PennState
College of Engineering

NucE 497: Reactor Fuel Performance

Lecture 28: LWR cladding alloys and fabrication

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Professor Motta's notes and slides from ANT international

Today we will begin our discussion on cladding

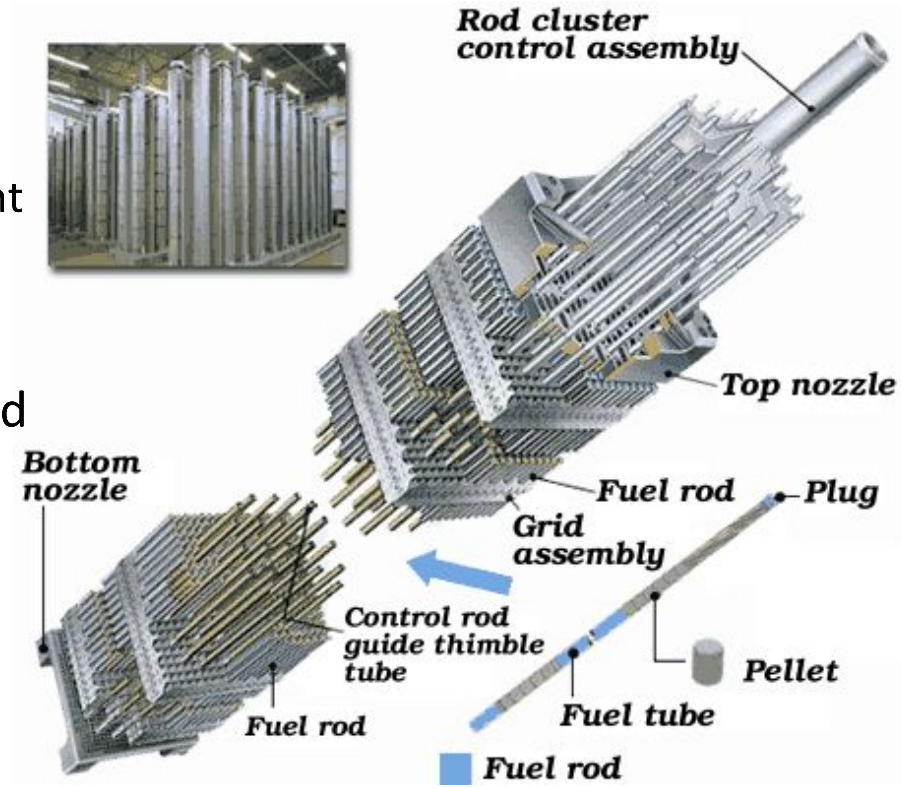
- Module 1: Fuel basics
- Module 2: Heat transport
- Module 3: Mechanical behavior
- Module 4: Materials issues in the fuel
- Module 5: Materials issues in the cladding
  - **Zirconium alloys and fabrication**
  - Cladding growth and creep
  - Irradiation hardening
  - Oxidation
  - Hydride formation
  - Stress corrosion cracking
- Module 6: Accidents, used fuel, and fuel cycle

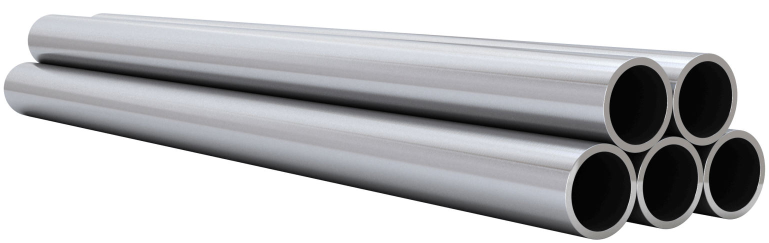
Here is some review from last time

- Fuel thermal conductivity decreases with burnup because of
  a) The decrease in U235 content
  b) Pellet fracture from thermal stresses
  c) Fission product formation and irradiation defects
  d) Temperature increases
- Which statement is true about empirical models correlated to burnup
  a) They are correct for any operating conditions of the fuel
  b) They mechanistically describe the fuel behavior
  c) They are easy to develop if temperature is available
  d) They are much better than mechanistic models

We have spent quite a while talking about the fuel, now we will focus on the cladding

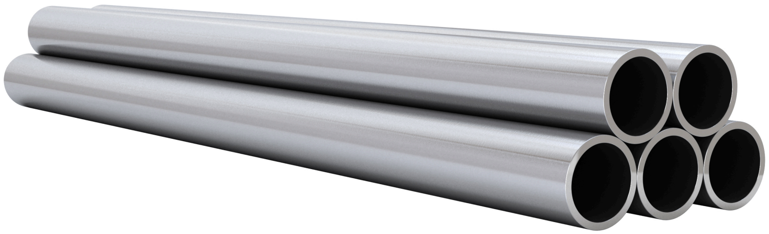
- The purpose of the cladding is to
  - Hold the pellets together so that coolant can freely flow past
  - Transport heat from fuel to the coolant
  - Contain fission products
  - Contain fuel fragments
- We would also prefer if the cladding had little to no impact on the neutron transport in the reactor

