Nuclear Fuels and Materials

Jon Carmack
Nuclear Fuels and Materials Division
Idaho National Laboratory

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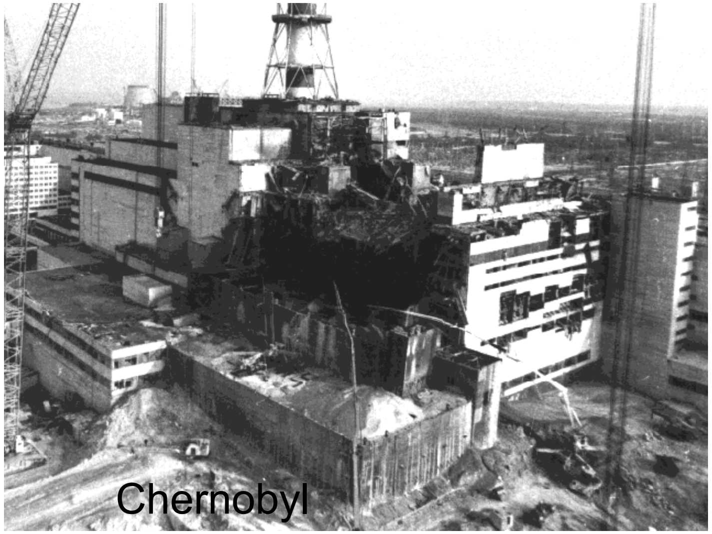
A Brief History of Nuclear Power

1946-1978 Major Progress

- Submarine and ship propulsion
- 435 reactors producing 17% of the world's supply of electricity

…but no definite back-end solution

EBR-I, 1951



Chernobyl

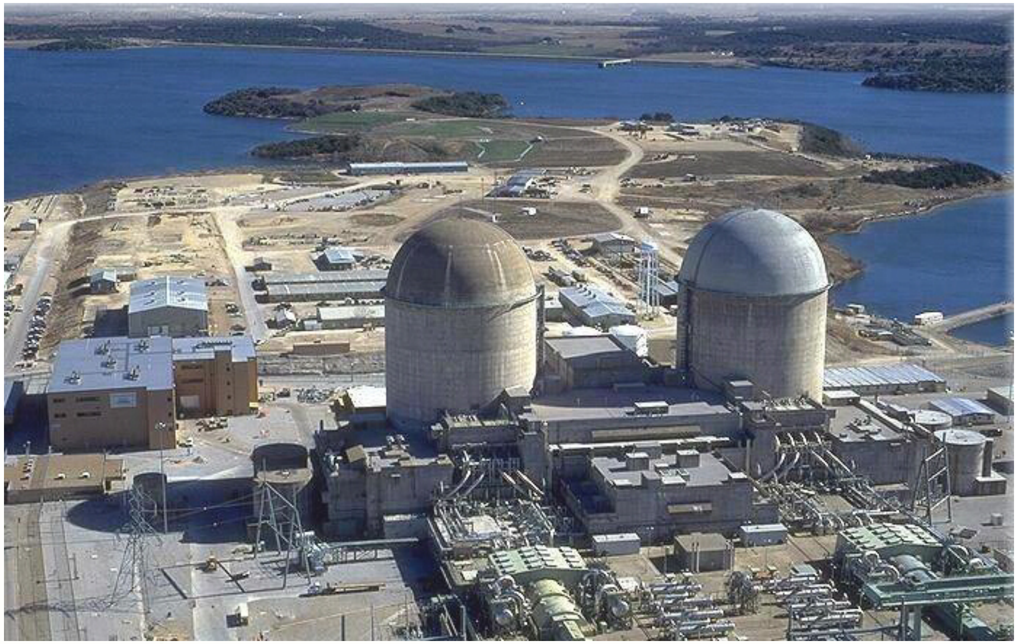
1978-1990's Major Setbacks

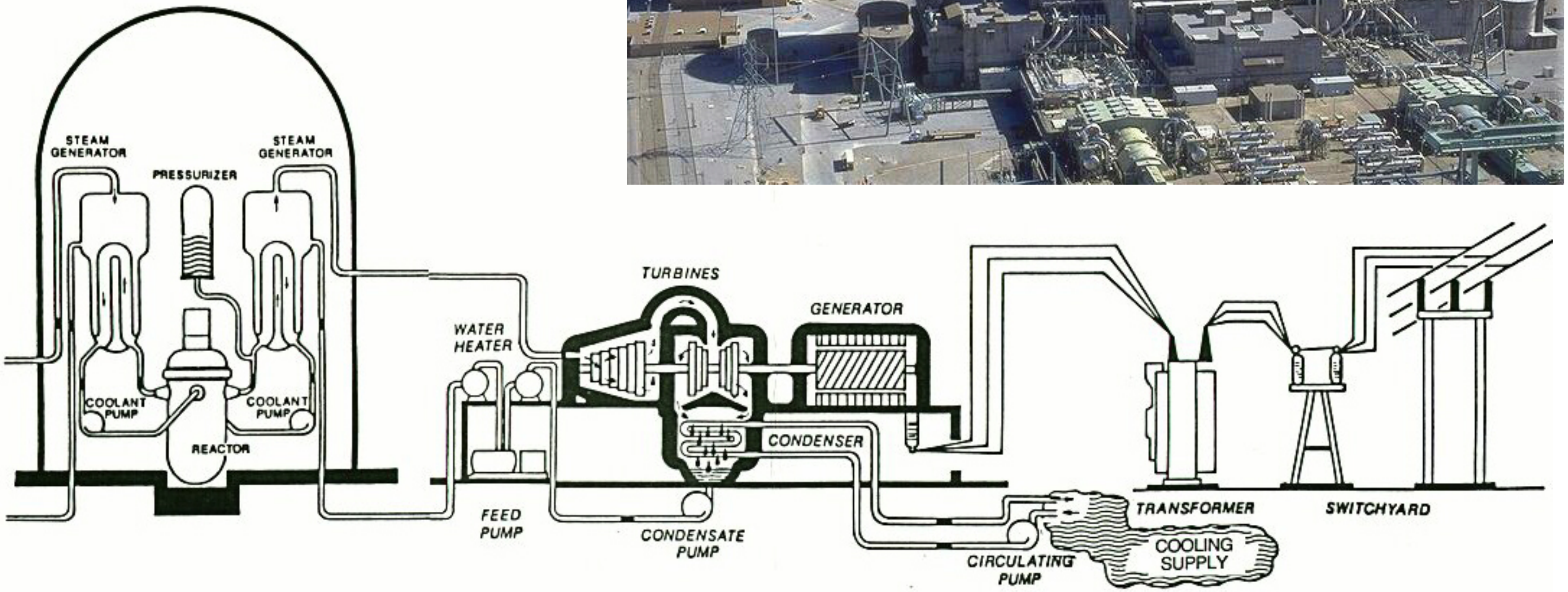
- **High costs & schedule delays**
- **Non-standardization**
- **TMI-II (1979)**
- **Chernobyl (1986)**

