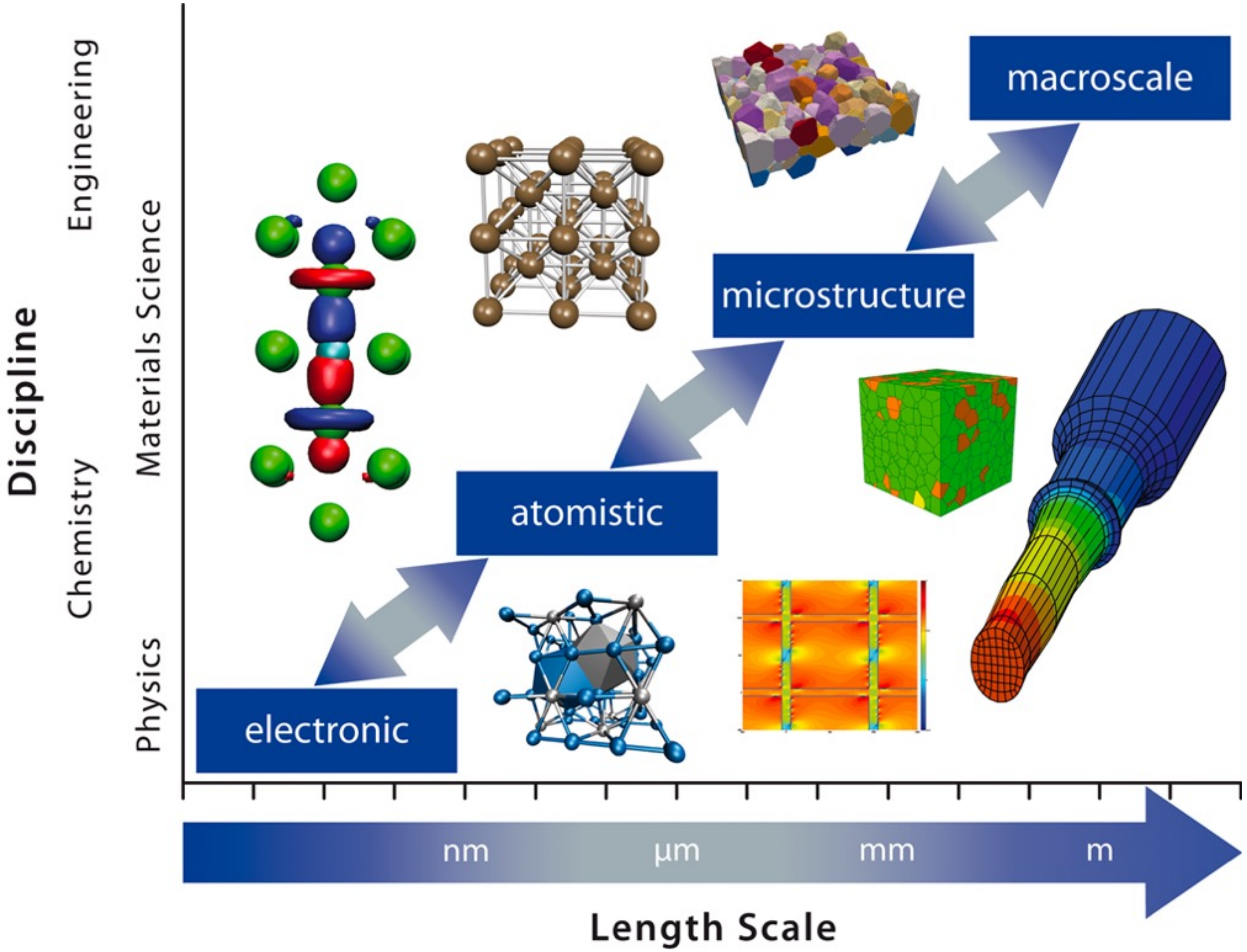
Brief Bio/Background

- 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



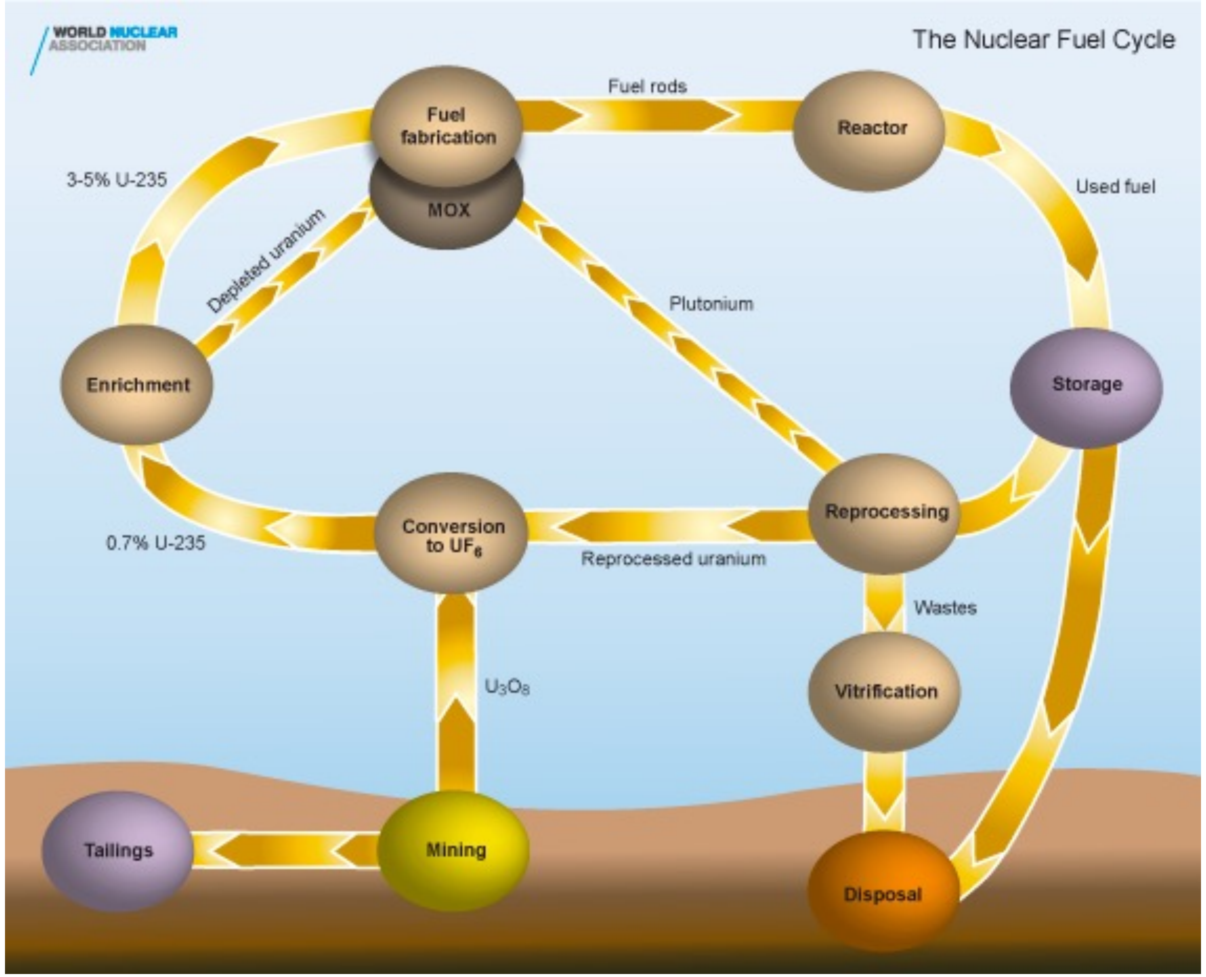
My viewpoint/approach

- 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



INTRODUCTION

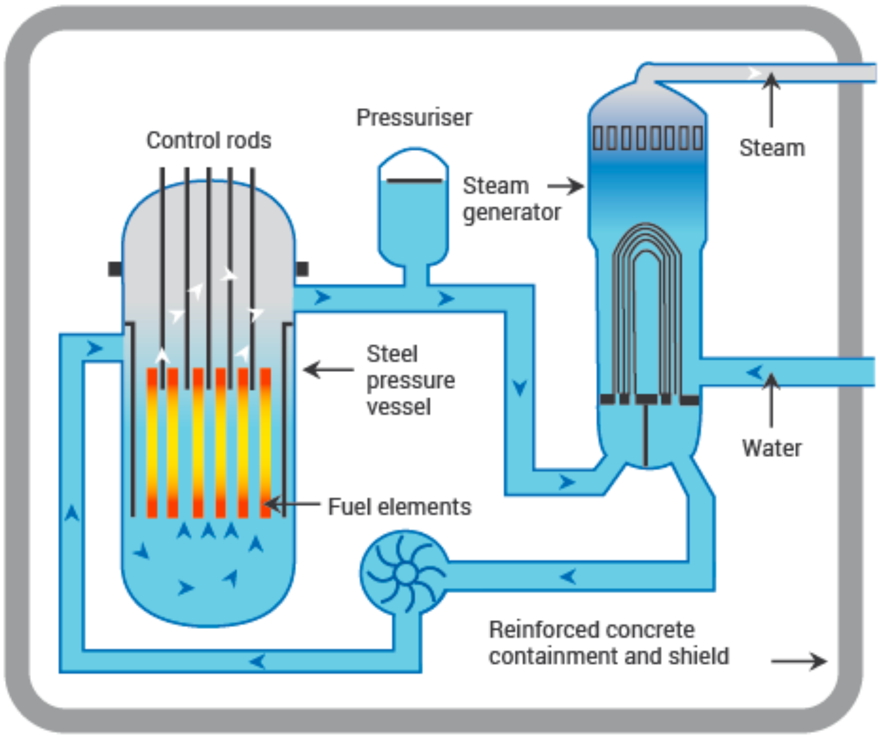
Complete nuclear fuel cycle



