Nuclear Fuel Performance

NE-533

Spring 2022

Last time

- Provided examples in UO2, UZr, USi, FeCrAl of mechanistic modeling efforts
- Introduced MOX fuel systems
  - MOX operates at much higher power and temperature than LWRs
  - Intended to reach high burnup (>15%)
  - Limiting phenomena are similar to that in LWRs
  - Temperature gradients, high fission product inventory, and O/M ratio govern the majority of key phenomena in these fuels

ACCIDENTS/TRANSIENTS IN MOX

SFR Transients

- For sodium fast reactors three main types of transient and accident scenarios are considered as references for the study of fuel transient and accident behavior:
  - the slow power transient representative of one control-rod withdrawal
  - the loss of cooling due to blockage of a subassembly
  - the unprotected loss of flow (ULOF) accident that might lead to a core disruptive accident

Control Rod Withdrawal Accident (CRWA)

- Slow power transients due to control-rod withdrawal are the most common transients occurring during reactor operation as they are used for regulation of the core power by the operators
- In case of an inadvertent control-rod withdrawal due operator action together with a failure of various protection systems, this transient might lead to severe consequences
- During such a transient, nominal power can increase by 1-3% per second, and may lead to partial fuel melting inside the pins of the subassemblies surrounding the control rod

Local blockage of a subassembly

- Local blockage formation in a fuel assembly due to ingression of some external material into the bundle may lead to pin failure with subassembly degradation and melting
- The hypothetical total instantaneous inlet blockage (TIB) of a subassembly at nominal power has been postulated as potential initiator for a core melt accident
- Owing to the complete and fast loss of flow in the faulted subassembly, the usual detection systems are not operating in due time, so core power can not be shut down in time
- The accident is characterized by overheating and melting of the fuel pins, degradation of the subassembly, wall failure, and possible propagation of molten materials into neighboring subassemblies
- The main safety issue is the risk of propagation of the accident beyond the neighboring subassemblies that might lead to critical events and generalized core melting
- Such an accident caused the Fermi-1 core meltdown in 1966

Unprotected loss of flow accident (ULOF)

- The ULOF accident is the result of loss of primary pump flow due to potential initiating events such as electrical break-down without reactor scram
- The first phase leads to sodium flow reduction and to associated power reduction linked to reactivity feedback
- The power to flow ratio increases so that sodium temperature reaches causes sodium boiling
- Due to the positive 'sodium void effect' in the central core regions, the ULOF leads to sodium boiling and channel voiding and may result in a core disruptive accident (CDA)
- This can lead to generalized core degradation: fuel melting, clad failure and/or melting, fuel ejection into coolant, fuel dispersal and relocation into the channels, and possible mechanical energy release
- Although this accident is initiated by a loss of coolant flow, it may rapidly evolve toward a fast reactivity insertion accident

Fuel Behavior Under Slow Power Transients

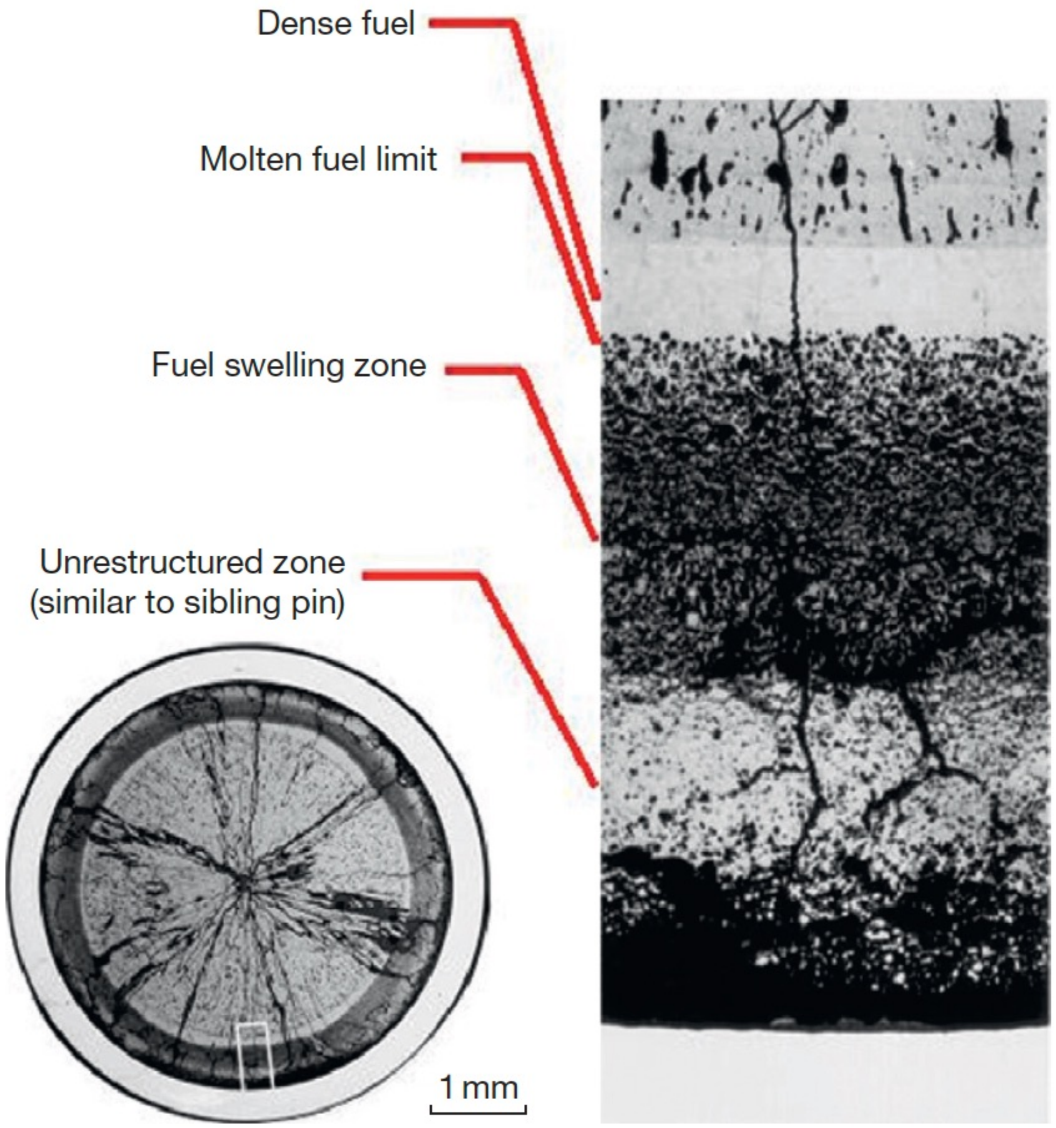
- In spite of high fission gas release rate observed with irradiated fuel due to high operation temperature (60-80% release) power increase and subsequent high temperature also activate fission gas-related phenomena that influence thermal and mechanical pin behavior
- Intragranular gas migration toward grain boundary related to thermal gradient
- Gas bubble growth due to coalescence, vacancy diffusion
- Fission gas-induced fuel swelling driven by increase in bubble pressure
- Saturation and interconnection of grain boundary bubbles leading to additional gas release
- Under slow power transients, fuel heat generation and heat removal by the sodium coolant are almost in thermal equilibrium, and these ‘quasi’ steady-state conditions allow the evaluation of the power level at which fuel melting occurs

Fuel Melting

- Fuel-melting occurrence depends on pin thermal behavior that is governed by thermal conductivity and heat exchange between fuel and clad through the pellet–clad gap and on melting temperature, most of these factors being function of burn-up level and of irradiation history
- High T plastic fuel creep may lead to central hole reduction and to increase of the macroscopic fuel porosity with subsequent reduction of the thermal conductivity and thus higher fuel temperature in the center that results in a lower power at melting onset
- High peaking factors (~1.3, compared to ~1.1 in LWRs), can increase the local temperatures in high power regions and increase probability of fuel melting

CABRI Experiment

- Decrease of fuel density and fuel fragmentation in the unmolten zone of the fuel pellet due to the slow power transient
- With low smear density fuel, a significant effect of the retained fission gas on the degradation of fuel thermal performance at overpower conditions has been
- With high smear density fuel, mechanical loading can be high enough to cause significant clad straining or even failure



METALLIC FUEL MICROSTRUCTURE AND PERFORMANCE

Why metallic fuel?