Commercial Nuclear Power Today

Nuclear Power Plants Supply:

- ~90% Availability
- 20% of U.S. electricity needs (104 NPP)
- 76% of France’s electricity
- 17% of the world’s electricity needs
- 6% of the world’s total energy needs





The USA's long nuclear slumber

1978	last nuclear plant order in US	
1979	last 2 construction permits issued	**Until last month**
1993	last operating license issued	**Until last year**
1995	last 2 orders cancelled	

259 Reactors ordered

124 Cancelled orders

132 Operating licenses issued

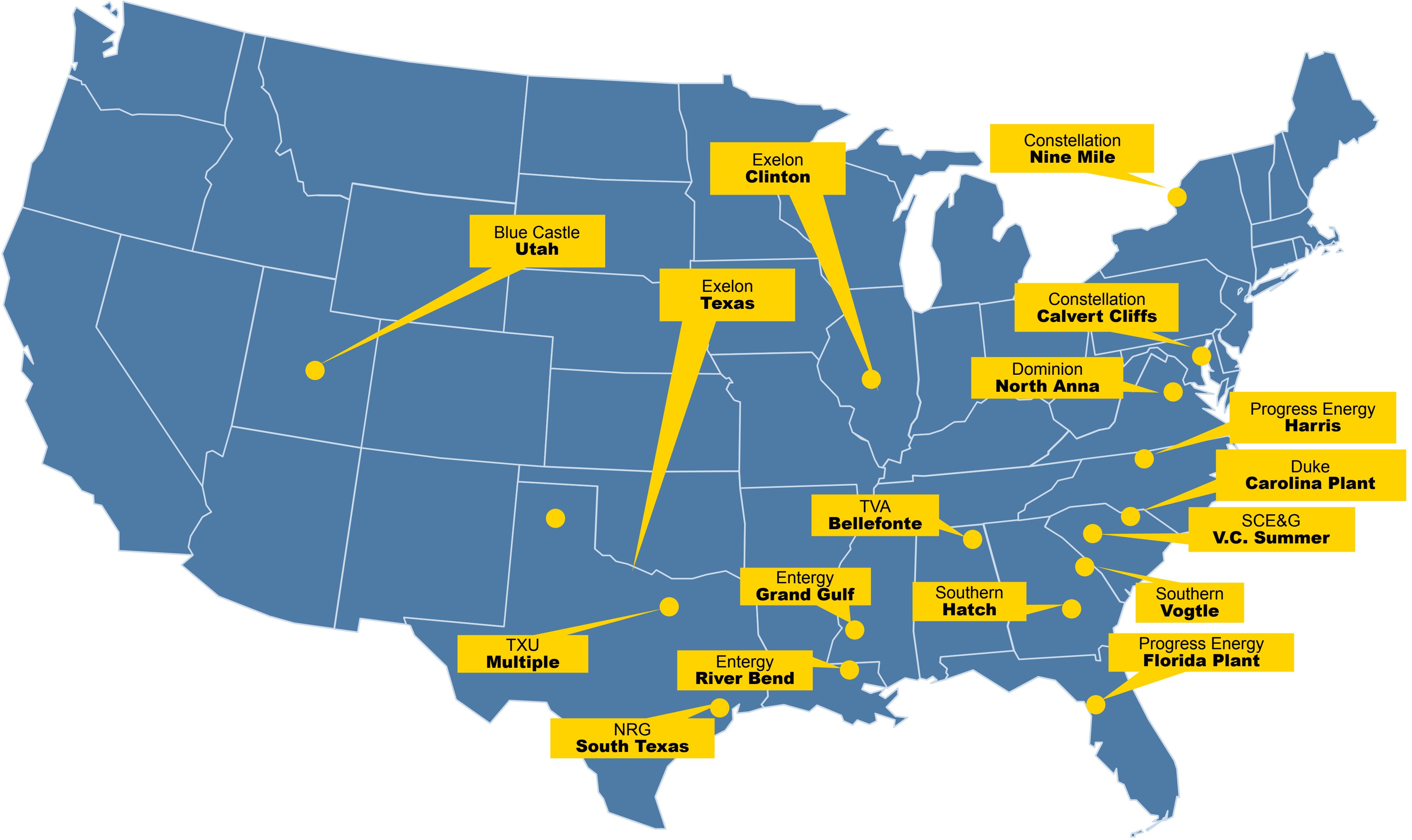
28 Plants shut down

104 Operating plants today

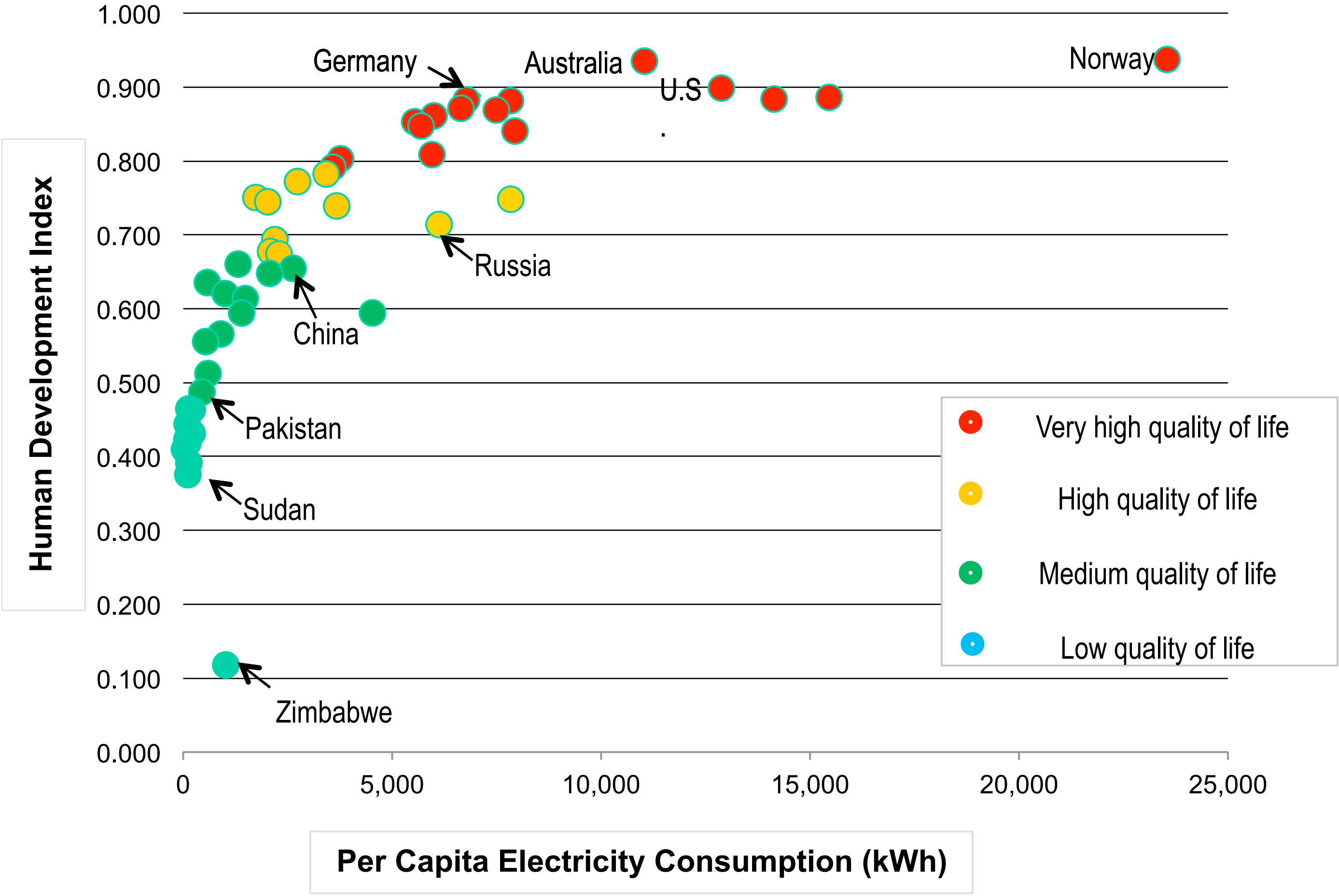
36 Nuclear Engineering programs terminated

Trojan (Oregon)

U.S. nuclear industry—more than 30 notifications to Nuclear Regulatory Commission for new build

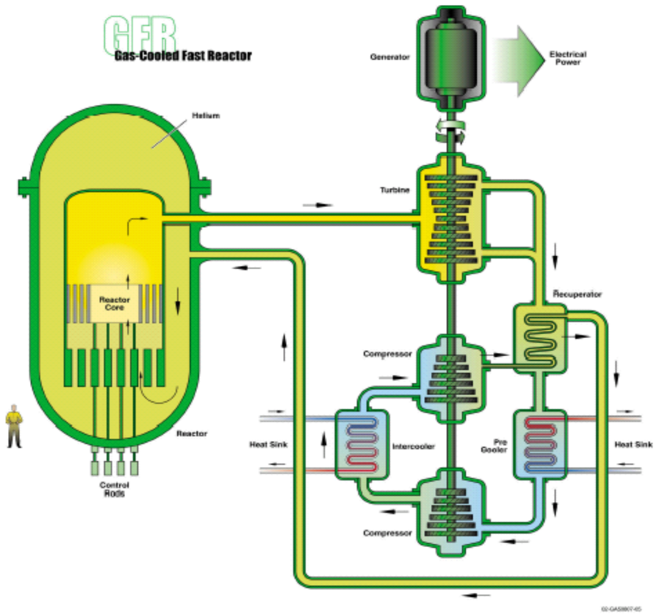


Correlation Between Human Development Index and Per Capita Electricity Consumption, 2009