Emphasis on In-Reactor Behavior of Fuel

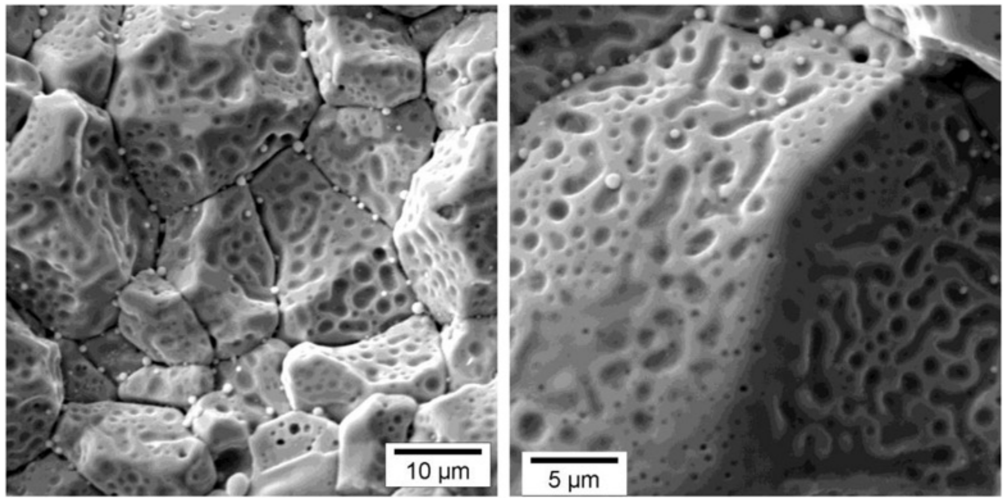
- The full reactor system is complex and substantial, and there are separate NE courses covering this area
- Although the fuel is a relatively small part of a reactor system, it determines thermal power, which drives electric power generation