- It has demonstrated a high burnup capability beyond 20%
- Metal fuel also has superior off-normal performance characteristics, in particular for the run-beyond-cladding-breach conditions due to the compatibility of metal fuel with sodium coolant
- The inherent passive safety potential where metal fuel is far superior to other fuel types (less stored Doppler reactivity)
- Metal fuel also allows a very simple injection-casting fabrication technique and electrorefining-based fuel cycle closure, which promises simpler waste management, proliferation-resistance, and much improved economics

Fig. 3 Oxide Fuel (9% burnup) RBCB Test

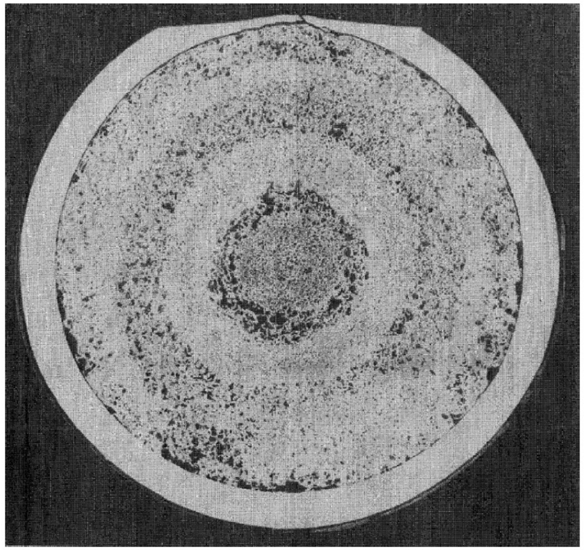
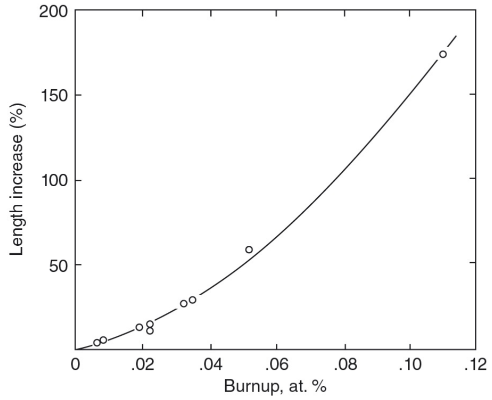
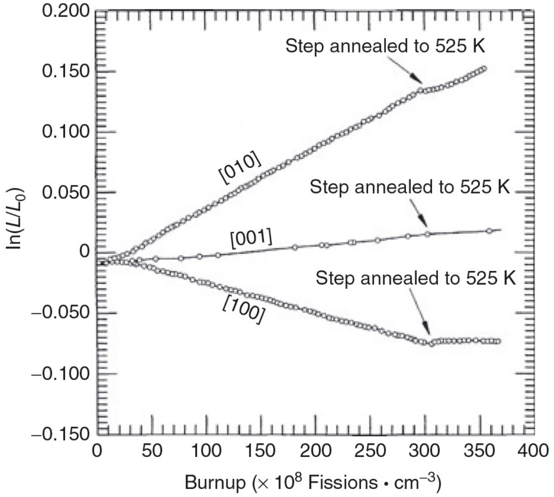


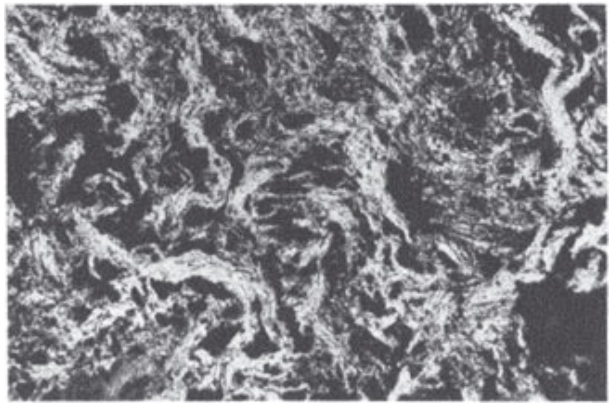
Fig. 4 Metal Fuel (12% burnup) RBCB Test

Why do we alloy?

- Unalloyed swelling can reach >150% at target burnups
- Anisotropic swelling of alpha U
  - thermal expansion
  - irradiation growth
- Cavitation swelling is characterized by large irregular cavities that form by mechanical tearing at grain and sub-grain boundaries, resulting in a very deformed “swirled” microstructure

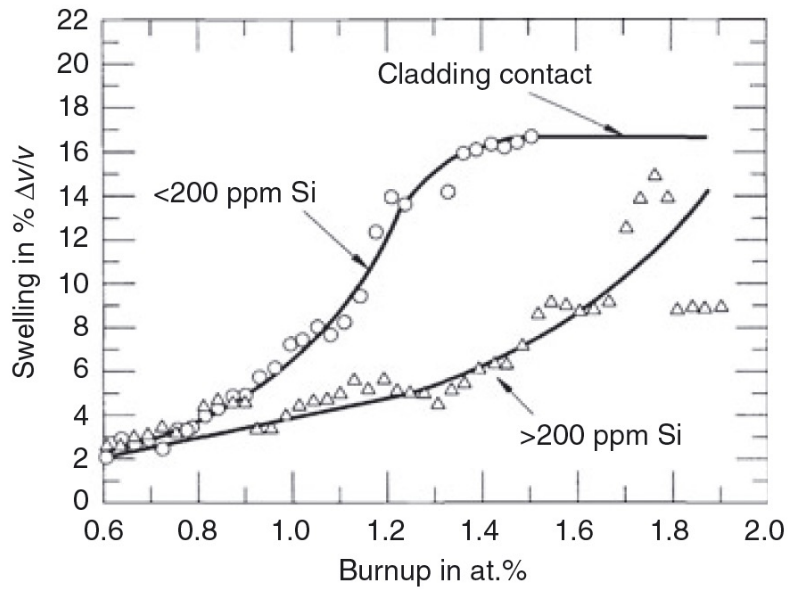






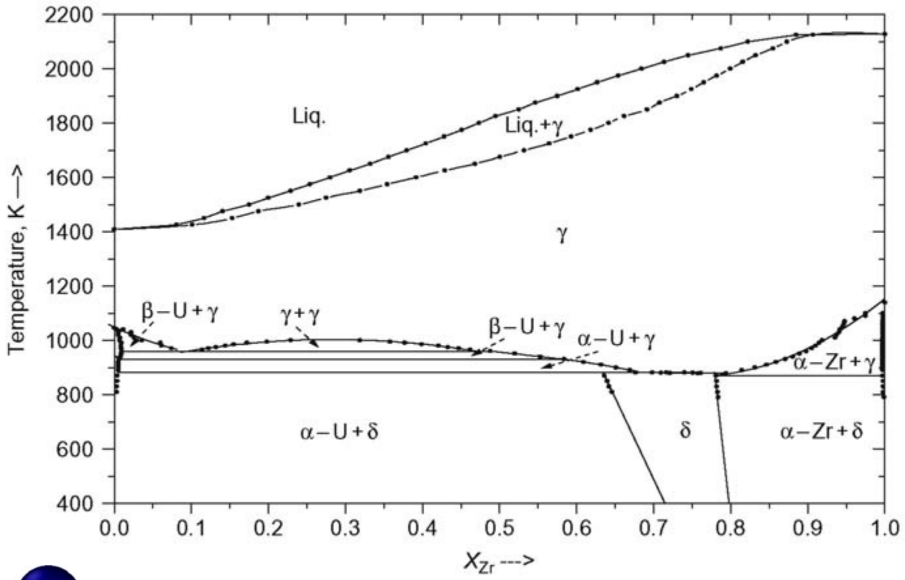
Alloying attempts

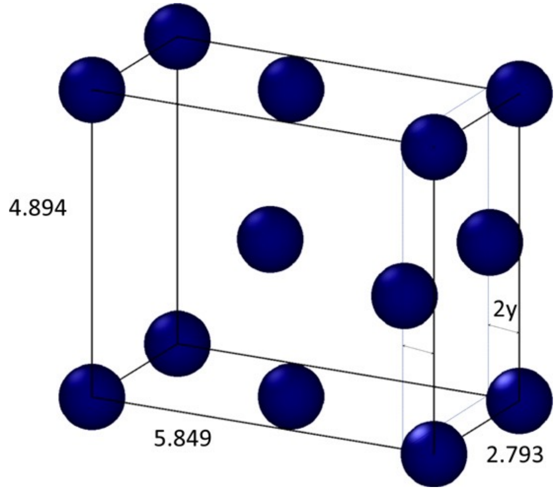
- Adjusted U
  - Small amounts of Al, Fe, or Si
- U-Fissium (U-Fs)
  - Fissium is an artificial mixture of the natural elements represented among the fission products to simulate the chemical composition of the material resulting from fission
- Further studies on U alloys have centered on elements that form extensive solid solutions with U in the high-temperature γ-phase, specifically Mo, Zr, Ti, and Nb
- U-Nb and U-Ti show excessive phase decomposition to alpha-dominated systems
- U-Mo is utilized in research reactors which operate at low T

