Introduction and Overview

NE 795: Advanced Reactor Materials and Materials Performance

Fall 2021

Dr. Benjamin Beeler

Office Hours

- Have generated a survey monkey to set a time for office hours
- Right now, tentatively set for Wednesday’s 10:15-11 am, subject to change pending survey results

Syllabus

Course Overview

In this course we will study the behavior of nuclear materials in advanced reactor environments. Students will be introduced to different advanced reactor systems and the materials that are either currently deployed, or plan to be deployed, within those reactors. Specific material phenomena and material evolution will be particularly emphasized, including, but not limited to: fission gas swelling, constituent redistribution, fission product attack, fission gas bubble superlattice, recrystallization, actinide salt chemistry, and radiation damage accumulation. A particular emphasis will be placed upon advanced fuel forms, however this course will also address advanced cladding and coolant systems.

Topical Outline

– Advanced Reactor Systems, Advanced Fuel types
– TRISO particles
– U-Zr (U-Pu-Zr) metallic fuel
– Molten salts
– U-Mo and U-Si
– Advanced reactor cladding
– Alternate reactor concepts
– DFT for Uranium-based systems

Exams, Projects, Grading

- Using the standard NCSU +/- grading system, as broken down in the syllabus
- Four quizzes will be conducted during normal class hours – 12.5% each
- Two project presentations will be via PPT and conducted during normal class hours – 15%
- Final project – 20%
- No final exam
- If this changes, sufficient advance notice will be given

Feedback

- This is a new course, 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
- I want this course to provide information that is currently not included in other courses, or to further expand upon materials issues that are briefly touched upon elsewhere

Working through COVID

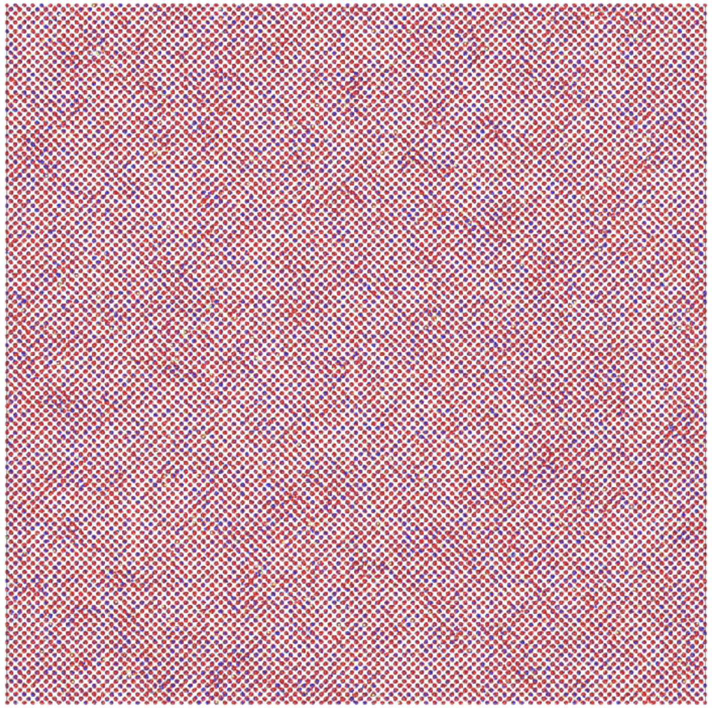
- Due to the COVID-19 pandemic, public health measures continue to be implemented across campus
- Students should stay current with these practices and expectations through the Protect the Pack website (https://www.ncsu.edu/coronavirus/)
- Additional information has been included in the syllabus

In Person/Hybrid

- Lectures will be recorded and available on Panopto
- All slides, and probably videos, will be available on moodle
- I have a ZOOM classroom set up to do simulcasting and redundant recording
- If we need to switch to virtual, or you all feel more comfortable moving to virtual, that can be done