- The performance of the fuel is measured by:
  - How much 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)



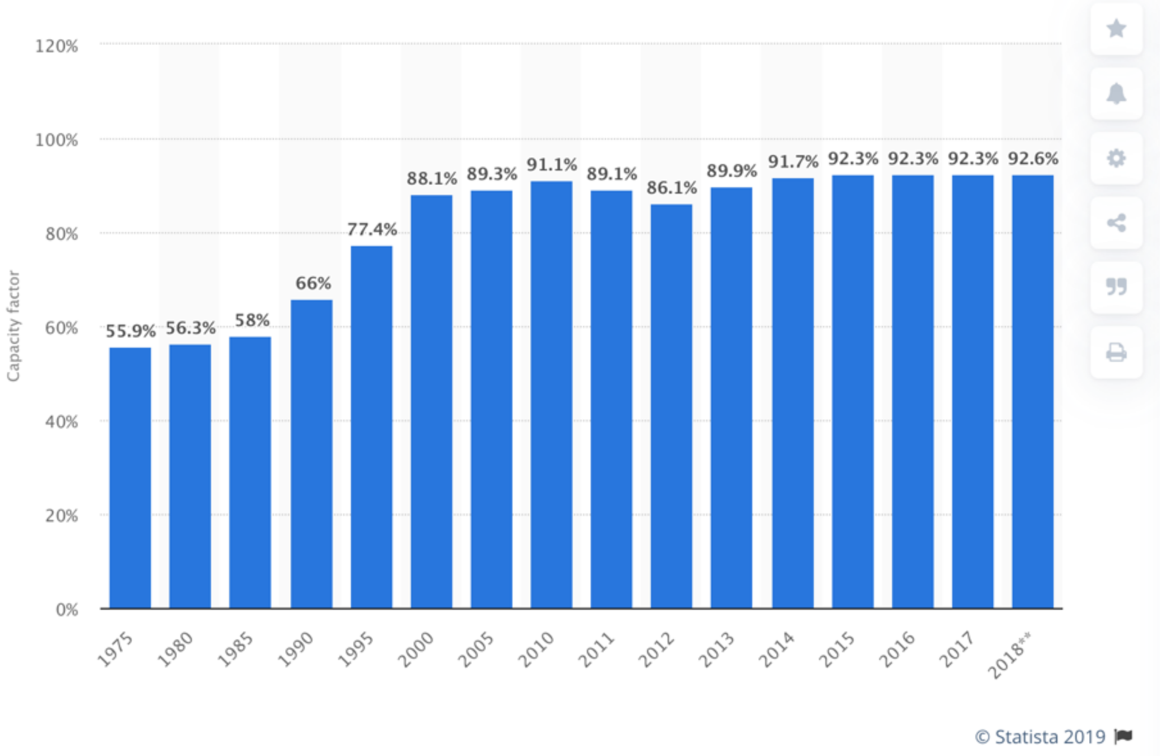
How much heat is delivered to the coolant?

- Heat 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
- How does thermal conductivity vary?