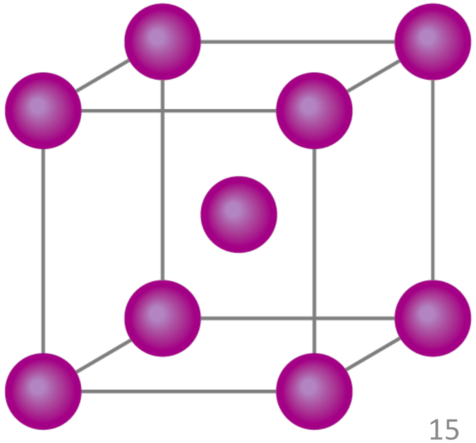


U-Zr (U-Pu-Zr)

- Alloying with Zr increases melting point and stabilizes the high temperature bcc phase
- Temperature range for fuel is ~800-1100 K
- Typically, 10 weight percent Zr (23 atomic percent)
- Directly in multiphase region
  - find bcc, beta, alpha U, delta UZr2, alternate bcc phases

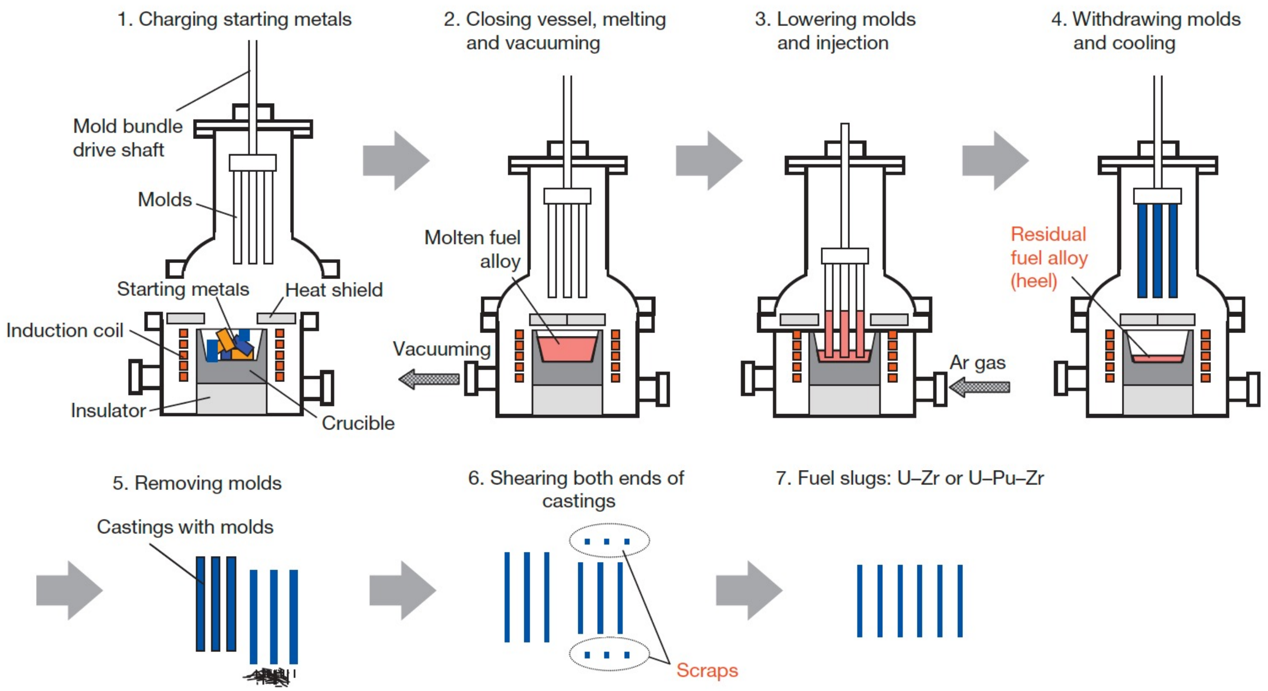






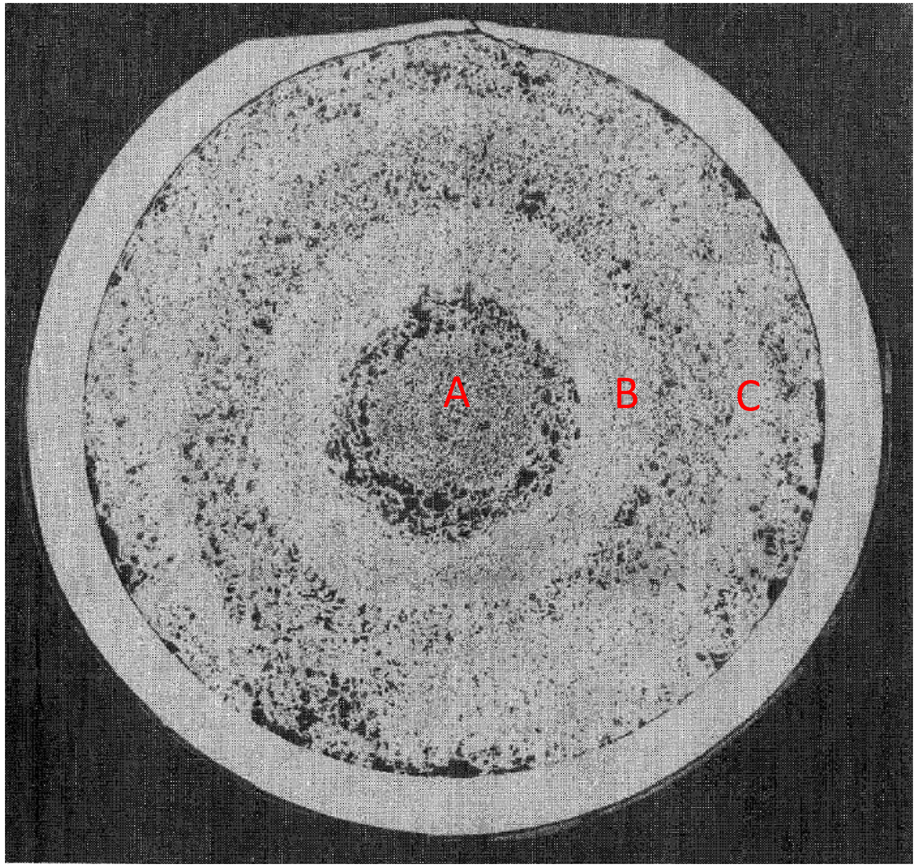
Fuel Fabrication

- Injection casting
  - starting materials are charged into the graphite crucible in the injection casting furnace
  - The crucible's interior is coated with yttria and the mold's interior is coated by zirconia for protection against reaction with molten uranium alloy
  - Silica tube molds with the top ends closed are set above the crucible
  - After melting, furnace is made a vacuum, molds lowered, then Ar gas refills the furnace, with pressure difference serving to inject the liquid metal into the molds