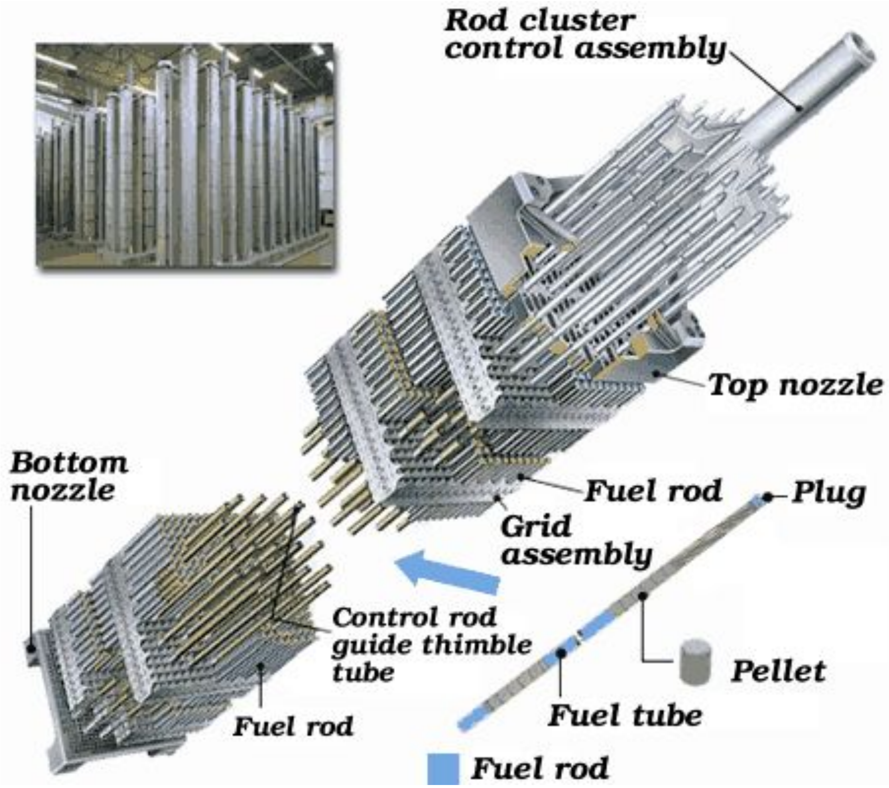




To optimize reactor performance, a cladding material must have the following characteristics:

- Low neutron absorption cross section
- corrosion resistance in 300°C water
- resistance to irradiation effects
- reasonable strength and ductility
- affordable cost
- availability in large quantities.





Various materials could be used as a cladding

Material	Young's mod. (GPa)	N.cross sect (barns)	Th. Cond. (W/mK)	α (10^{-6} 1/K)	Oxidation in water	Oxidation in steam	Brittle?
Zircaloy	99, 125	0.185	22	6.7	Good	Bad	No
316SS	193	3.21	16.3	15.9	Good	Good	No
SiC	410	0.086	120	4	Good	Poor	Yes
FeCrAl	250	2.42	20	11	Good	Good	No

Zirconium alloys have been used in reactors since the early 1950s because they meet all the requirements

Benefits
- Low neutron cross section
- Corrosion resistance in 300°C water
- Resistance to void swelling
- Adequate mechanical properties
- Good thermal conductivity
- Affordable cost
- Available in large quantities

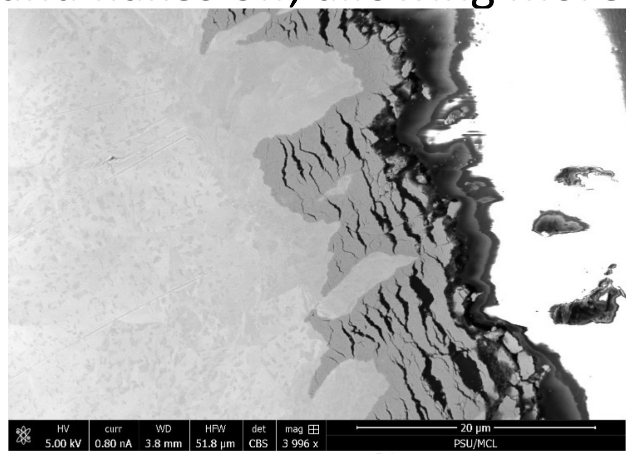
Problems?
- Corrosion under high temperature steam
- Hydride embrittlement
- Anisotropic characteristics lead to creep and growth

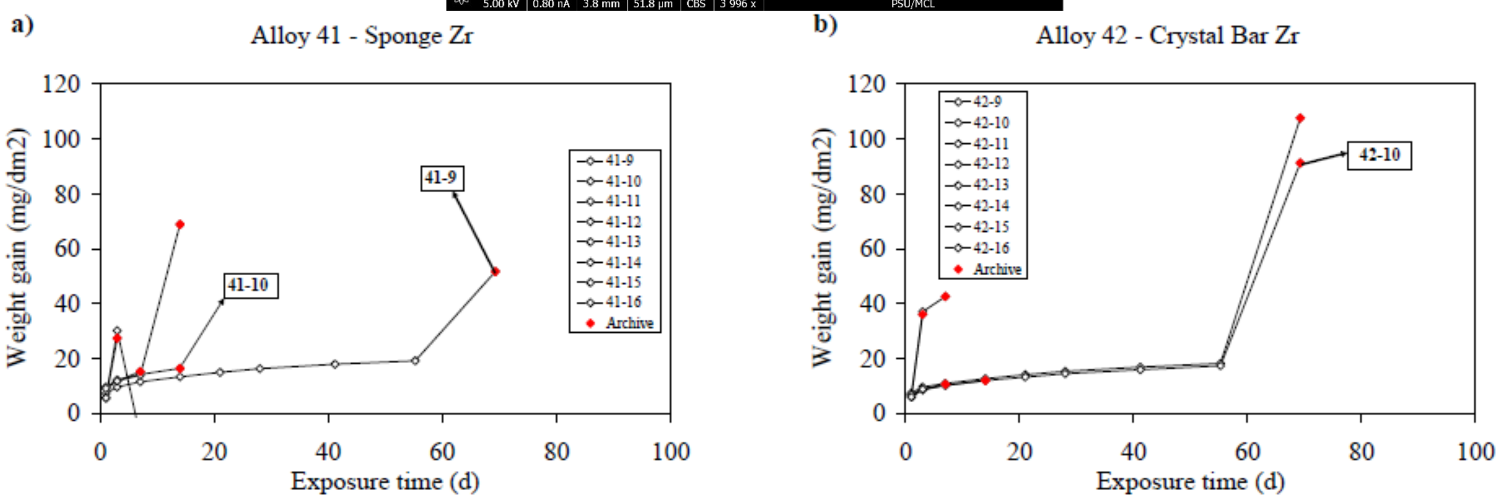
Zirconium comprises 0.03% of the Earth's crust and is the 12th most common element

- Zirconium is naturally occurring with 2% halfnium, with a very high neutron absorption cross section
- Before it could be used as a cladding material, a process had to be developed to separate Hf from the Zr (1947, Oak Ridge National Laboratory)
- History:
  - 1953 - Zr was used in the submarine prototype Mark 1
  - 1954 - Zircaloy-2 used in the Nautilus submarine, 1954
  - 1956 - Beach sand reduced to zirconium in production-sized batches
  - 1957 - Shippingport pressurized water reactor used Zircaloy-2