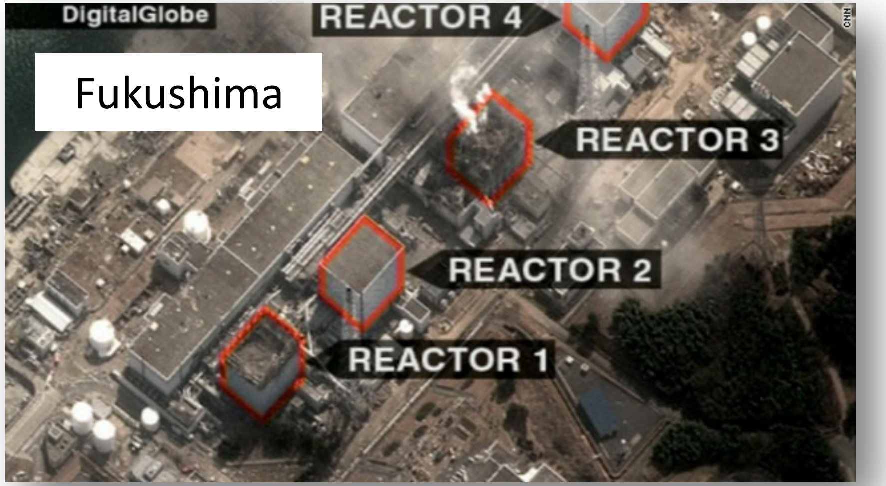
The length of time fuel operates without any problems

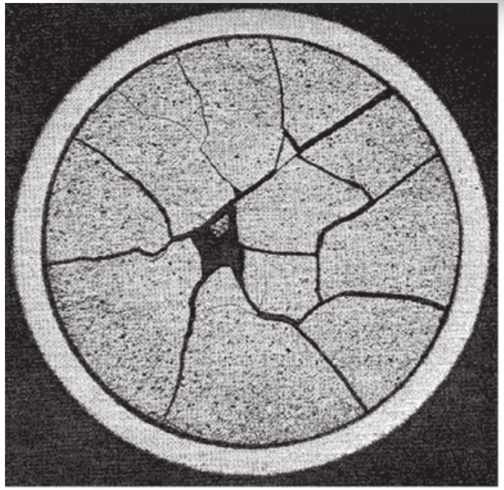
- There are 98 operating nuclear reactors in the US, producing 20% of the electricity
- The net capacity factor is the ratio of an actual electrical energy output to the maximum possible electrical energy output over a period of time
- Nuclear reactor capacity factor is ~92% over the past decade
- The ability to maintain high capacity factor, limit shutdown time, is key in making nuclear power economical
- Fuel is the primary component forcing reactor downtime

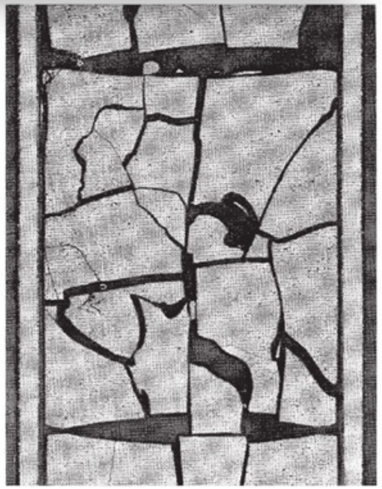


Fuel behavior during accidents

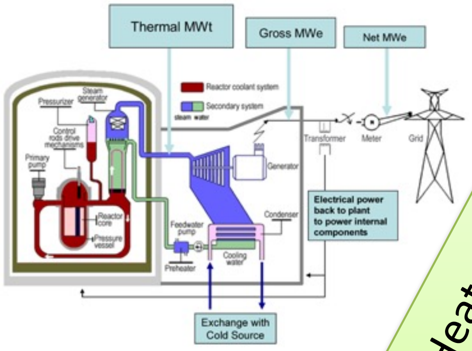
- In addition to normal operating conditions, the behavior of the fuel during accidents is of critical importance
- Predictable, and hopefully stable, behavior is desired during a variety of accident scenarios
- Even low impact accidents are detrimental to public opinion surrounding nuclear energy