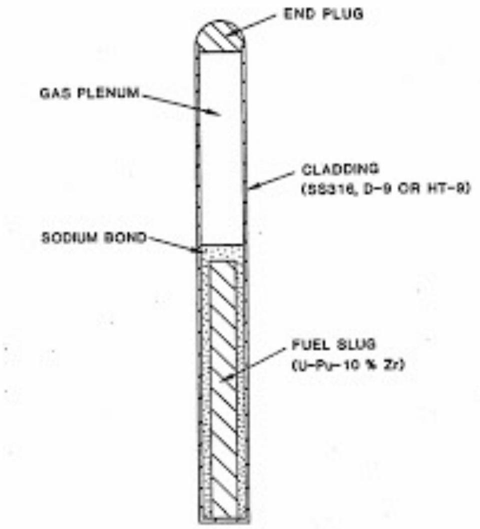


Fuel Redistribution

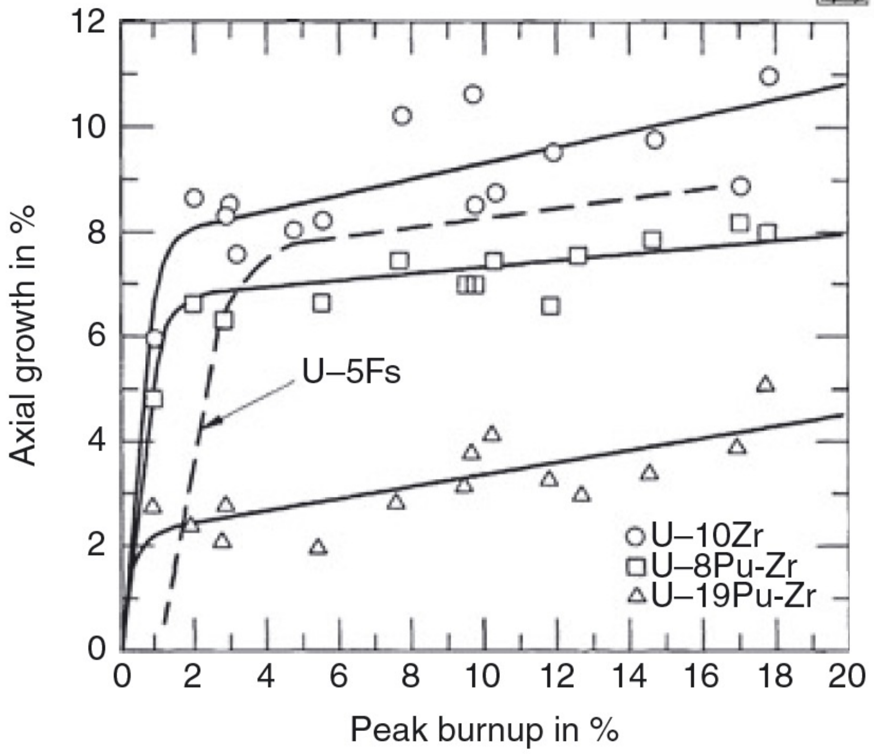
- Zr diffuses via Soret diffusion up the temperature gradient
- Zr also possesses different solubilities in each phase of U
- This leads to distinct zones of Zr content in radial rings
- A) gamma phase, high Zr content, B) beta phase-ish, low Zr content, C) alpha/delta phase, as-fabrication Zr content
- Lower Zr content = lower melting temperature
- Also, different elastic and thermal properties for each phase and each Zr content



Swelling of Metallic Fuel

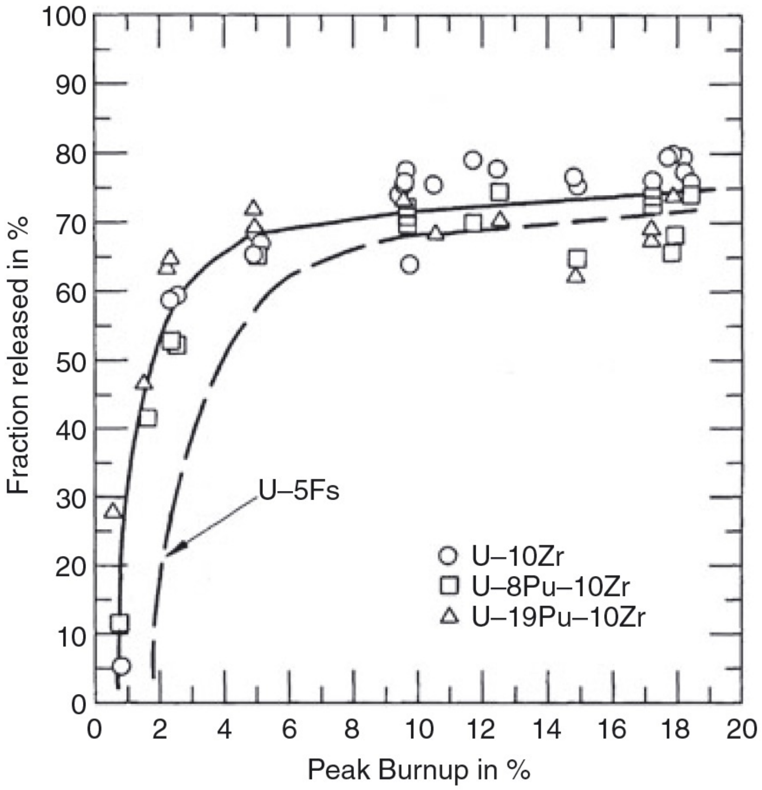


- While oxide fuels well a few percent, metallic fuels swell by as much as 30 %
- This swelling occurs very rapidly, e.g. in the first few percent burnup, then displays a linear increase
- Fuel swells anisotropically: more radially than axially
- Swelling is accounted for by low smear density
- Swelling rate decreases due to fission gas bubble interconnection and release
- Low slope of swelling vs burnup for burnup > 5% is largely due to solid fission product generation



Fission Gas Release

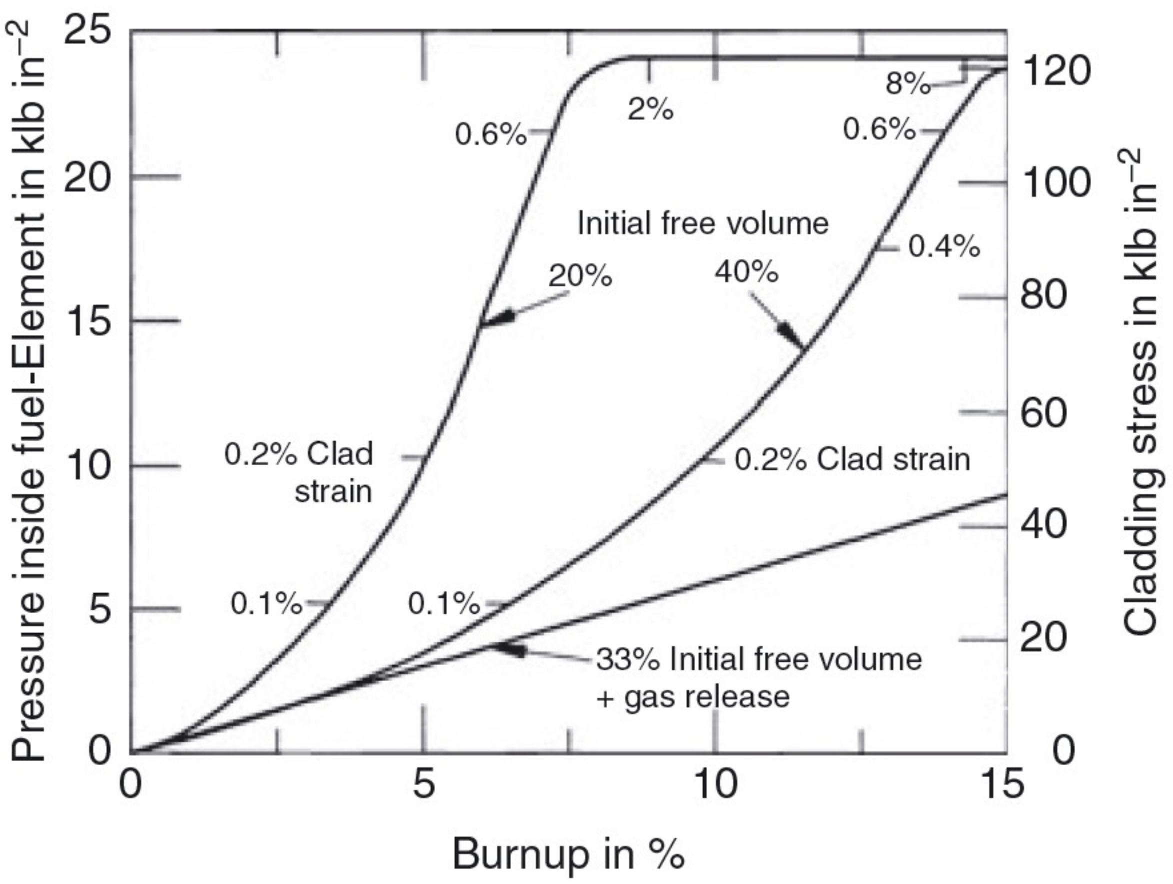
- Gas release is not wholly understood, but largely presumed to be intragranular bubble growth and interconnection
- Bubble interconnection, and thus fission gas release, typically occurs within the first 3-5 percent burnup
- There exists limited experimental data, but this is a key phenomenon affecting fuel swelling and performance
- Gas released into the plenum leads to internal pressure increase



$$\overline{\sigma_\theta} = \frac{pR}{\delta} \qquad \overline{\sigma_z} = \frac{pR}{2\delta} \qquad \overline{\sigma_r} = -\frac{1}{2}p$$