Pure zirconium was not acceptable due to its oxidation behavior

- Oxygen with water reacted to form an oxide layer
- The oxide layer is brittle and flakes off, allowing more oxidation to occur



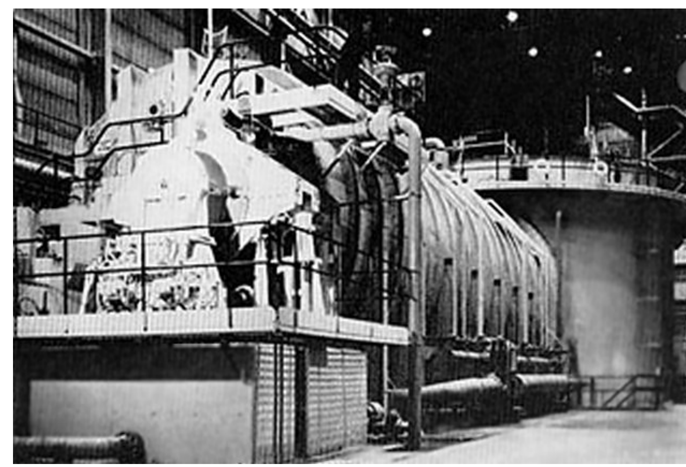


Zircaloys were developed to improve corrosion resistance

- Zircaloy-1 composition was designated as Zr-2.5Sn
  - Corrosion rate of Zircaloy increased with time
- Zircaloy-2 was discovered by accident in 1952 and was used in the Nautilus in 1955
  - Highly resistant to corrosion
- Zircaloy-3 was suggested for high-temperature corrosion
  - Alloy exhibited non-uniform corrosion

Admiral H.G. Rickover

USS Nautilus



Prototype of Nautilus reactor, SSN-571, at S1W facility

Commercial alloys in BWRs

Alloy	Sn %	Nb %	Fe %	Cr %	Ni %	O %	Fuel Vendor
BWRs (structural components and fuel rods)							
Zircaloy-2 (SRA)/ RXA)	1.2-1.7	-	0.07-0.2	0.05-0.15	0.03-0.08	0.1-0.14	All fuel vendors
Liner/Barrier							
Sponge	-	-	0.015-0.06	-	-	0.05-0.1	Only used in Japan and Russia
ZrSn	0.25	-	0.03-0.06	-	-	0.05-0.1	W
ZrFe	-	-	0.4	-	-	0.05-0.1	AREVA
ZrFe	-	-	0.10	-	-	0.05-0.1	GNF P8

Peter Rudling

Commercial Zr Alloys in PWRs

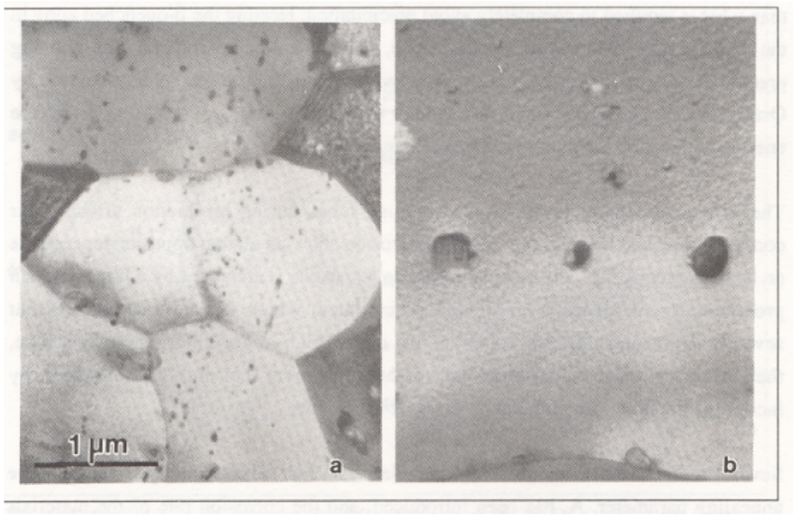
Alloy	Sn %	Nb %	Fe %	Cr %	Ni %	O %	Fuel Vendor
PWRs (structural components and fuel rods)							
Zircaloy-4 (SRA)	1.2-1.7	-	0.18-0.24	0.07-0.13	-	0.1-0.14	
ZIRLO (SRA)	1	1	0.1	-	-	0.12	W
Optimized ZIRLO (pRXA)	0.7	1	0.1	-	-	0.12	W
M5 (RXA)	-	0.8-1.2	0.015-0.06	-	-	0.09-0.12	AREVA
HPA-45 (SRA/RXA)	0.6	-	Fe+V	-	-	0.12	AREVA
NDA (SRA)	1	0.1	0.3	0.2		0.12	NFI
MDA (SRA)	0.8	0.5	0.2	0.1		0.12	MHI/MNF

Peter Rudling

The alloying elements impact the microstructure of the material

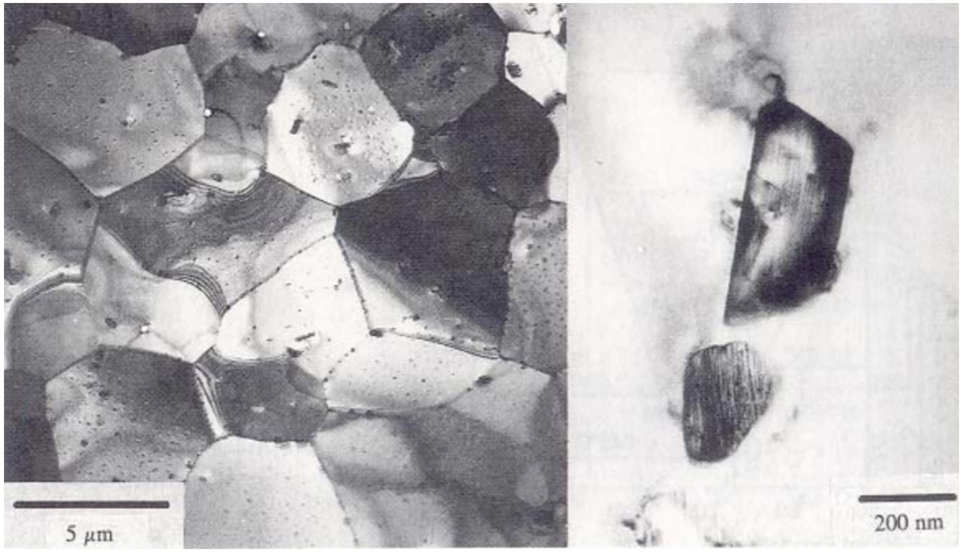
- Sn is found in solid solution (it lives in the crystal lattice)
- Fe, Cr, and Ni form intermetallic precipitates