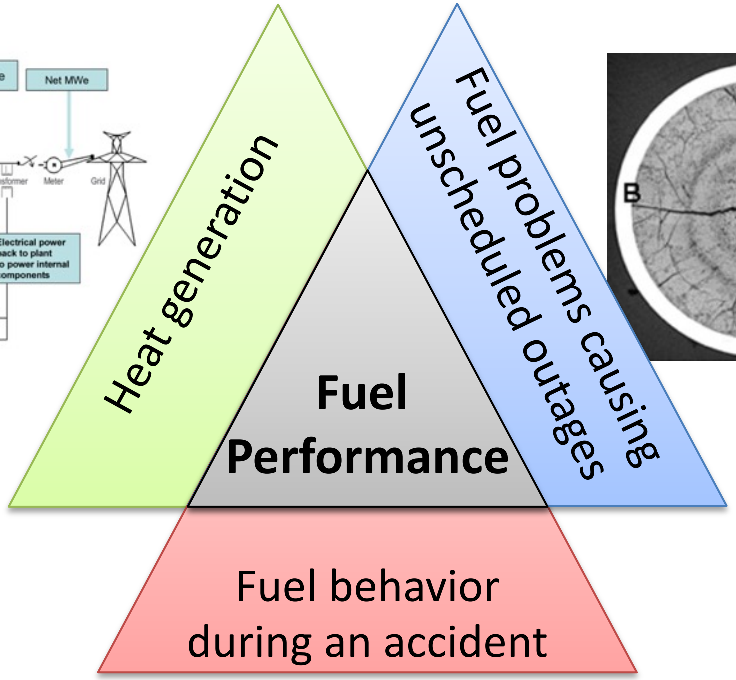


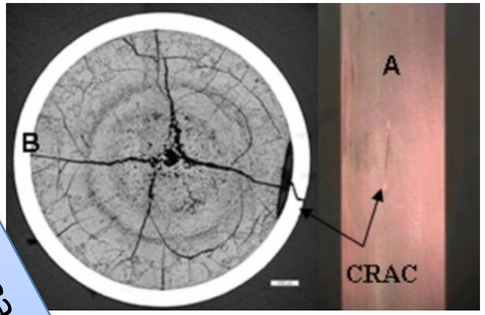




All of these factors together represent what we call “fuel performance”





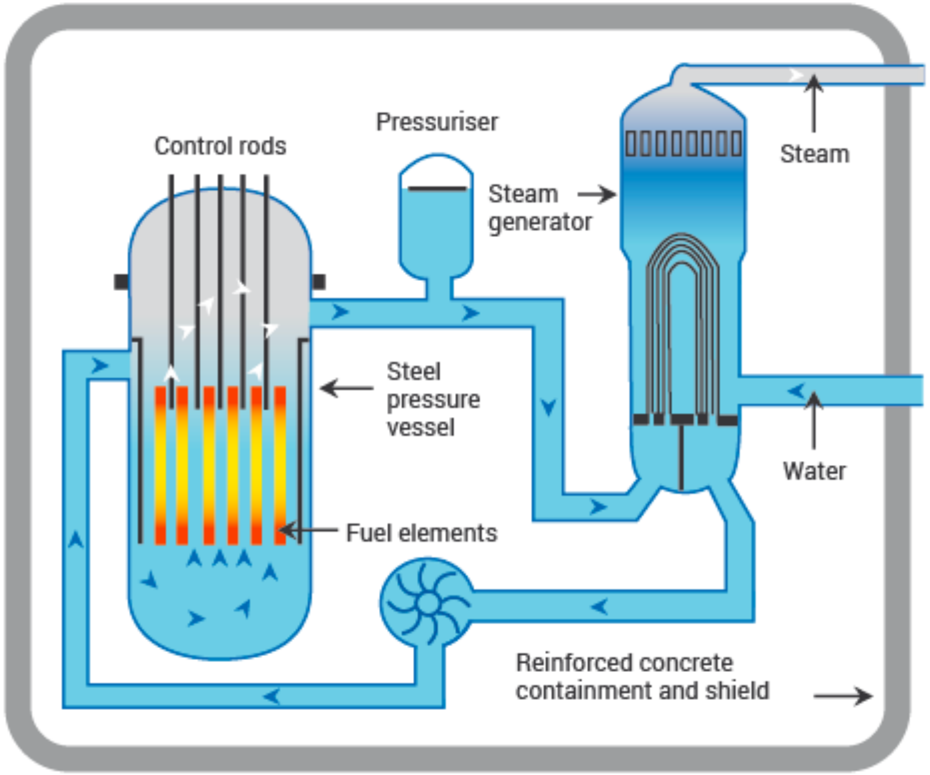


FUEL TYPES

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 $(A\text{-}Z) = 2 \times Z - N$, where $N = 43 \pm 2$ are fissile (with some exceptions)

Potential fuel candidates

- The heavy elements with $90 \leq Z \leq 100$
  - Thorium (Th), Protactinium (Pa), Uranium (U), Neptunium (Np), Plutonium (Pu), Americium (Am), Curium (Cm), Berkelium (Bk), Californium (Cf), Einsteinium (Es) and Fermium (Fm)
- Lets apply the fissile rule to U ($2 \times Z - N$)
  - $(A-Z) = 2Z - (43 \pm 2)$
  - $(A-Z) = 2 \times 92 - [41, 42, 43, 44, 45] = [143, 142, 141, 140, 139]$ 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