Brief Bio/Background

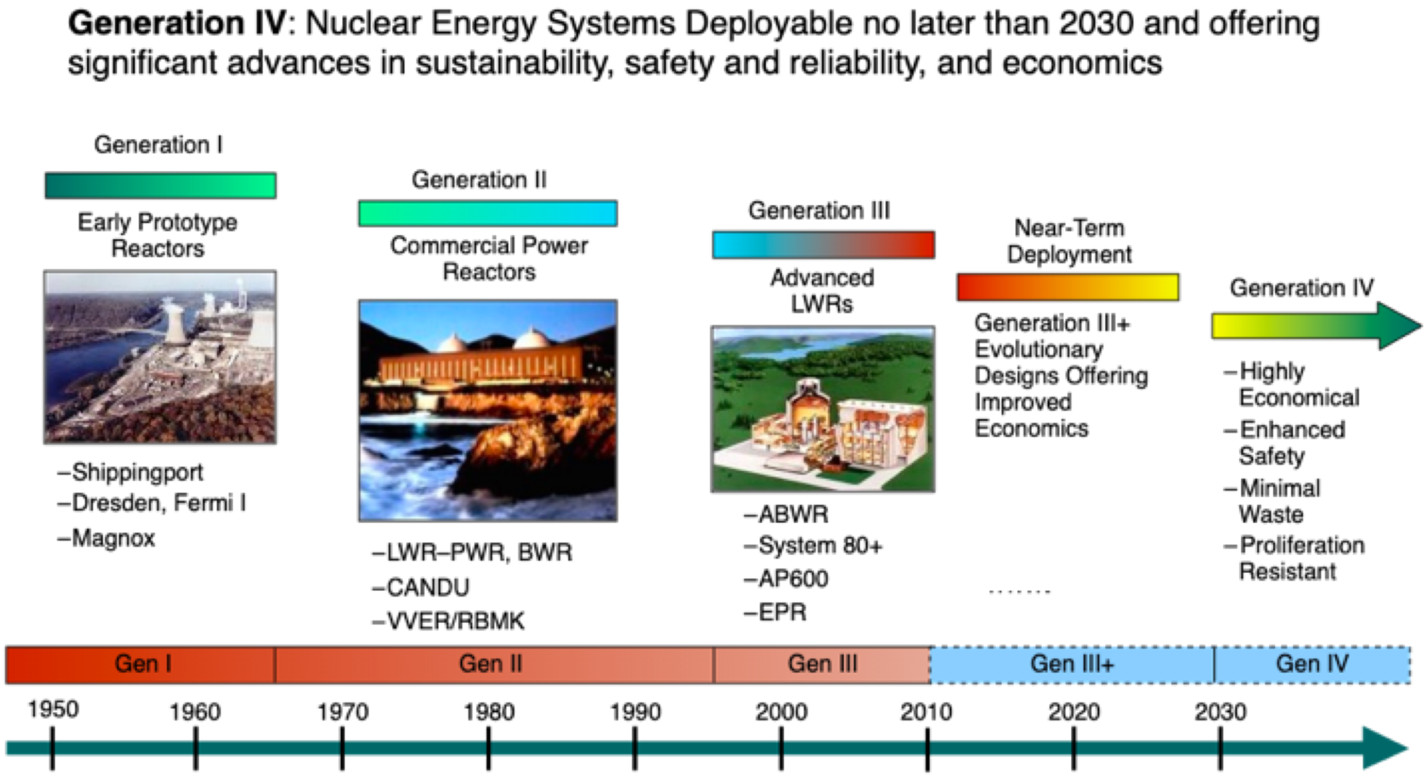
- Computational Nuclear Materials Scientist
- Expertise in advanced nuclear fuels
- Ph.D. in Nuclear Engineering from Georgia Tech
- Previously a staff scientist at Idaho National Laboratory in Fuel Modeling and Simulation Group
- Atomistic simulations: density functional theory and molecular dynamics



ADVANCED REACTOR SYSTEMS

What do I mean by advanced reactors?

- Several generations of reactors can be distinguished
- Generation I reactors were developed in 1950-60s, and are no longer operational
- Generation II reactors are the present US and French fleets and most in operation elsewhere