α-recrystallized β-quench



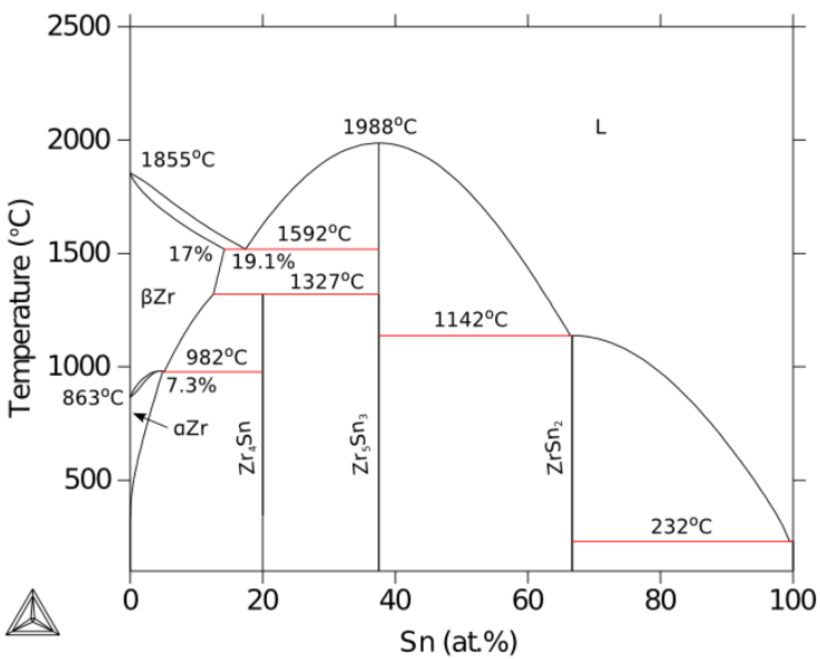
The intermetallic precipitates significantly improve the oxidation behavior

- In zircaloy 2, the precipitates are
    - $Zr(Cr, Fe)_2$
    - $Zr_2(Ni, Fe)$
- In Zircaloy 4, the precipitates are
    - $Zr(Cr, Fe)_2$
- Phosphides (Zr_3P) and silicides (Zr_3Si) are also occasionally found.
- The precipitate distribution, size, morphology, and composition all impact the properties of the material

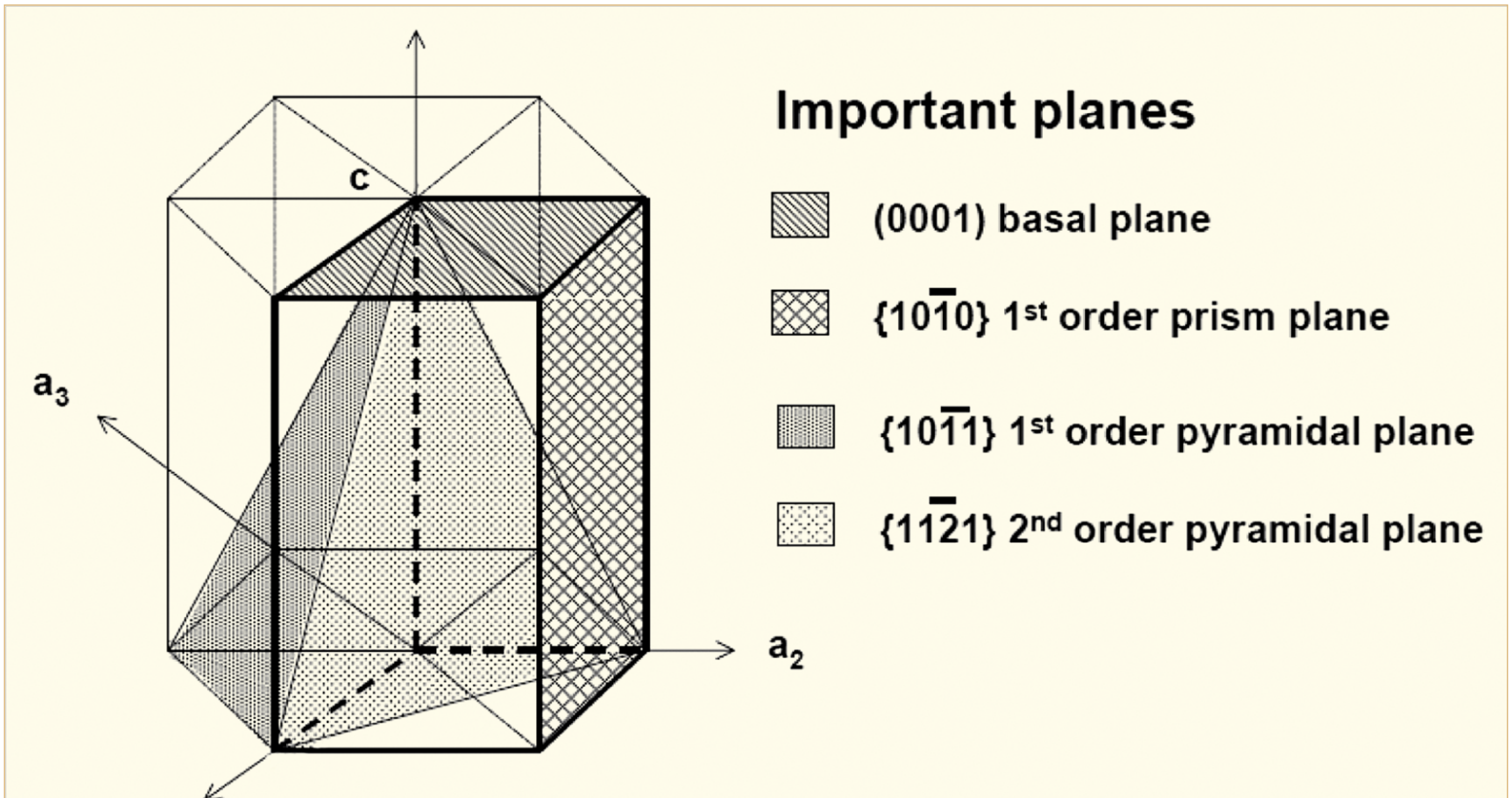


Zirconium and its alloys have two primary phases

- The α-Zr phase has a hexagonal-close-packed (HCP) structure.
  - At temperatures below about 863°C
  - Has the most desirable properties
- The β-Zr phase has a body-centered-cubic (BCC) structure
  - We try to avoid this phase