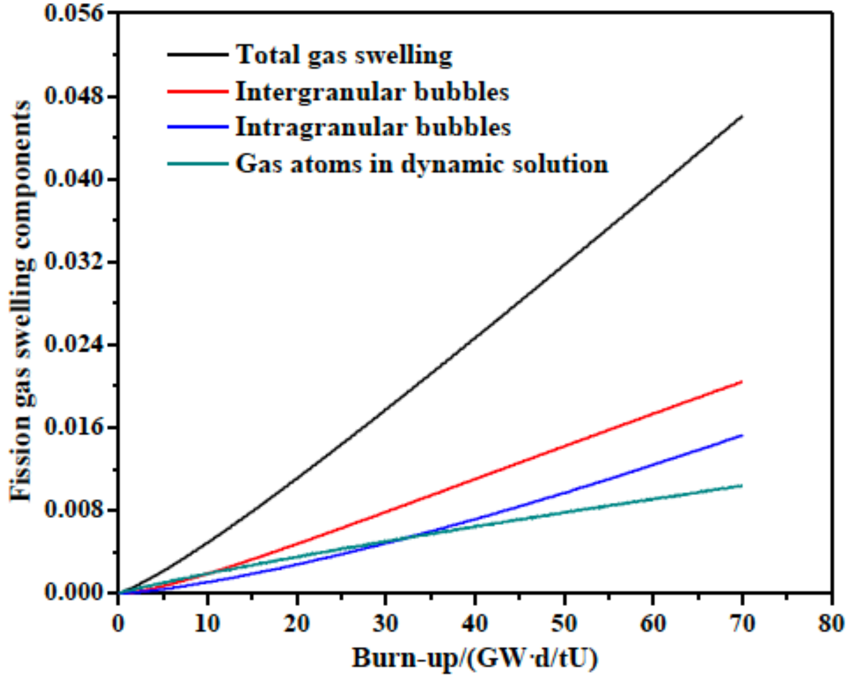
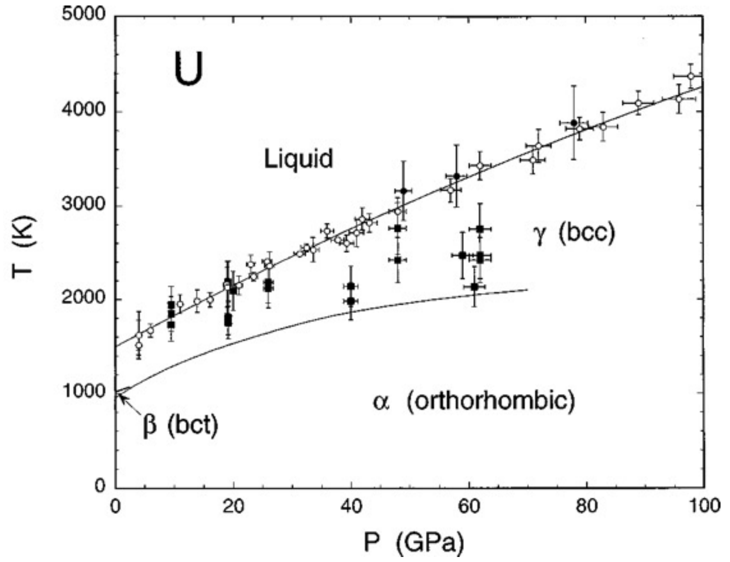
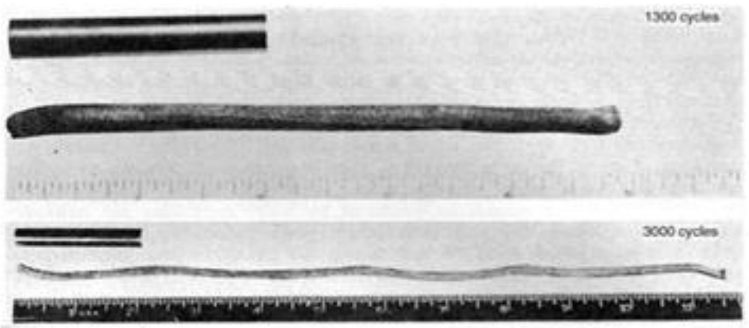


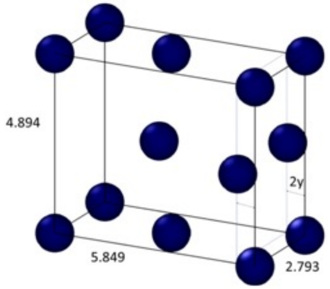
Fig. 4. Variation of swelling rate components of fission gas in UO_2 fuel with the burn-up.

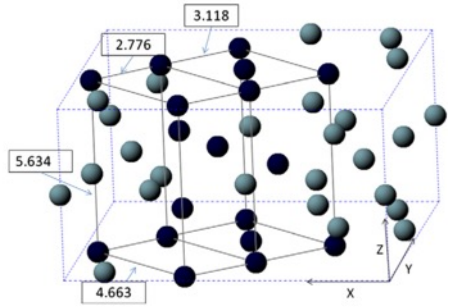
Why not use pure uranium metal?

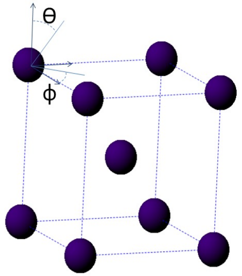
- Pure uranium has three phases
  - α-phase is orthorhombic
  - β-phase is tetragonal
  - γ-phase is body-centered cubic
  - During thermal cycling, pure uranium dramatically swells
  - Alpha U has both anisotropic thermal expansion and anisotropic irradiation growth