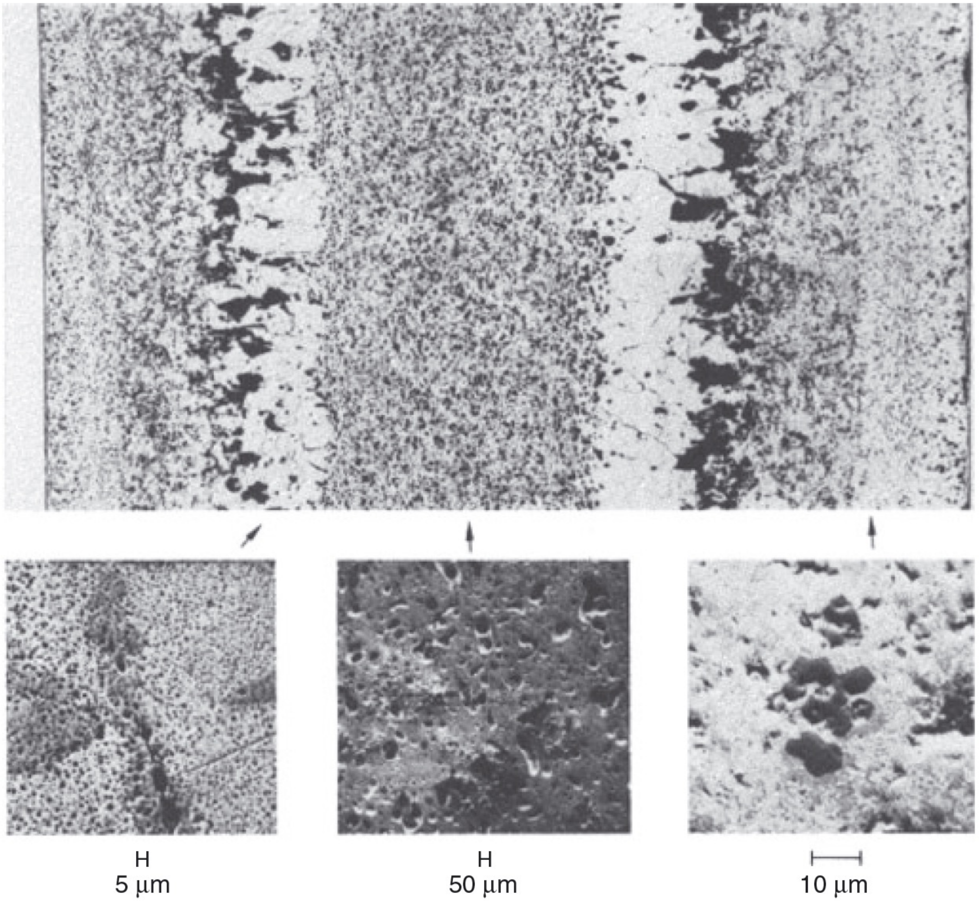
Cladding Strain

- Since most of the fission gas was released from the fuel at ~30% swelling, it was clear that the pressure inside the fuel element could be decreased by providing a plenum for this gas
- Thus, with smear density ~75% and a large plenum, allow for both swelling and gas release without excessive stress on cladding

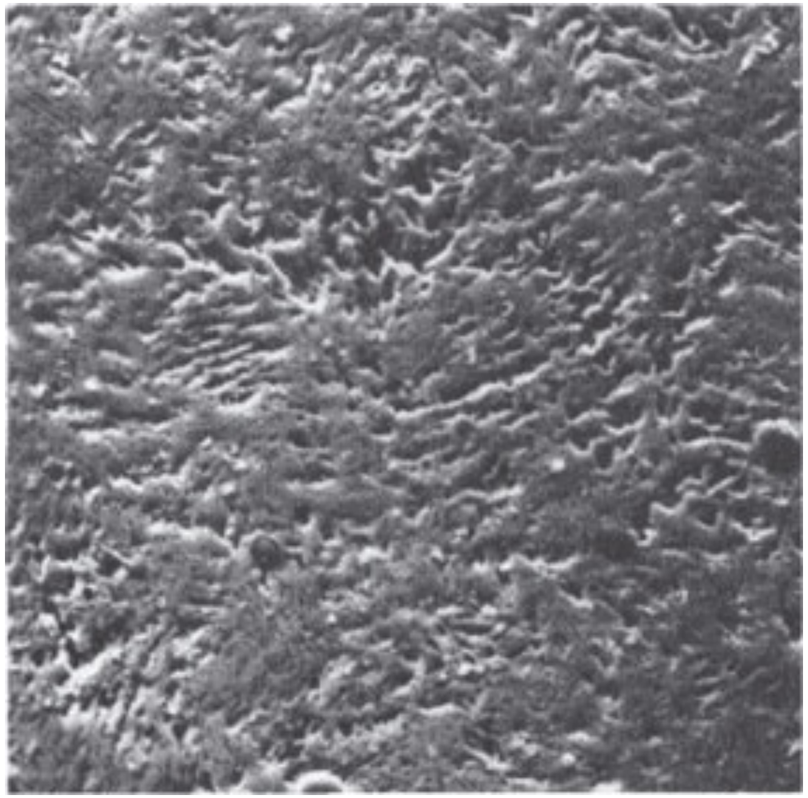


Radially Varying Bubble Morphologies

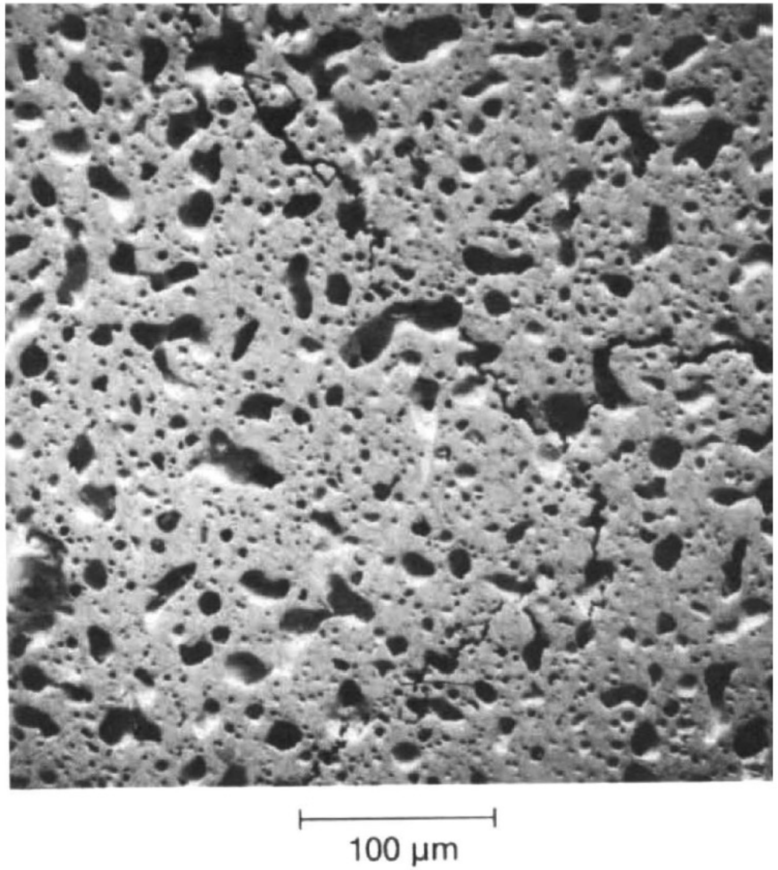
- In the center part of the fuel pin, where the γ-phase predominates, large gas bubbles form; this is indicative of a higher plasticity of the fuel
- Whereas at lower temperatures, where the U α-phase predominates, the characteristic tearing-type porosity is evident
- The fission gas pressure in the center may result in a near-biaxial loading of the peripheral shell, the radial stress component being twice the axial component
- This stress effect results in a larger diametral than axial strain, and hence anisotropic swelling