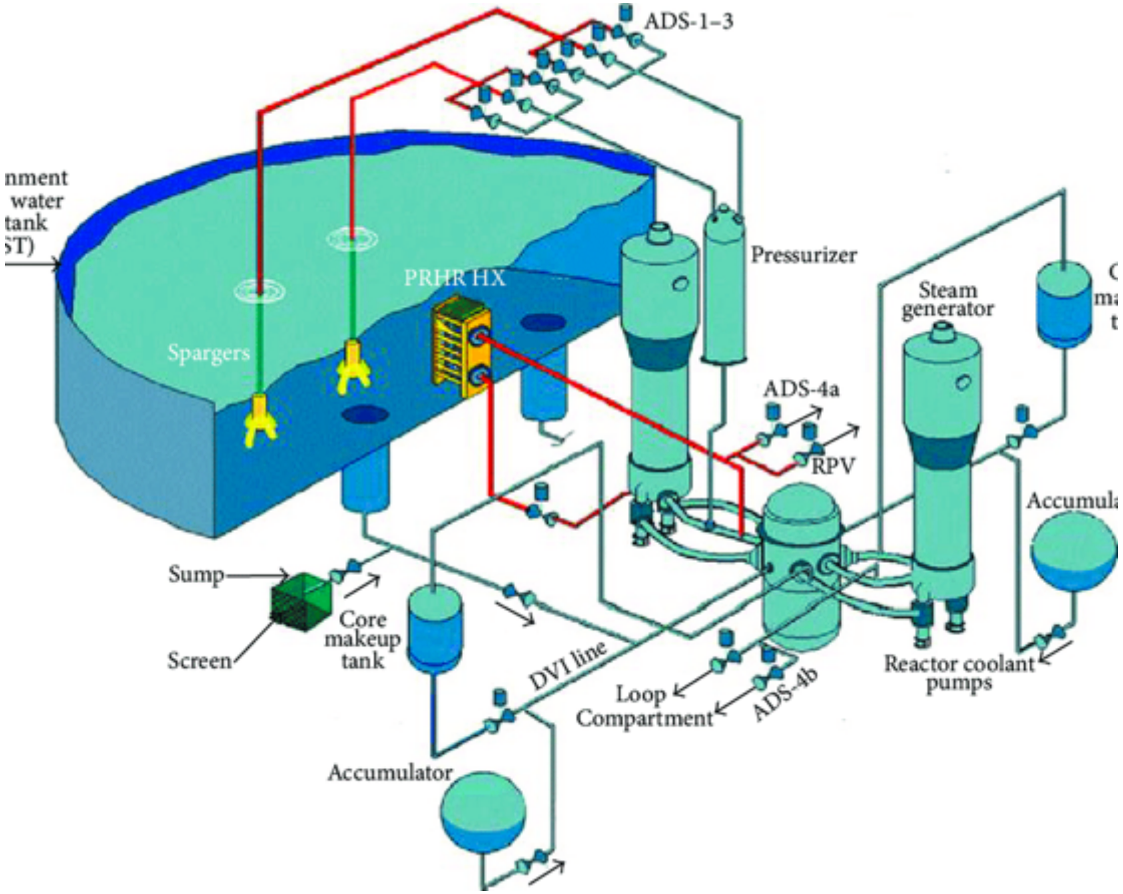


What do I mean by advanced reactors?

- Generation III or III+ have been constructed and typically have:
  - A more standardized design for each type to expedite licensing, reduce capital cost and reduce construction time.
  - A simpler and more rugged design, making them easier to operate and less vulnerable to operational upsets.
  - Higher availability and longer operating life – typically 60 years.
  - Further reduced possibility of core melt accidents
  - Stronger reinforcement against aircraft impact than earlier designs, to resist radiological release
  - Higher burn-up to use fuel more fully and efficiently, and reduce the amount of waste.
  - Greater use of burnable absorbers ('poisons') to extend fuel life

Generation III Reactors

- The greatest departure from Gen II reactors is the incorporation passive of safety features
- Construction is often modular, allowing for offsite manufacturing and onsite assembly
- Examples include AP1000, EPR, ABWR



What do I mean by advanced reactors?

- Generation IV
  - designs are largely still conceptual
  - typically incorporates six reactor designs
  - four of these types are fast reactors
  - all operate at higher temperatures
  - all six systems represent advances in sustainability, economics, safety, reliability and proliferation-resistance