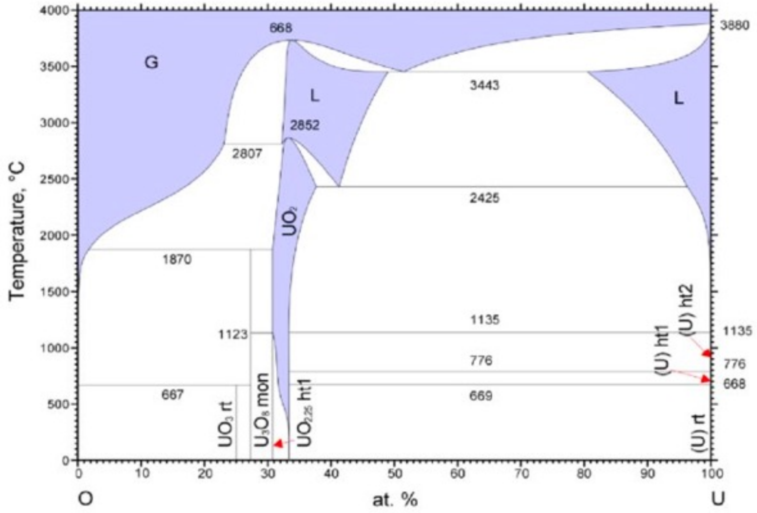


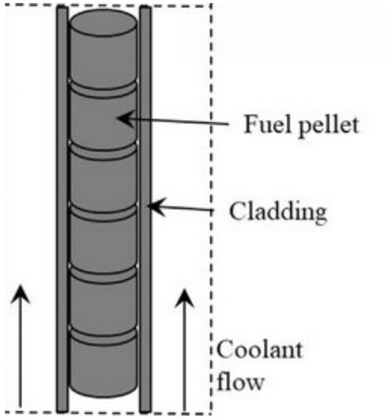
Fuel Types and Associated Reactor Types

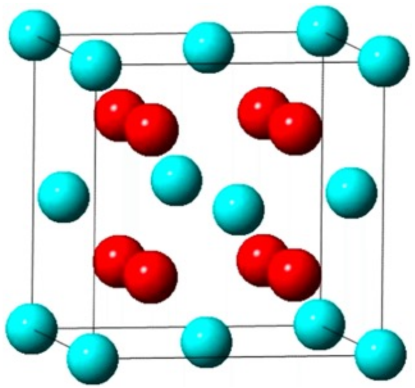
- UO_2 – Light Water Reactors
  - Mixed oxide (MOX)
  - Accident tolerant/Advanced Technology Fuel (ATF)
- UZr – Sodium Cooled Fast Reactors
- UMo – Research Reactors
- UC/UCO – High Temperature Gas Reactors
- UN – Lead Cooled Fast Reactors
- Other

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

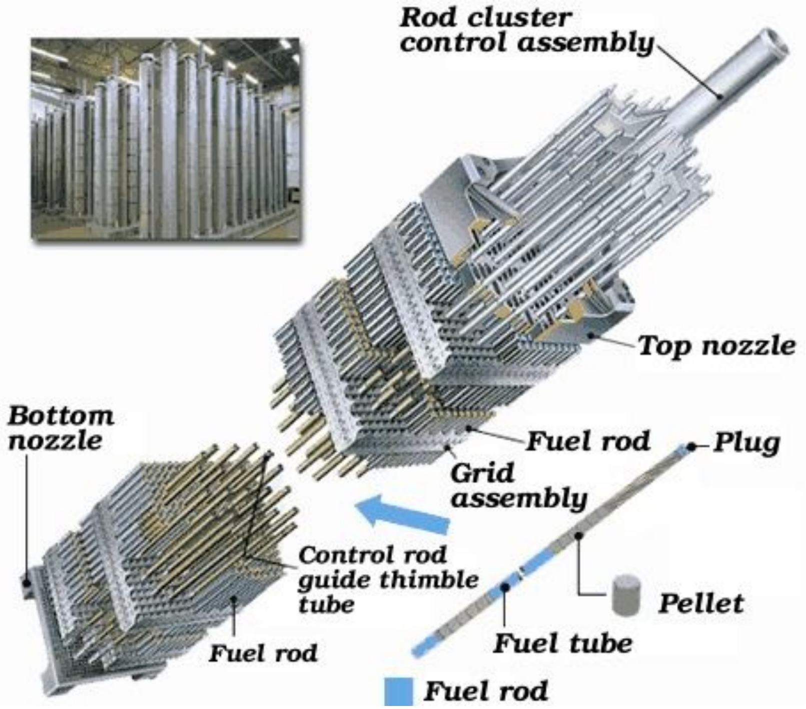




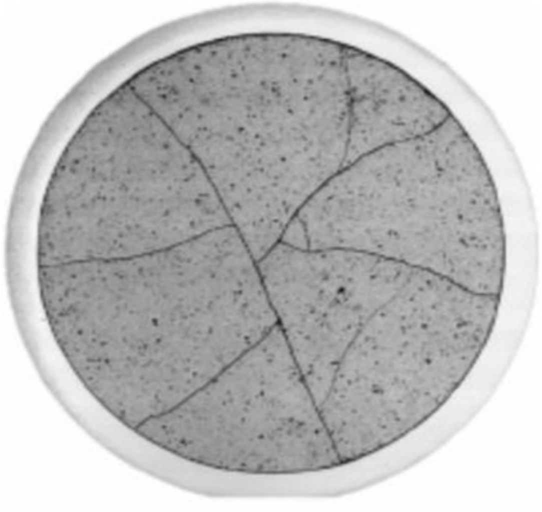


Uranium Dioxide (UO2)