Fission Gas Bubble Morphology in alpha vs gamma U



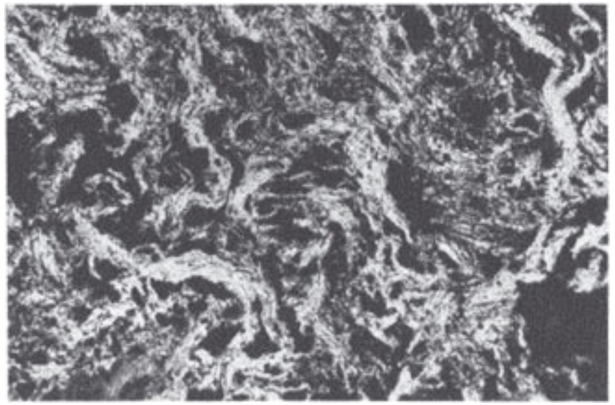
alpha



gamma

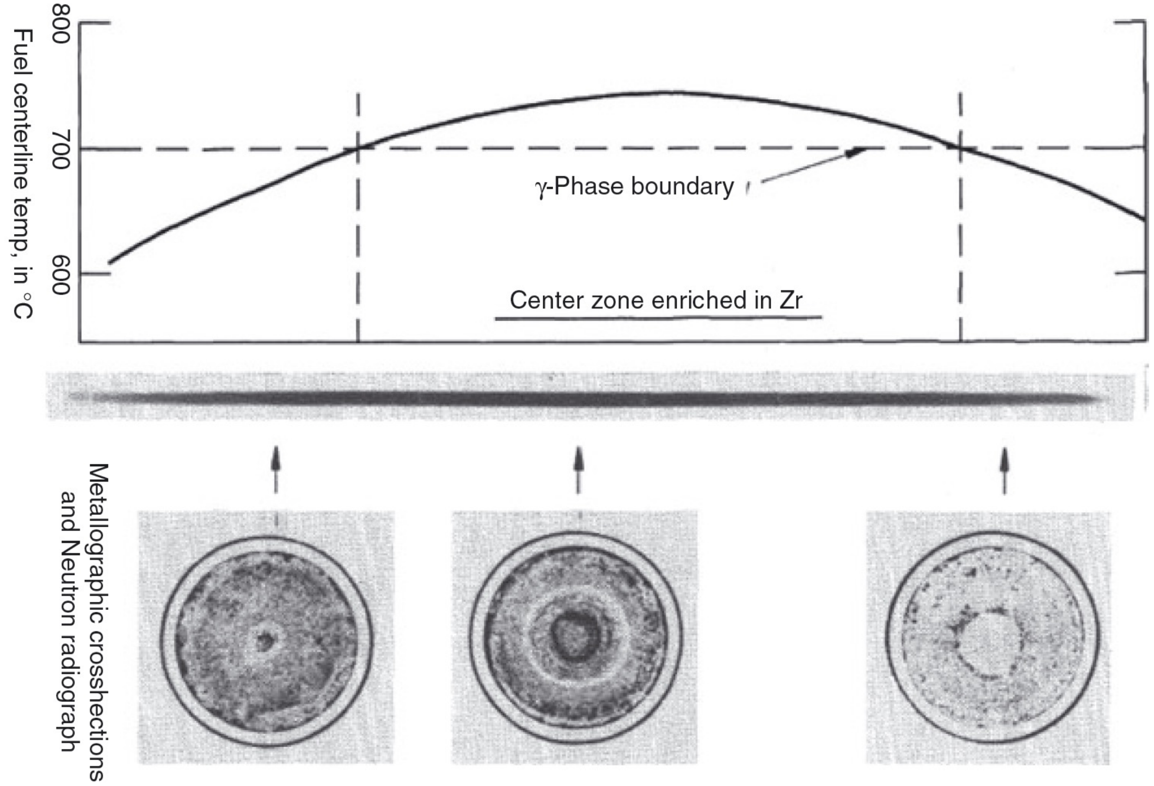
alpha U Tearing

- Between 400 and 600 C, alpha U swelling is overwhelmingly dominated by cavitation
- Cavitation swelling is characterized by large irregular cavities that form by mechanical tearing at grain and sub-grain boundaries, resulting in a very deformed "swirled" microstructure
- In addition to these large cavities, many small cavities, or tears, develop within the α grains, particularly in the 500–600 C range
- These intergranular cavities are crystallographically aligned and appear to be related to twin boundaries



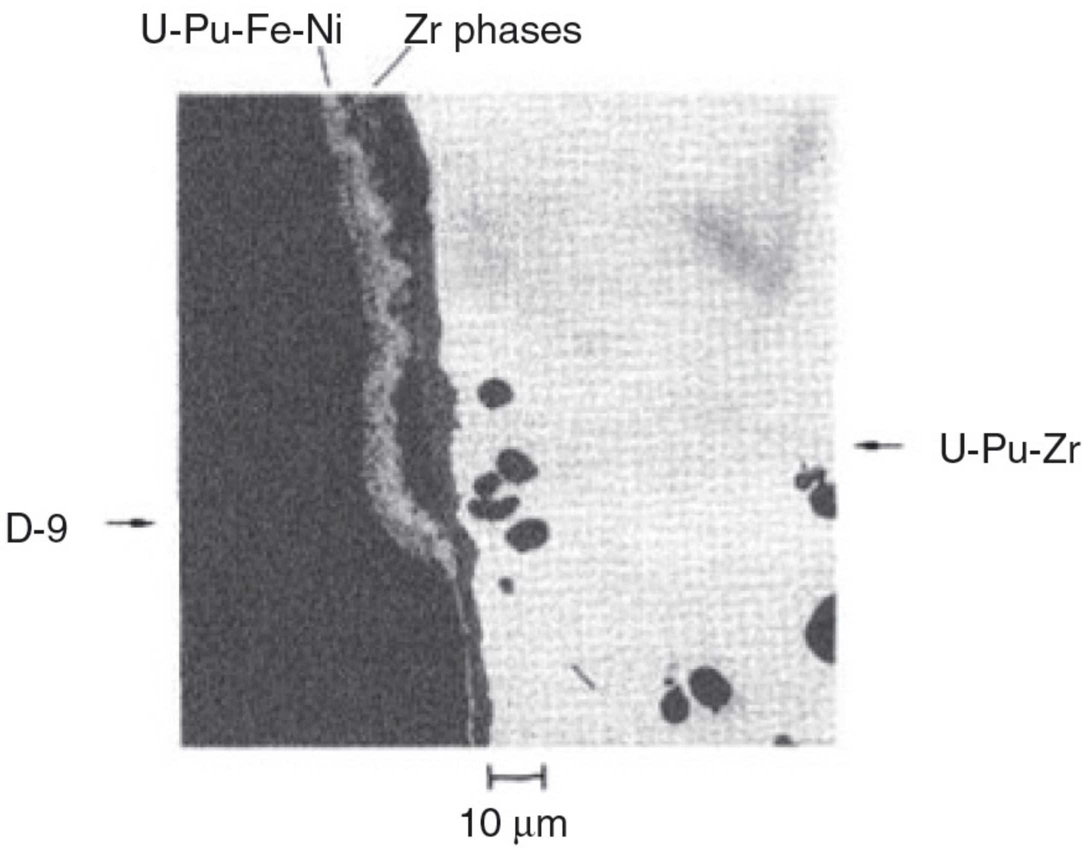
Axial Varying Microstructure

- The location of the radial zones essentially follows isotherms in the fuel which are determined by the various phase boundaries of the alloy
- In the usual situation of upward coolant flow and a cosine-shaped axial power profile in the fuel, the peak fuel temperature occurs between the center and top of the fuel column