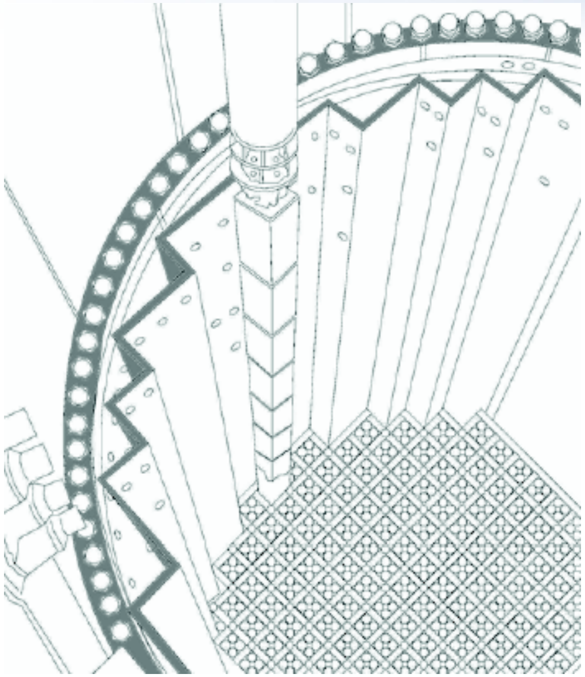
Human Development Index - Human Development Report 2010, United Nations (2009 data)
Per Capita Electricity Consumption (kWh) - Key World Energy Statistics, International Energy Agency (2009 data)

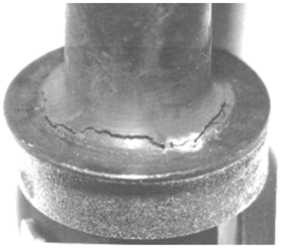
Nuclear Energy Tomorrow

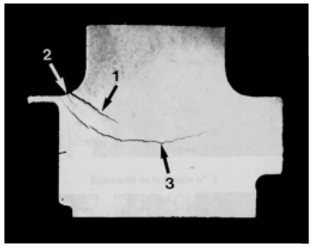


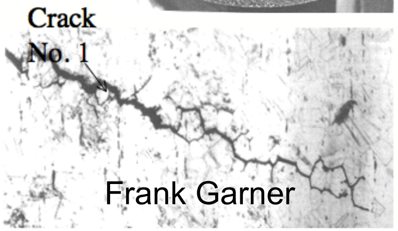
- Continued deployment of Gen III+ reactors
- Development of fourth generation systems
  - Very High Temperature Reactor (VHTR)
  - Sodium Fast Reactor (SFR)
  - Supercritical Water-cooled Reactor (SCWR)
  - Gas-cooled Fast Reactor (GFR)
  - Lead Fast Reactor (LFR, SMR)
  - Molten Salt Reactor (MSR)
- Generation IV Goals
  - Safety
  - Sustainability
  - Economics
  - Proliferation Resistance
- Advances in fuels/materials technology play a critical role in achieving goals for advanced nuclear energy systems
- Nanotechnology may play a role in meeting advanced material needs

Reactor Materials







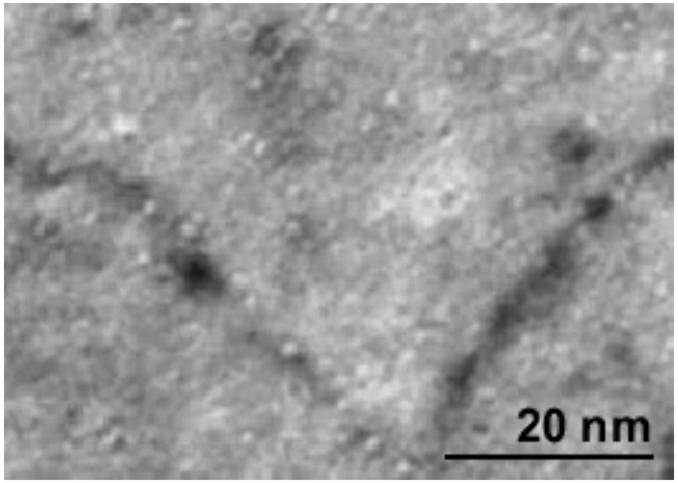


Frank Garner

- Nuclear reactors are expensive machines ($5 - $7 B)
- Operating lifetime of 60(+) years
- Materials issues are difficult to deal with
- Material performance is very sensitive
  - Process history
  - Operating environment (stress, coolant chemistry)
- Very conservative approach to material selection
- Emphasis on engineering solutions over material solutions where possible
- Todays reactors are constructed from 'old-fashioned' materials
- There may be some areas where advanced materials make sense (fuel cladding)