In the HCP structure, there are three different kinds of planes in the crystal structure



(Tenckhoff,2005)

The cladding tubes are fabricated using various processes that SEVERELY deform the material

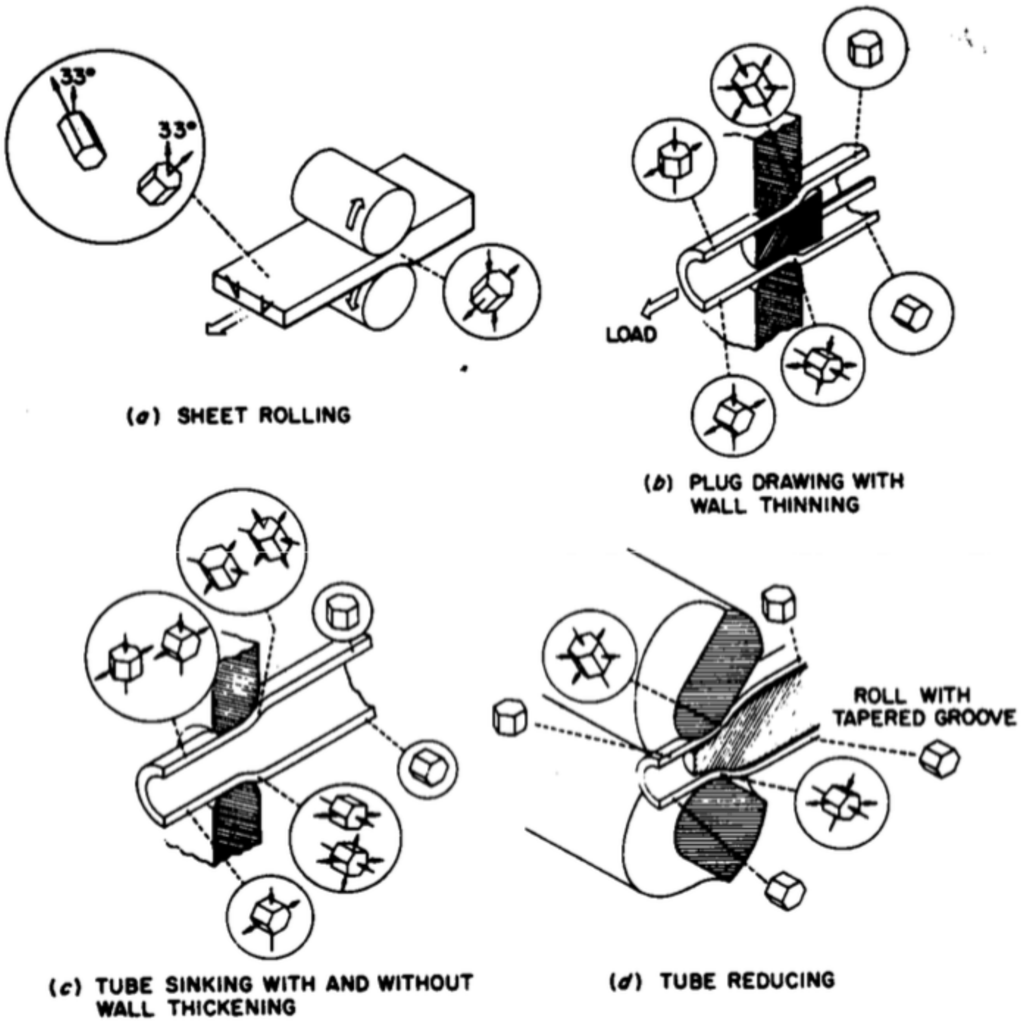
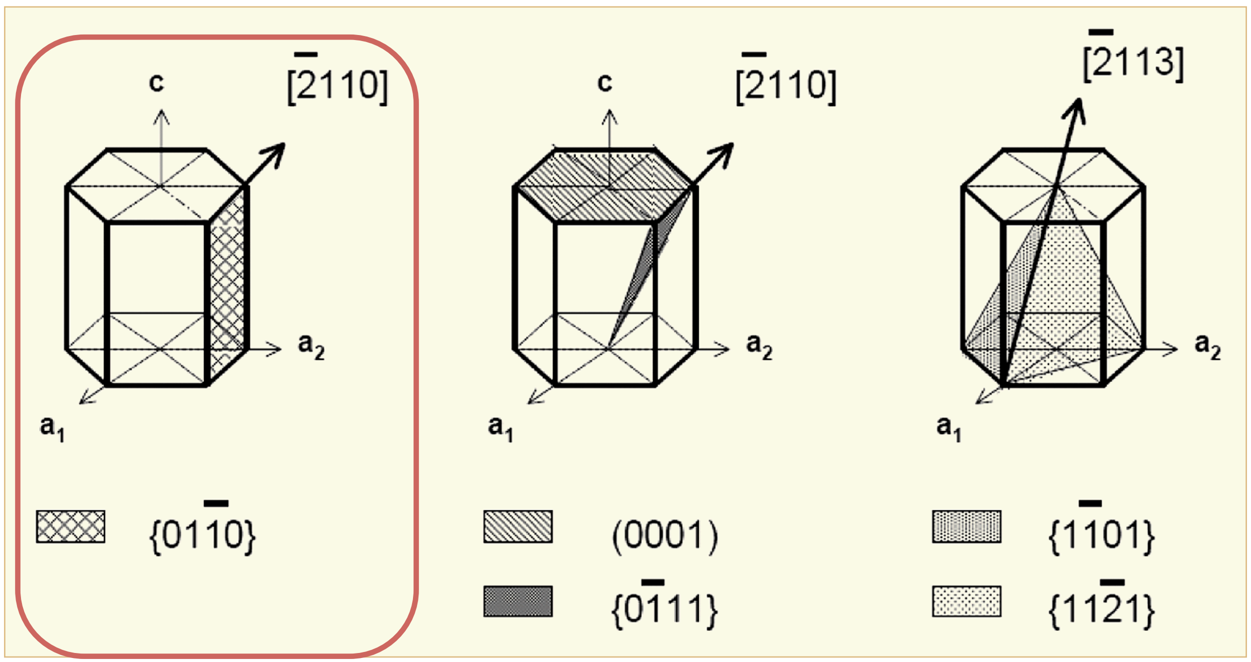