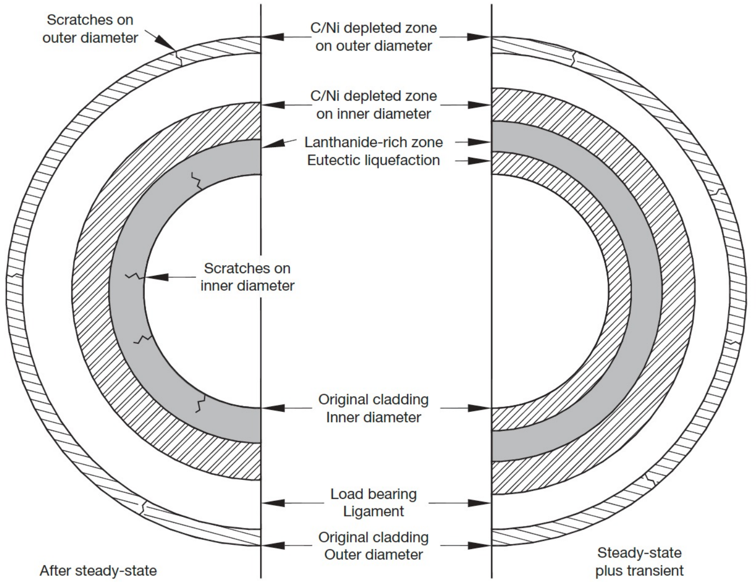
Fuel-Clad Chemical Interaction

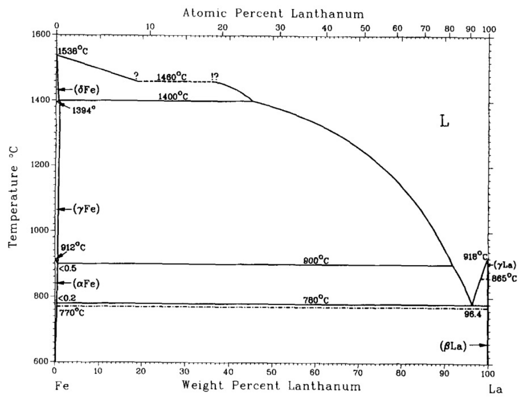
- FCCI in an all-metallic fuel element is in essence a complex multicomponent diffusion problem
- At least five major constituents participate in the diffusion process, in addition to minor alloy components such as C, N and O, as well as fission products
- The potential problem of interdiffusion of fuel and cladding components is essentially twofold: (i) a weakening of the cladding's mechanical properties; and (ii) the formation of relatively low melting point compositions in the fuel

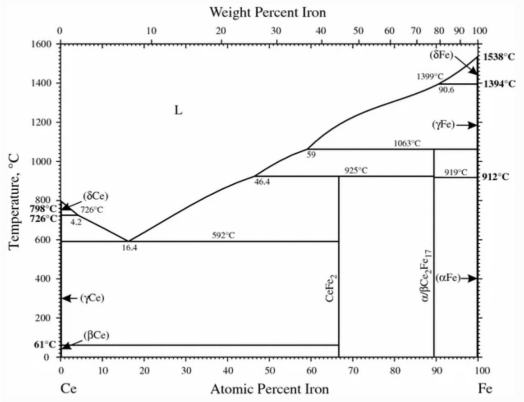


Cladding wastage mechanisms

- Prior to accumulation of lanthanide FPs at the fuel–cladding interface (due to FPs migration), FCCI is characterized by a ferritic layer formation, which is a result of Ni depletion in austenitic cladding or decarburization of the martensitic cladding
- Severe wastage is due to interaction of cladding with FPs, generating eutectic low melting phases
- Fe-96Ln has a melting point of 770˚C, Fe-92Ce has a melting point of 590˚C

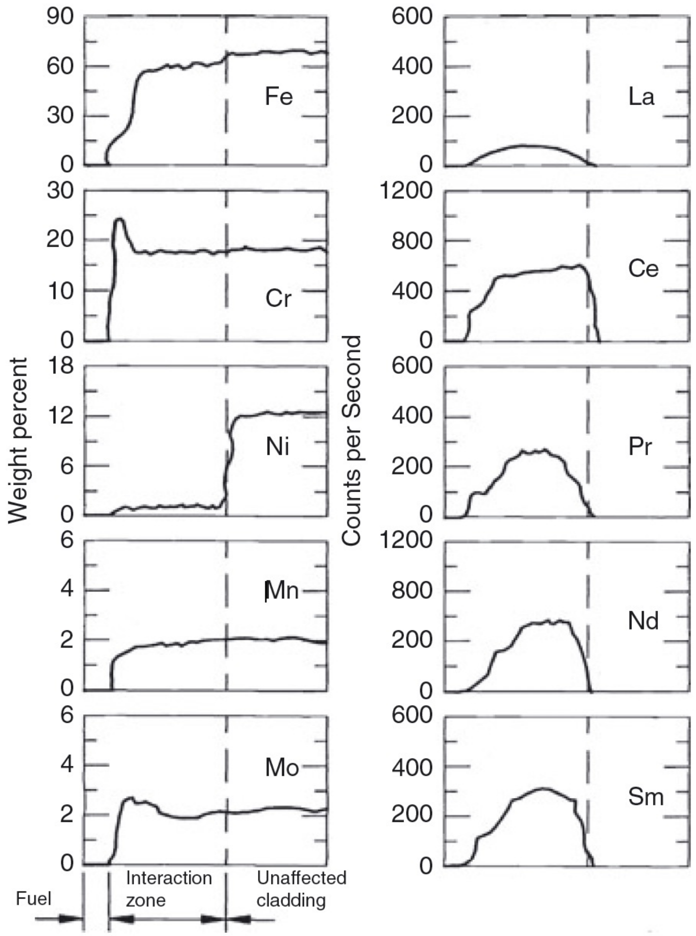






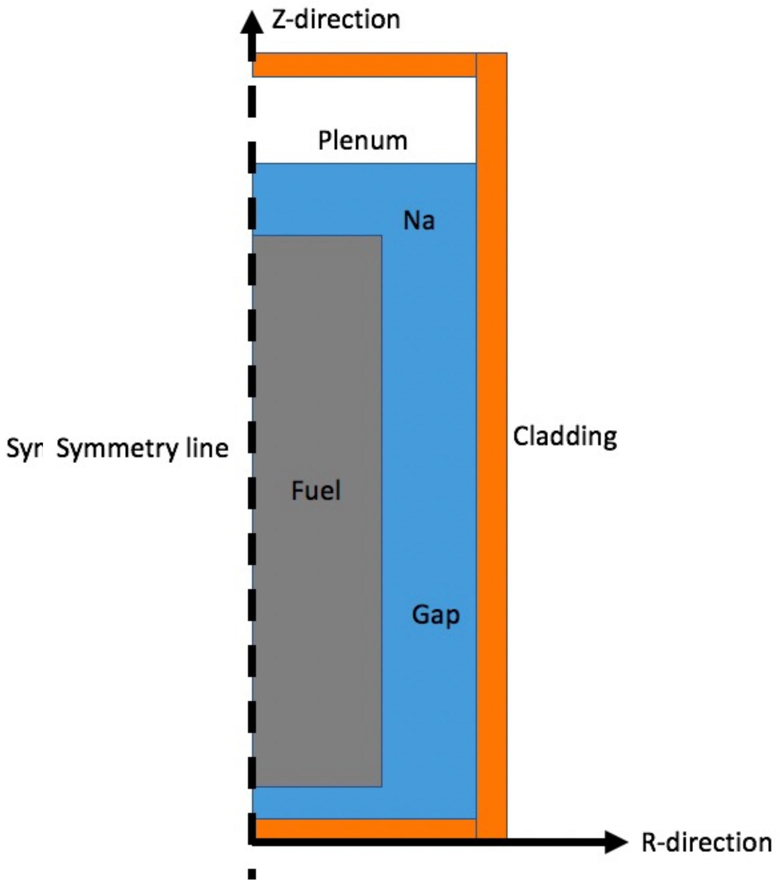
Chemical Species Diffusion and Interaction

- Lanthanides (Ln) ultimately control FCCI, and their presence at the internal cladding surface depends not only on burnup but also very strongly on their radial migration in the fuel
- Nd and Ce are two of the most commonly found Ln in FCCI regions
- Fission products diffuse into the Fe-based cladding and segregate along grain boundaries, further weakening the cladding
- It is key to develop transport models for Ln species through the fuel, in order to develop a source term for FCCI, but very little is known about Ln transport in metallic fuel