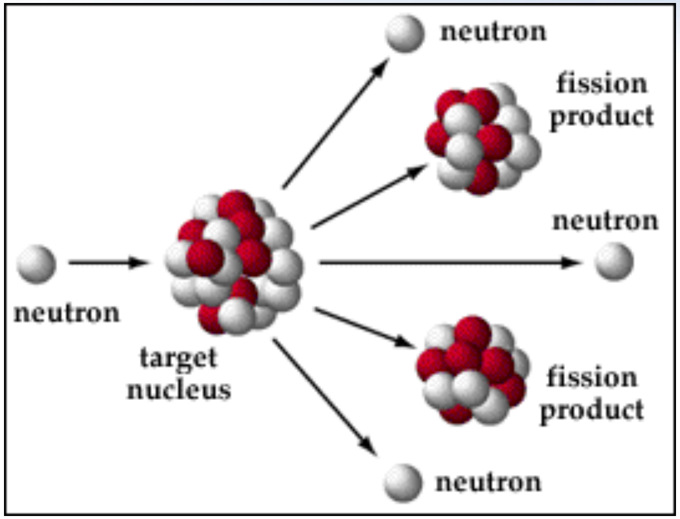
Example of a potential ‘modern material’ : Nano-structured Ferritic Alloys (NFA)

- PM process used to fabricate
- 1-2 nm Y-Ti-O precipitates
  - V~0.65 vol.%, N ~ 5×10^{23} m^{-3}
- Y-Ti-O stabilize dislocation structure
- High creep strength
- Evidence that NFAs have high resistance to void swelling under irradiation to 100 dpa
- Thermally stable
- Challenges
  - Anisotropic microstructure and mechanical properties of tubes/sheet
  - Joining
  - Fracture toughness
  - Lacking detailed understanding of structure/property relationships
  - Little fatigue data
  - Fabrication of large components



Irradiated MA957

Nuclear Fission



Primary FP's (at./100 at. ^{235}U fissioned)

Zr - 29.4

Xe - 21.9

Mo - 20.4

Cs -18.9

Nd -16.7

Ru - 16.1

Ce - 16.0

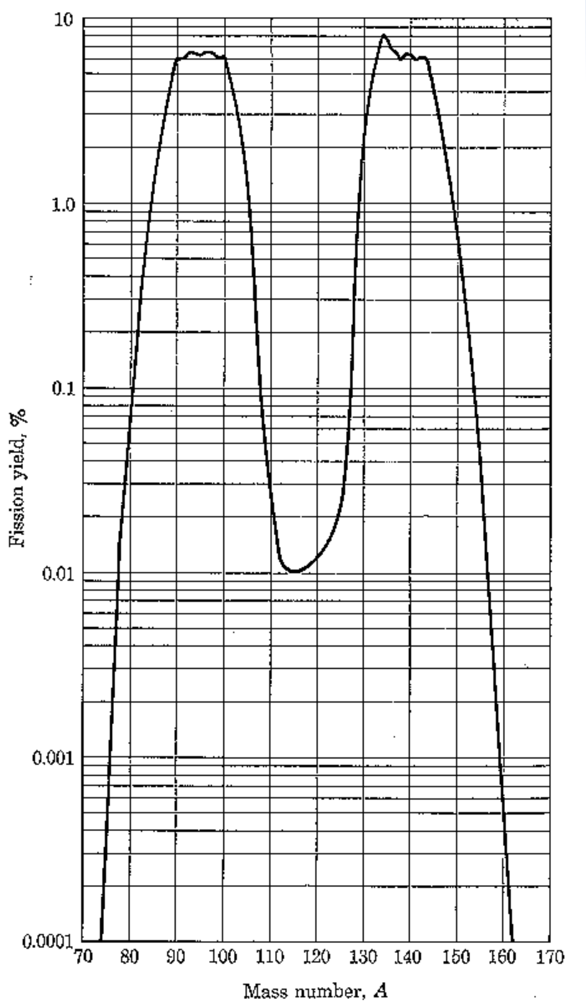
Sr -9.9

Ba - 6.9

La - 6.2

Tc - 6.0

Y - 4.9



Nuclear Fission:

- Unstable nucleus formed

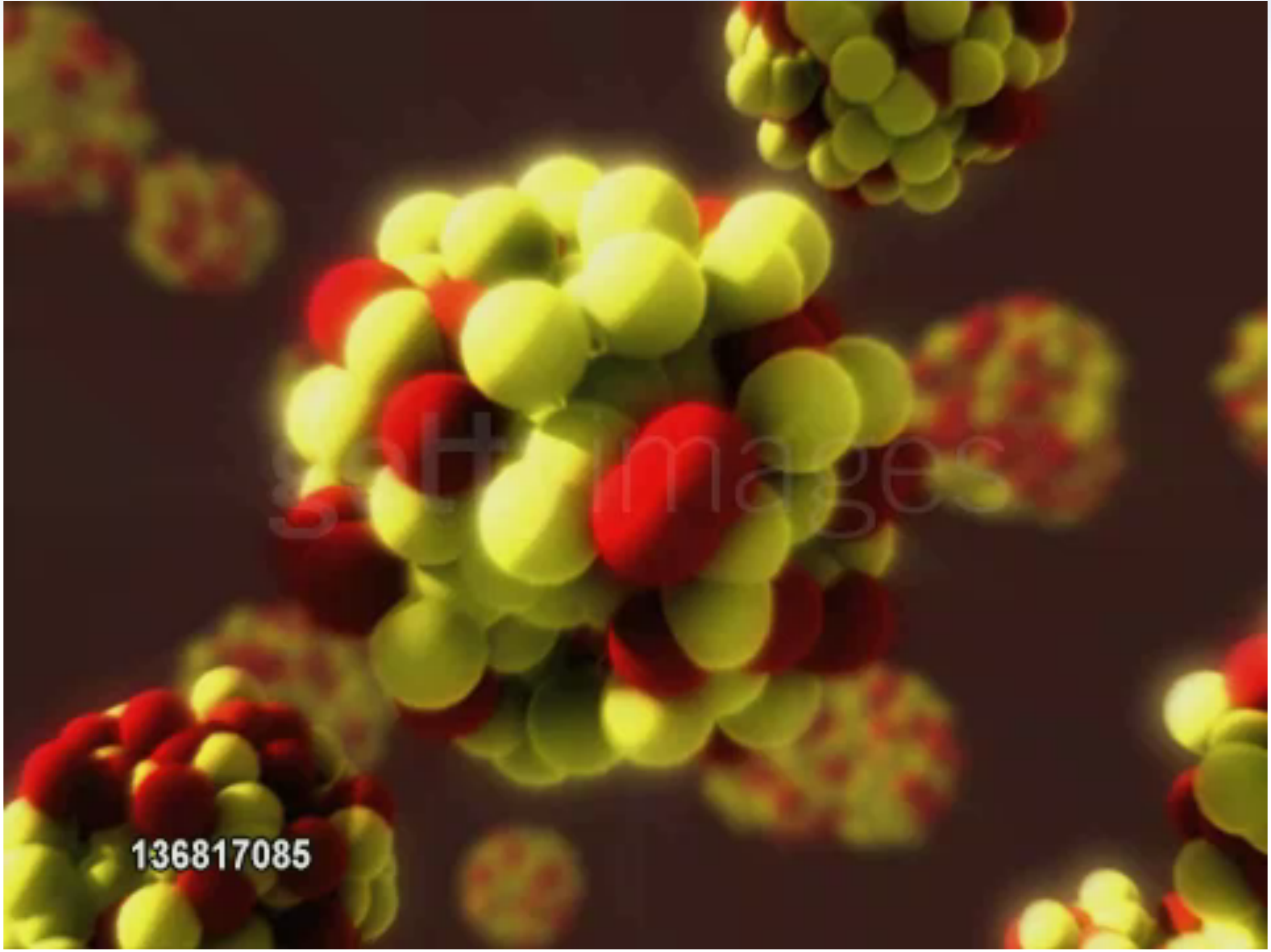
$^{235}U + n \rightarrow {}^{236}U$

$^{236}U \rightarrow F_1 + F_2 + 2.43\ n + E$

- E = 200 MeV/fission (190 MeV useful)
- E = 21,600 kWhr/g ^{235}U

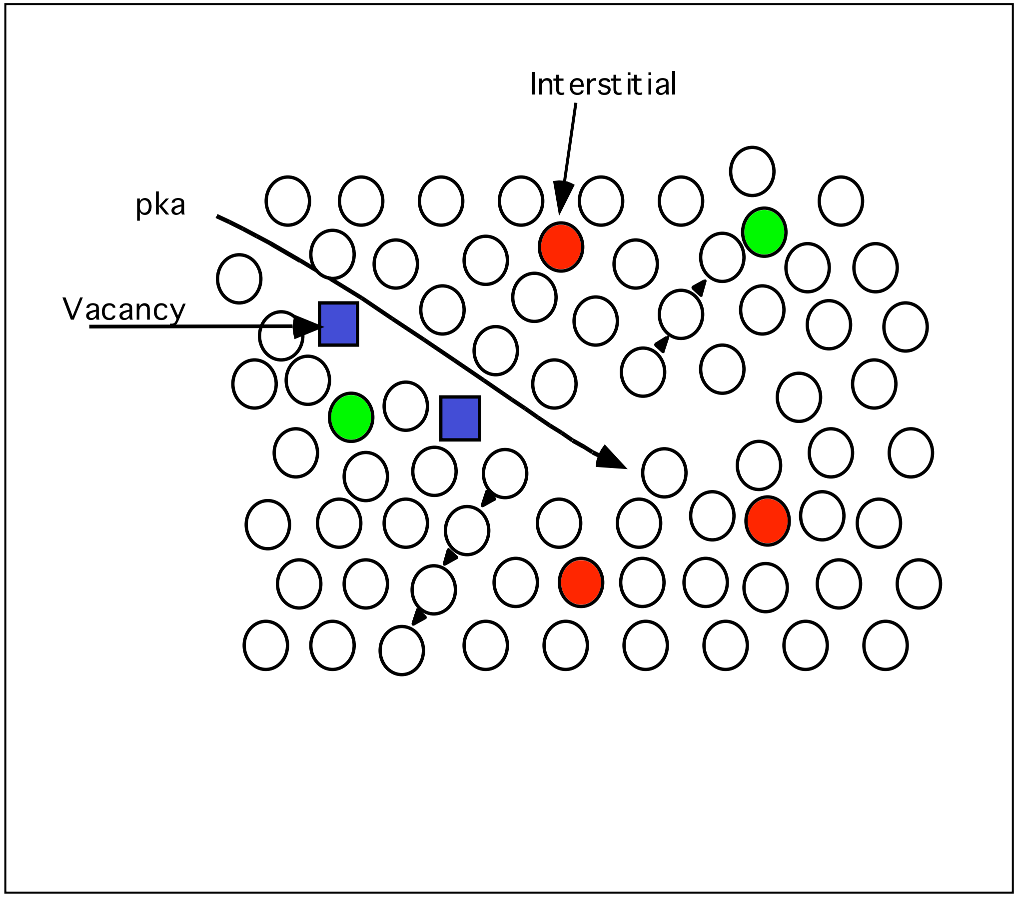
This is both wonderful (for nuclear engineers) and terrible (for material scientists)