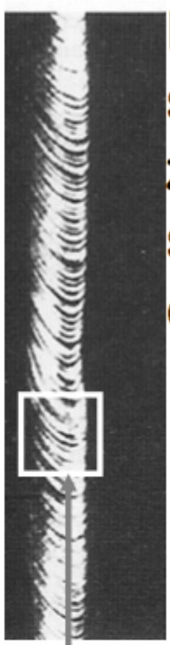
FIG. 48. Strain states for various types of fabrication of Zircaloy-2 [109].

The deformation in zirconium alloys typically occurs on prism planes up to about 500°C

- The severe plastic deformation causes significant dislocation hardening, that can make the tube material too brittle



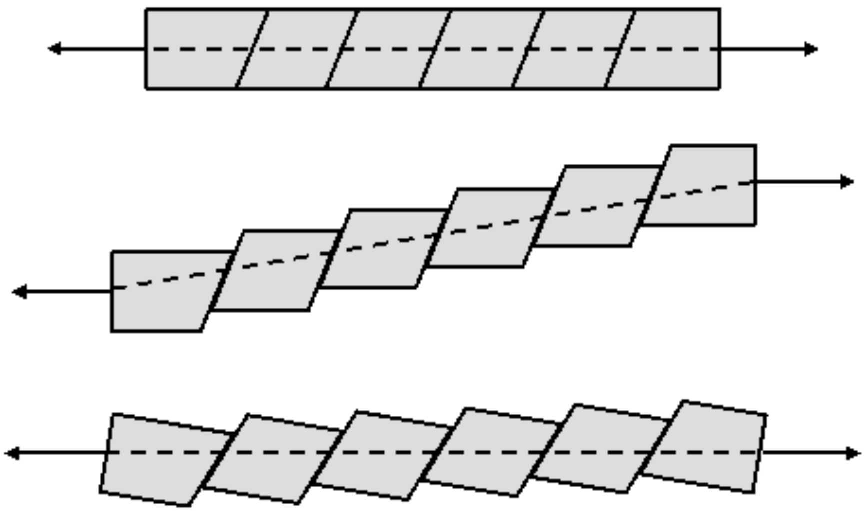
Plastic deformation along slip planes results in reorientation of the grains



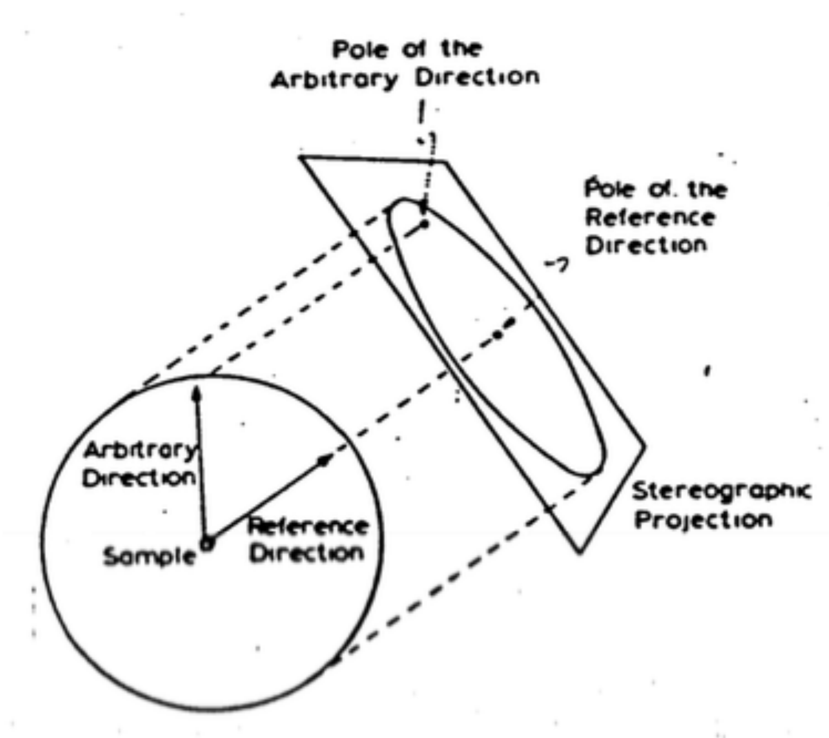
Plastically stretched zinc single crystal.

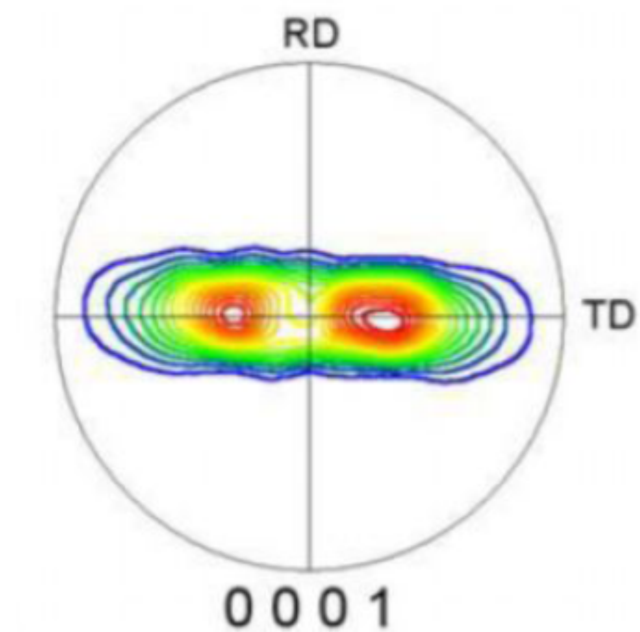
Adapted from Fig. 7.9, *Callister 6e.* (Fig. 7.9 is from C.F. Elam, *The Distortion of Metal Crystals*, Oxford University Press, London, 1935.)