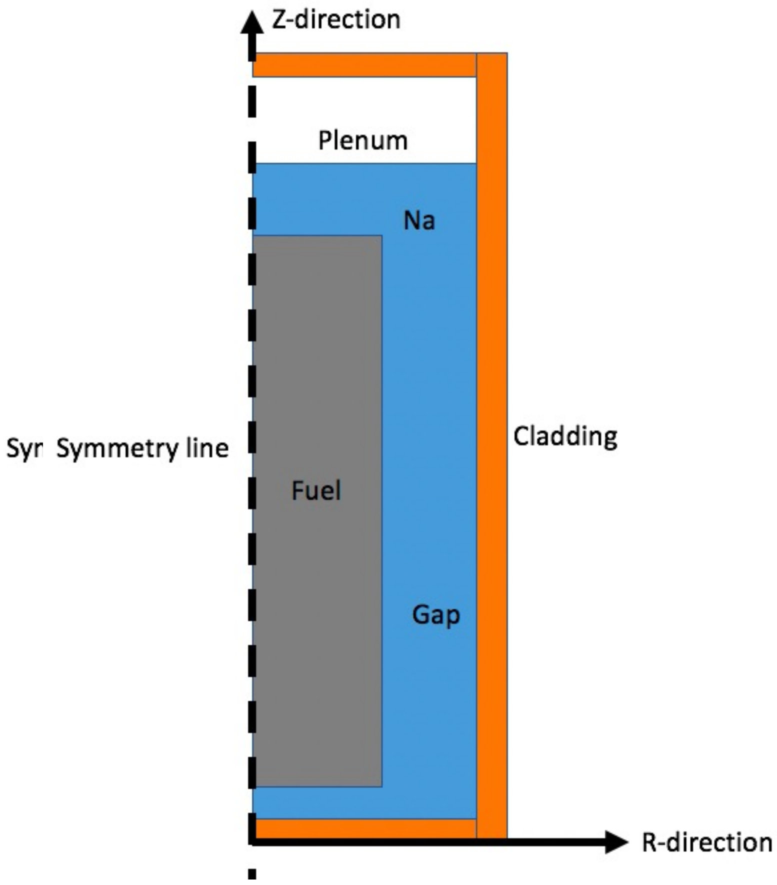
Metallic Fuel Performance Modeling - BISON

- The mechanical performance of the fuel is governed by a model that represents the elastic moduli as functions of temperature, porosity, and zirconium and plutonium content
- A creep model that is a function of fission rate, temperature, and porosity is also used
- Eigen strains (stress free strains) are modeled by constant thermal expansion along with gaseous and solid fission product swelling models
- The solid swelling model is a straight-forward model directly proportional to fission rate
- The gaseous swelling model comes from a force balance applied to a bubble with the metallic fuel and generates porosity at all material points (quadrature points) in the domain



Metallic Fuel Performance Modeling

- The thermal conductivity model in the fuel is a function of temperature, porosity, and zirconium and plutonium content
- The heat capacity models are functions of temperature and alloy phase
- The fission gas model is simply based on fission rate for gas generation and the fission gas released is governed by the value of porosity
- Cladding mechanical response is governed by constant elastic moduli and thermal expansion, with thermal and irradiation creep
- Thermal conductivity and heat capacity models are functions of temperature
- The redistribution of zirconium is governed by Fickian and Soret diffusion



Metallic Fuel Performance Modeling

- Compare BISON to EBR-II experiments

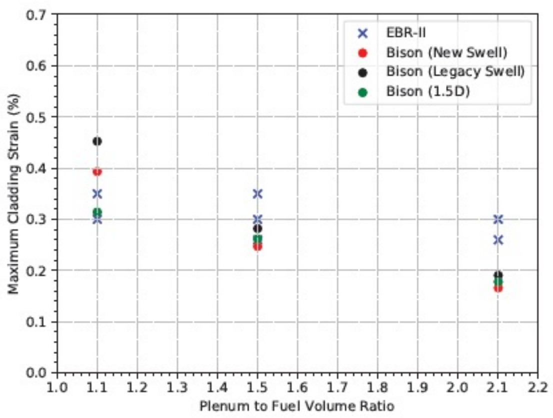


Figure 2: Comparison of BISON results and EBR-II experimental data for clad hoop strain vs. plenum/fuel volume ratio.

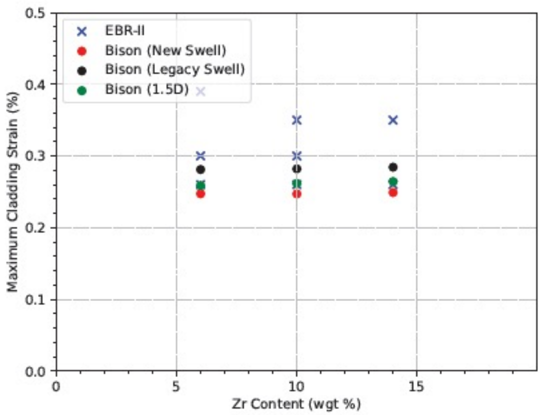


Figure 3: Comparison of BISON results and EBR-II experimental data for clad hoop strain vs. Zr content.

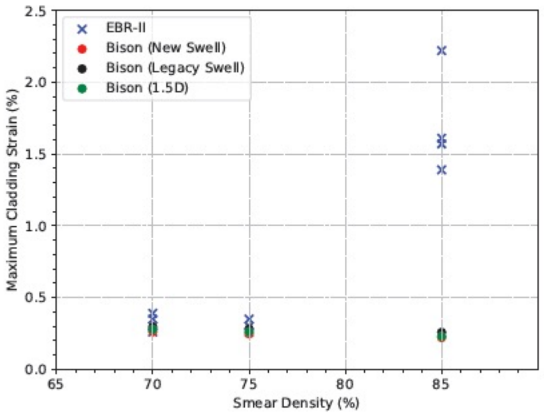


Figure 4: Comparison of BISON results and EBR-II experimental data for clad hoop strain vs. smear density.

Other Metallic Fuel Codes

- LIFEMETAL
  - ANL code that has evolved from the LIFE series of codes that perform steady-state and transient analyses for the thermal, mechanical, and irradiation behavior of nuclear fuel, and was originally developed for UO2
- ALFUS
  - ALloyed Fuel Unified Simulator, Japanese development (CRIEPI), is an irradiation behavior analysis code for metallic fast reactor fuel
- FAST
  - the current NRC thermal-mechanical fuel performance code that is the next evolution of FRAPCON

Incorporation of lower length scale information

- Surface energy
- Porosity interconnection threshold
- Fission gas bubble number density
- Alpha tearing/initial porosity

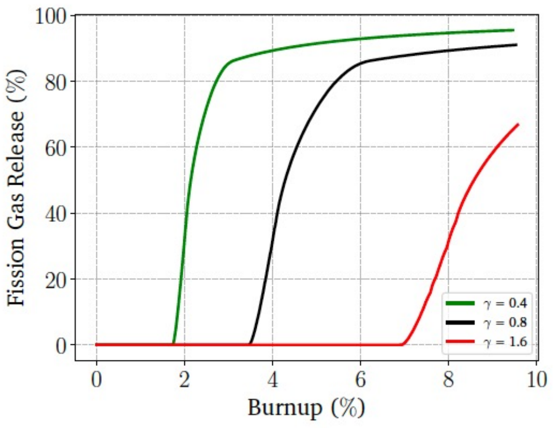


Figure 5: Comparison of fission gas release as a function of fuel surface tension.

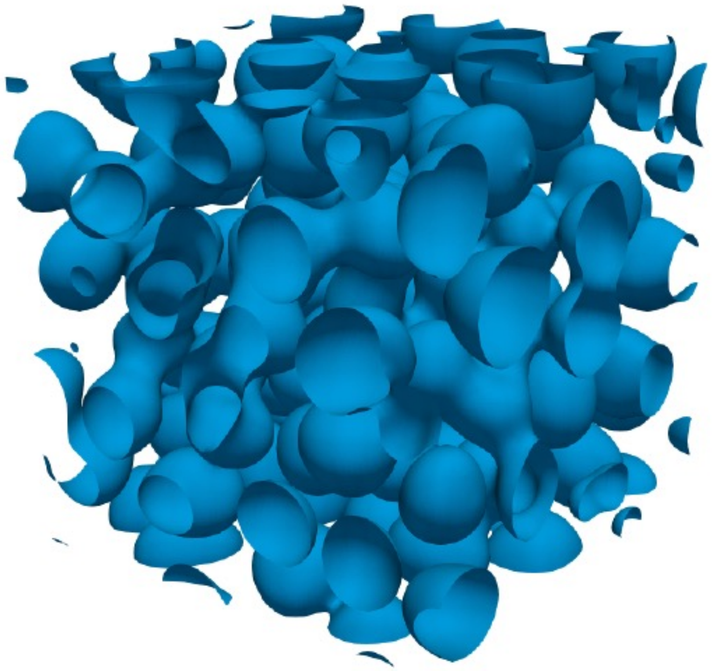


Figure 7: Final microstructure of interconnected bubbles.

Summary

- Metal fuel can go to high burnup, good accident performance, inherent safety, easy to make
- Complex phase and composition environment
- Rapid, substantial swelling, followed by fission gas release
- Fission gas bubble behavior is very phase dependent
- Observe constituent redistribution radially, in addition to axially varying microstructure
- FCCI is a major factor in cladding failure, dependent upon thermodynamics and kinetics of a number of lanthanides, actinides and transition metals
- We are trying to model all of this!