- Good Characteristics
  - Very high melting point, about 2800 C
  - Maintains a stable fluorite phase up to melting
  - Very compatible with Zircaloy clad (no interaction zones forming/no FCCI)
  - Relative stability in water
  - Reasonably radiation resistant
    - no amorphization
    - Can incorporate a large number of fission products as substitutional defects



Uranium Dioxide (UO2)



- Bad Characteristics
  - Brittle (thermal stress fractures, fragmentation)
  - Poor thermal conductivity
  - Properties very sensitive to stoichiometry
  - Limited linear heating rates
  - Non-negligible thermal expansion/swelling
  - Higher stored thermal energy than other fuel materials

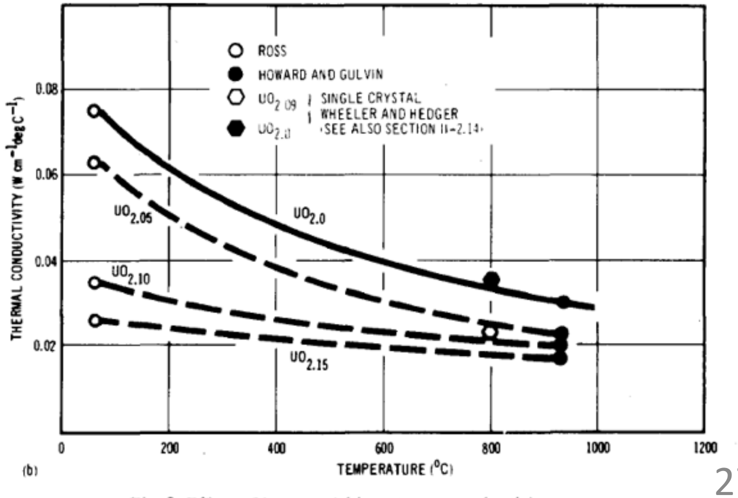
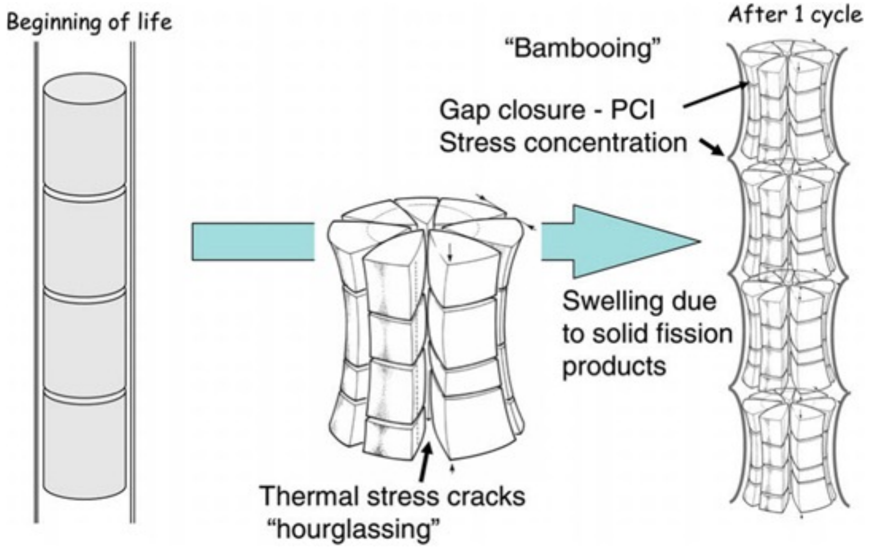
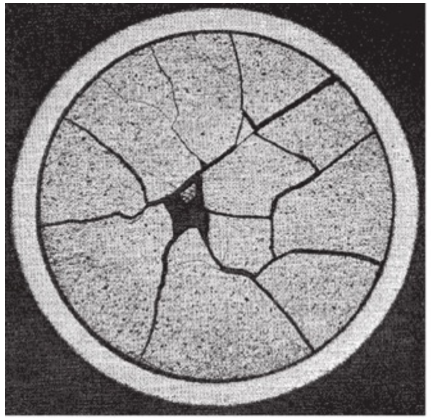


Fig. 9. Effect of hyperstoichiometry on conductivity.

Uranium Dioxide (UO2)

- Critical Phenomena
  - Thermal conductivity (and degradation)
  - Fission gas release, leading to pressure increase inside the cladding
  - Fuel fragmentation and relocation under transients
  - Bambooing creating stress concentrations
- All 98 operational reactors in US utilize UO2





Mixed Oxides (MOX)

- Can be combined with PuO2 for a mixed oxide (MOX) fuel for use in fast reactors
- Allows to burn excess weapons grade plutonium
- About 30 reactors in Europe currently utilize a partial MOX core
- Similar behavior to UO2, but different neutronics, fission gas release, thermal conductivity, etc.
- Less common is inclusion of minor actinides in MOX to burn waste