Nuclear Fission



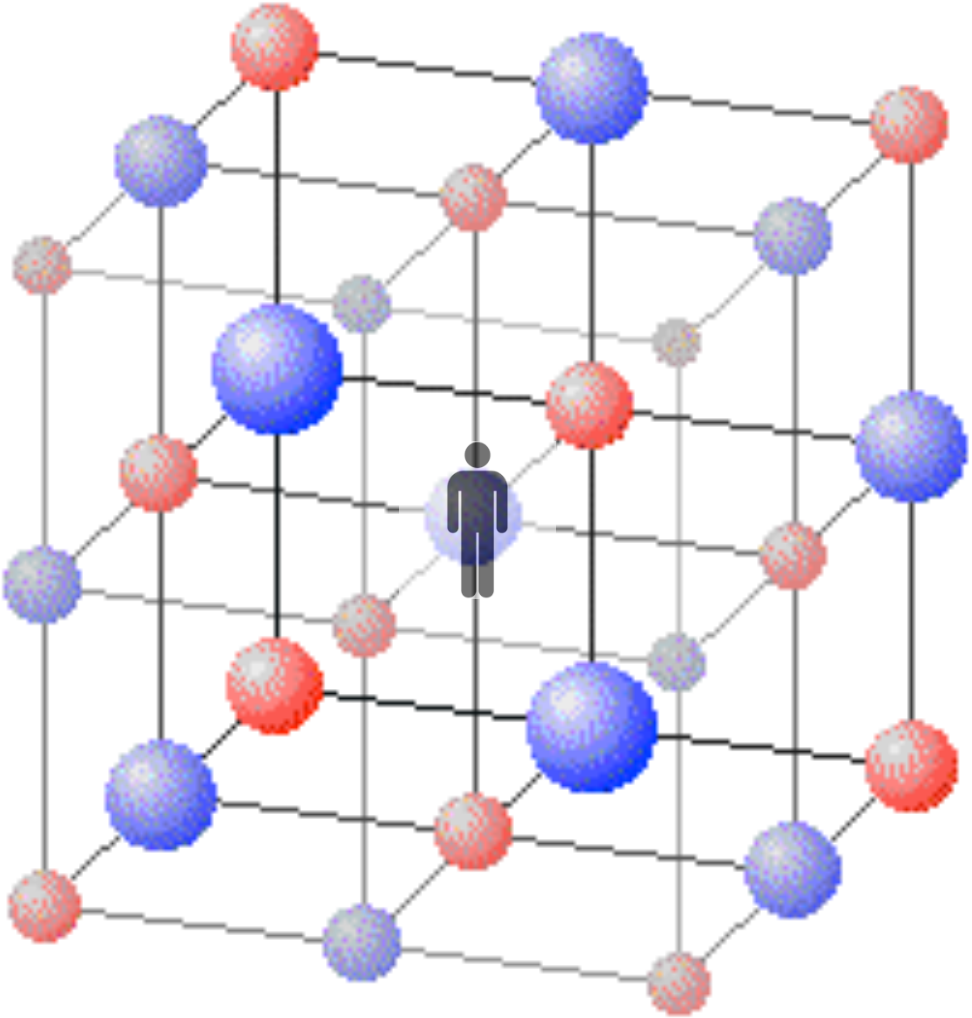
Fission neutrons

Neutron Displacement Damage



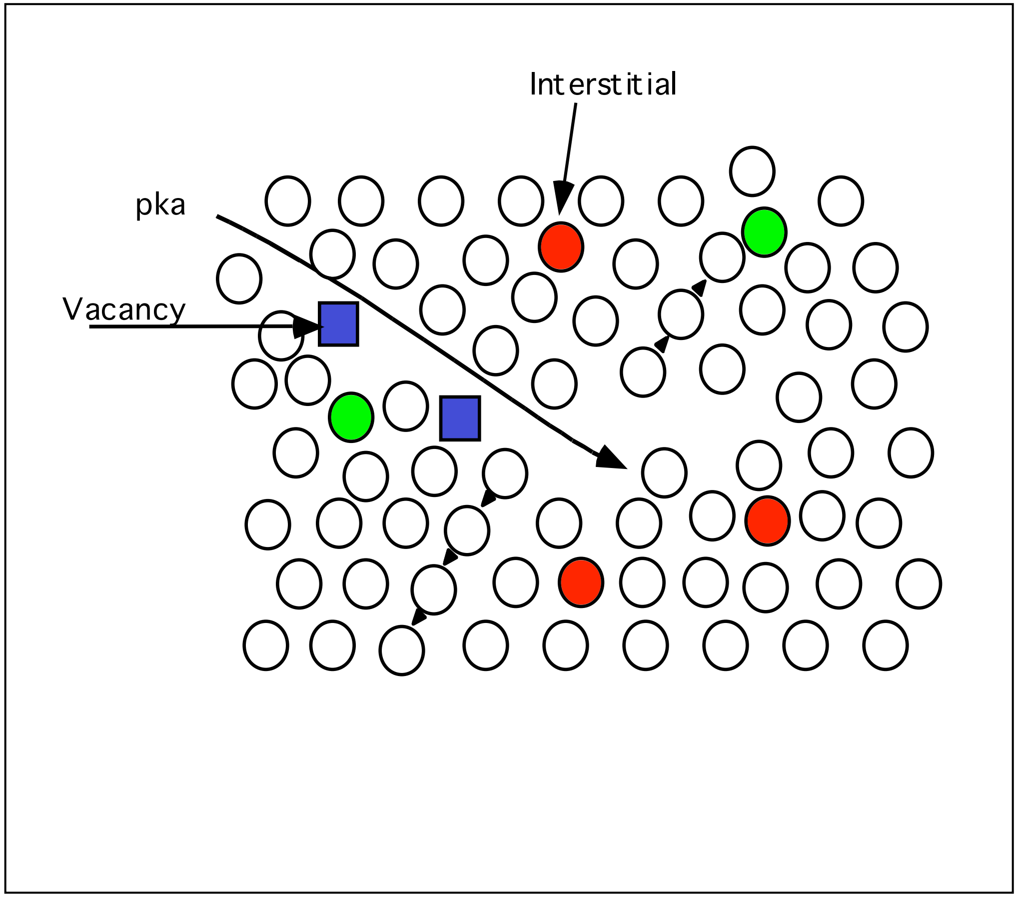
- Production of primary defects – 10^{-11} seconds (defect cascades)
- Diffusion of defects that drive changes to microstructure – seconds
- Property changes – hours, days, months
- DPA (displacement per atom is the average number of displacements of each lattice atom
- Varies with neutron energy – fast neutrons (>0.1 MeV) cause more dpa per event