Adapted from Fig. 7.8, *Callister 6e.*



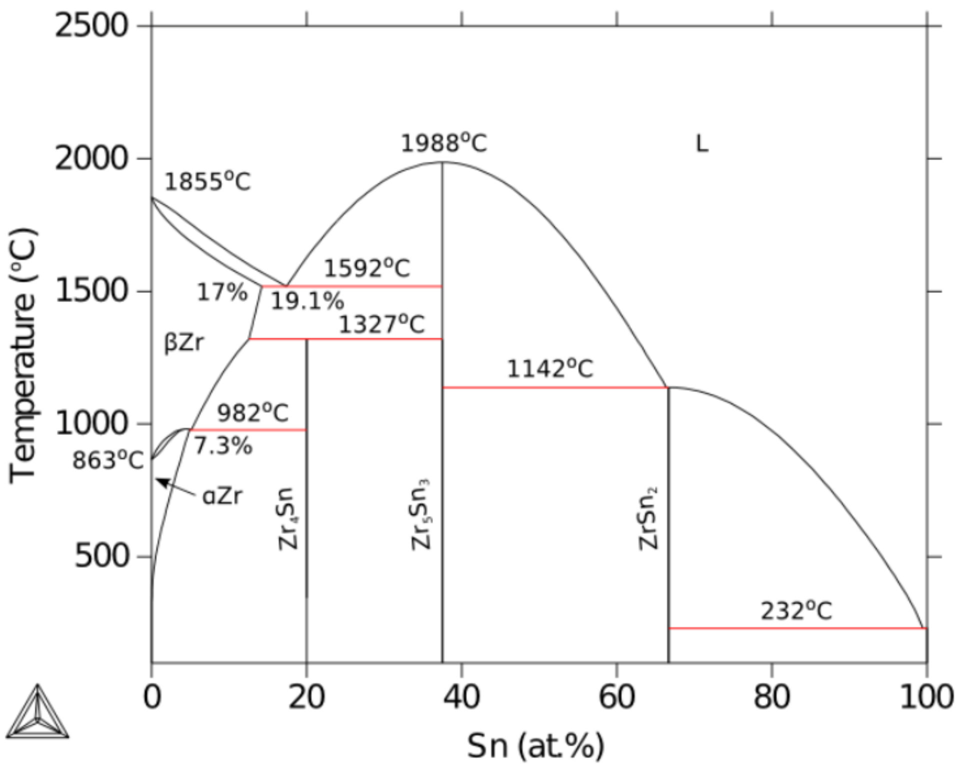
Significant grain reorientation occurs in the cladding as it is formed, which can have negative effects

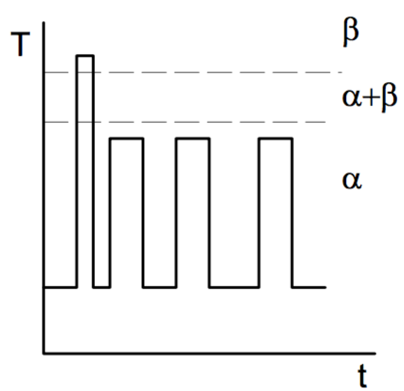


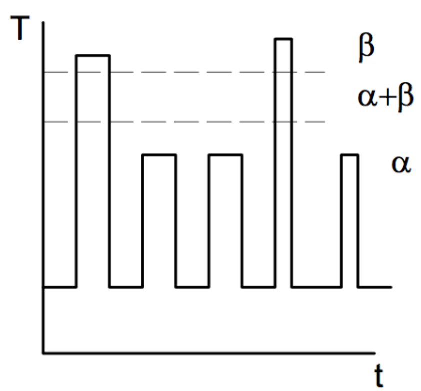


The properties of the material are controlled by heat treatment

- Raising the temperature, but below 863°C, anneals the sample to reduce cold work (stress-relieved)
- Raising the temperature above 863°C changes to the β phase. They then quench the sample to create a random texture in the α phase.