	Neutron spectrum (fast/thermal)	Coolant	Temperature (°C)	Pressure*	Fuel	Fuel cycle	Size (MWe)	Use
Gas-cooled fast reactors	fast	helium	850	high	U-238 +	closed, on site	1200	electricity & hydrogen
Lead-cooled fast reactors	fast	lead or Pb-Bi	480-570	low	U-238 +	closed, regional	20-180** 300-1200 600-1000	electricity & hydrogen
Molten salt fast reactors	fast	fluoride salts	700-800	low	UF in salt	closed	1000	electricity & hydrogen
Molten salt reactor - advanced high-temperature reactors	thermal	fluoride salts	750-1000		UO_2 particles in prism	open	1000-1500	hydrogen
Sodium-cooled fast reactors	fast	sodium	500-550	low	U-238 & MOX	closed	50-150 600-1500	electricity
Supercritical water-cooled reactors	thermal or fast	water	510-625	very high	UO_2	open (thermal) closed (fast)	300-700 1000-1500	electricity
Very high temperature gas reactors	thermal	helium	900-1000	high	UO_2 prism or pebbles	open	250-300	hydrogen & electricity

What do I mean by advanced reactors?

- Small Nuclear Reactors
  - Small Modular Reactors (SMRs)
  - Micro-Reactors
- Reduces the cost associated with building 1000 MW scale reactors, and can provide power away from large grid system
- SMRs are 300 MWe or less, designed with modular technology using module factory fabrication, pursuing economies of series production and short construction times
- Microreactors (or very small modular reactors vSMRs) are up to 25 MWe

Small Nuclear Reactors

Small reactors for near-term deployment – development well advanced

Name	Capacity	Type	Developer
VBER-300	300 MWe	PWR	OKBM, Russia
NuScale	60 MWe	Integral PWR	NuScale Power + Fluor, USA
SMR-160	160 MWe	PWR	Holtec, USA + SNC-Lavalin, Canada
ACP100/Linglong One	125 MWe	Integral PWR	NPIC/CNPE/CNNC, China
SMART	100 MWe	Integral PWR	KAERI, South Korea
BWRX-300	300 MWe	BWR	GE Hitachi, USA
PRISM	311 MWe	Sodium FNR	GE Hitachi, USA
Natrium	345 MWe	Sodium FNR	TerraPower + GE Hitachi, USA
ARC-100	100 MWe	Sodium FNR	ARC with GE Hitachi, USA
Integral MSR	192 MWe	MSR	Terrestrial Energy, Canada
Seaborg CMSR	50 MWe	MSR	Seaborg, Denmark
BREST	300 MWe	Lead FNR	RDIPE, Russia
RITM-200M	50 MWe	Integral PWR	OKBM, Russia
BANDI-60S	60 MWe	PWR	Kepco, South Korea
Xe-10	75 MWe	HTR	X-energy, USA
ACPR50S	60 MWe	PWR	CGN, China

Small reactors operating

Name	Capacity	Type	Developer
CNP-300	300 MWe	PWR	SNERDI/CNNC, Pakistan & China
PHWR-220	220 MWe	PHWR	NPCIL, India
EGP-6	11 MWe	LWGR	at Bilibino, Siberia (cogen, soon to retire)
KLT-40S	35 MWe	PWR	OKBM, Russia
RITM-200	50 MWe	Integral PWR, civil marine	OKBM, Russia

Very small reactor designs being developed (up to 25 MWe)

Name	Capacity	Type	Developer
U-battery	4 MWe	HTR	Urenco-led consortium, UK
Starcore	10-20 MWe	HTR	Starcore, Quebec
MMR-5	5 MWe	HTR	UltraSafe Nuclear, USA
Holos Quad	3-13 MWe	HTR	HolosGen, USA
Gen4 module	25 MWe	Lead-bismuth FNR	Gen4 (Hyperion), USA
Sealer	3-10 MWe	Lead FNR	LeadCold, Sweden
eVinci	0.2-5 MWe	Heatpipe FNR	Westinghouse, USA
Aurora	1.5 MWe	Heatpipe FNR	Oklo, USA
NuScale micro	1-10 MWe	Heatpipe	NuScale, USA

Advanced Reactors in This Course

- Generation IV or adjacent concepts:
  - Sodium cooled fast reactors
  - Molten salt reactors (both salt cooled and salt fueled)
  - Gas cooled reactors (both fast and thermal spectra)
  - Lead cooled reactors
  - Supercritical water cooled reactors
  - Research reactors
- Many of these concepts have overlap with SNRs

Subject Matter

- Explore unique aspects of each reactor type
- Identify operational parameter space (temperature, flux, cycle, etc.)
- Identify fuel and cladding materials relevant to each reactor design
- **Explore materials challenges and materials phenomena impacting the deployment and lifetime of advanced reactors**

QUESTIONS?