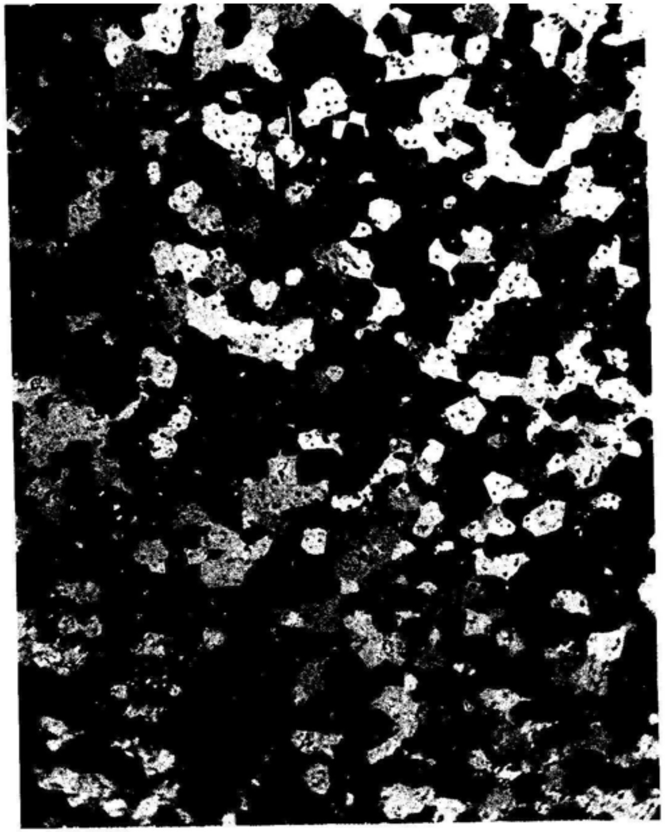






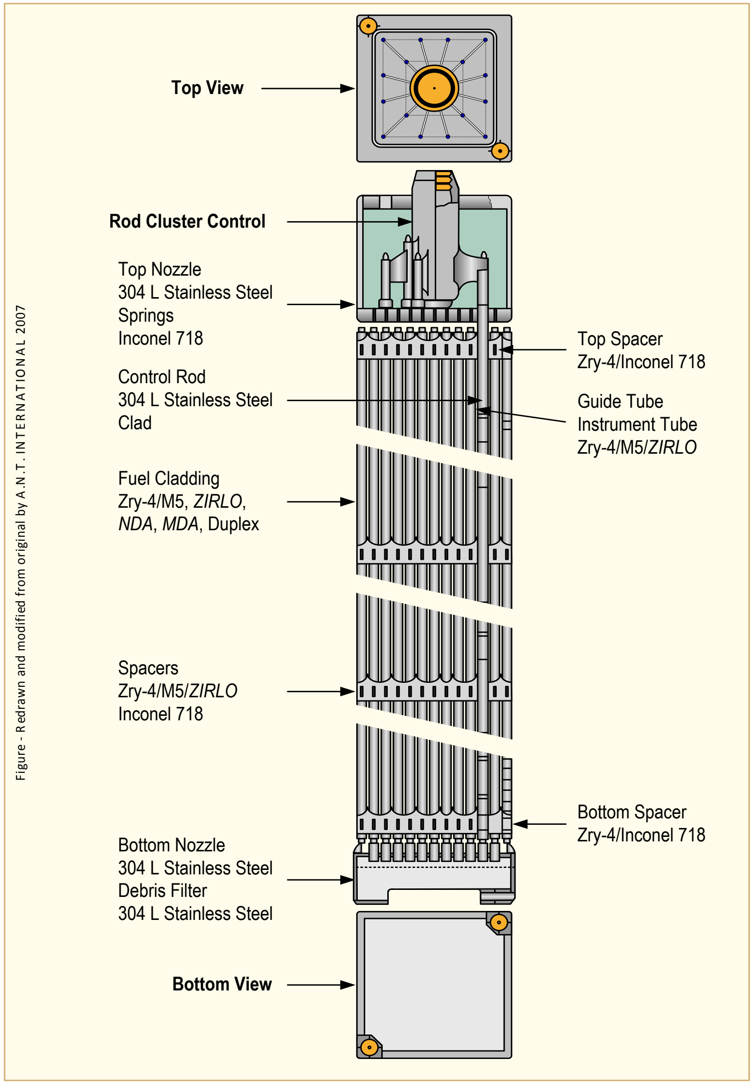
Here are examples of the different microstructures

Fully recrystallized after quench



Stress-relieved microstructure

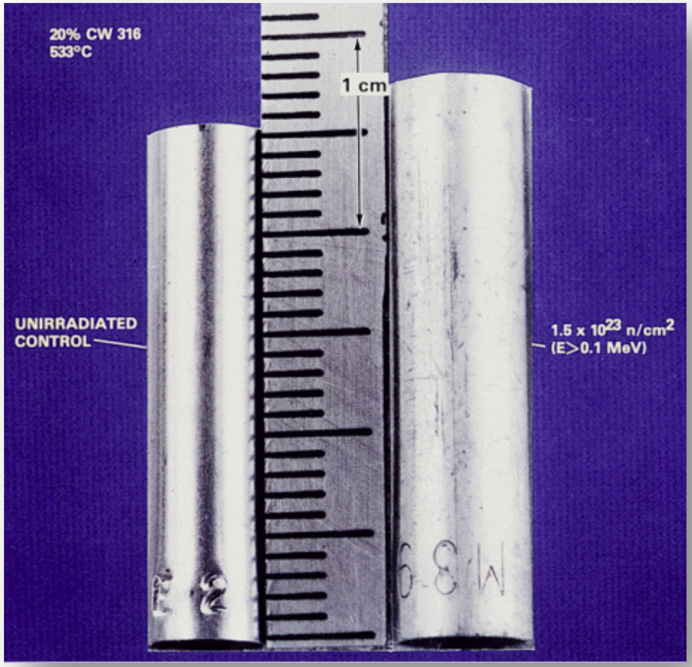
Other materials are used in areas where neutron absorption isn’t a problem



Typical PWR Fuel Assembly

Steels are used for cladding in fast breeder reactors

- Steel microstructure and properties varies widely with alloying elements and fabrication methods
- General properties:
  - Pros: High strength, can have high corrosion resistance
  - Cons: High neutron cross section, void swelling
- They are used in breeder reactors as cladding because neutronic conditions are less important than mechanical properties and corrosion behavior.



Summary

- The cladding separates the fuel from the coolant, allowing the coolant flow to be unobstructed and to contain dangerous fission products and fuel fragments.
- Zirconium alloys are used as LWR cladding because they have satisfactory mechanical properties, are resistant to corrosion with water, and have a low neutron absorption cross section
- Various alloys have been developed, with current alloys showing improved performance
- Cladding tubes are fabricated using large deformation, and must be heat treated to obtain desired properties

Once you get a job, there are many things you can do to keep that job

The first secret to job security is don’t get fired

- Don’t lie about or cover up mistakes
  - If you confess to a mistake, you may face some consequences
  - If you cover up a mistake, you will destroy your career
- Don’t break company policy, for example
  - Don’t look at porn at work
  - Don’t watch Netflix during on your work computer
  - Don’t use illegal drugs
  - Don’t drink and come back to work (this might be OK in some countries)
  - Don’t go to online gambling sites on your work computer

Life lesson: How do have job security in an uncertain economy? Or, how can I be a good engineer?

- If you screw up, you get fired
- However, in a lay-off or a reduction in force (RIF), people loose their jobs without having screwed up. How can you make sure that isn't you?
- In a lay-off or RIF, even though people are just let go, they tend to target the people they want to get rid of, but don't have a "fireable" reason.
- So, be an excellent scientist/engineer, and they will typically keep you around, though you may change jobs.
- If they don't keep you around, a good scientist/engineer will quickly get picked up by someone else.

A good scientist/engineer takes initiative

A good scientist/engineer does more than he is asked to do

A good scientist/engineer puts up with some crap

A good scientist/engineer seeks out collaborators every where and helps out in their own time