Neutron Displacement Damage



Simulation of Neutron Displacement Damage

Neutron Displacement Damage



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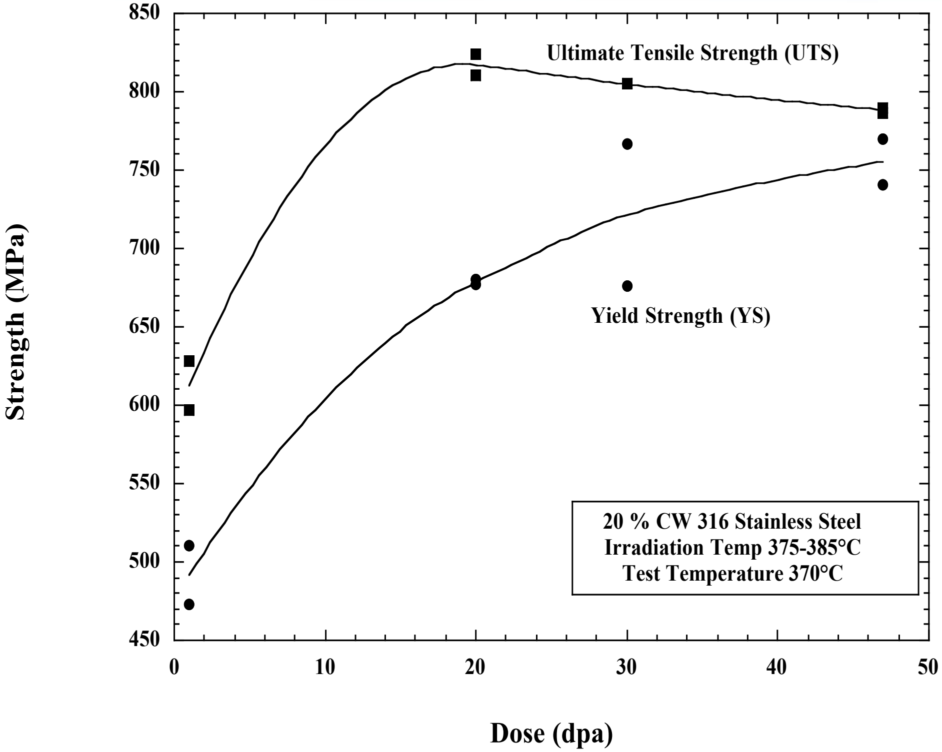
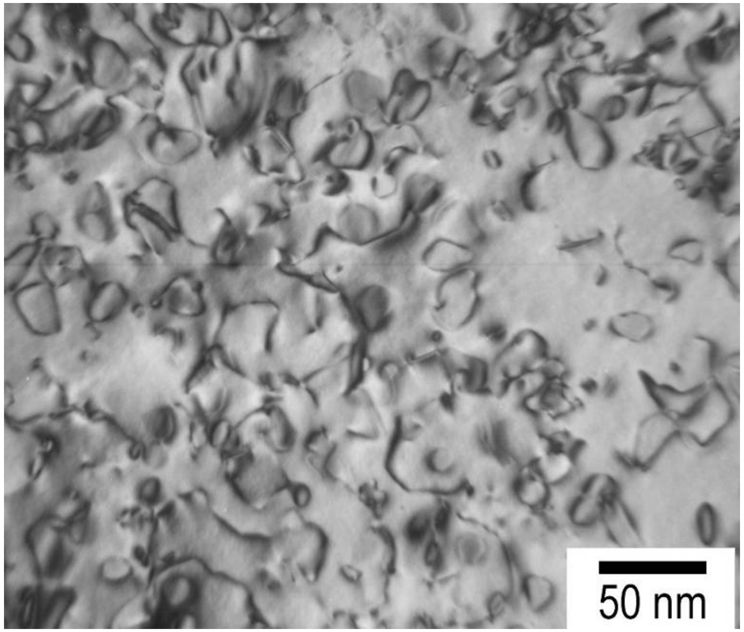
Changes in Material Properties

- Hardening/strengthening
- Void swelling
- Radiation induced segregation (RIS)
- Irradiation assisted stress corrosion cracking (IASCC)
- Radiation induced precipitation
- Irradiation enhanced creep (can be beneficial)
- Radiation enhanced diffusion (RED)
- Neutron transmutation (ex. Al-> Si)
- He gas generation (larger issue for 14 MeV fusion neutrons)
- Anisotropic growth (zirconium alloys)
- Corrosion (zirconium alloys)

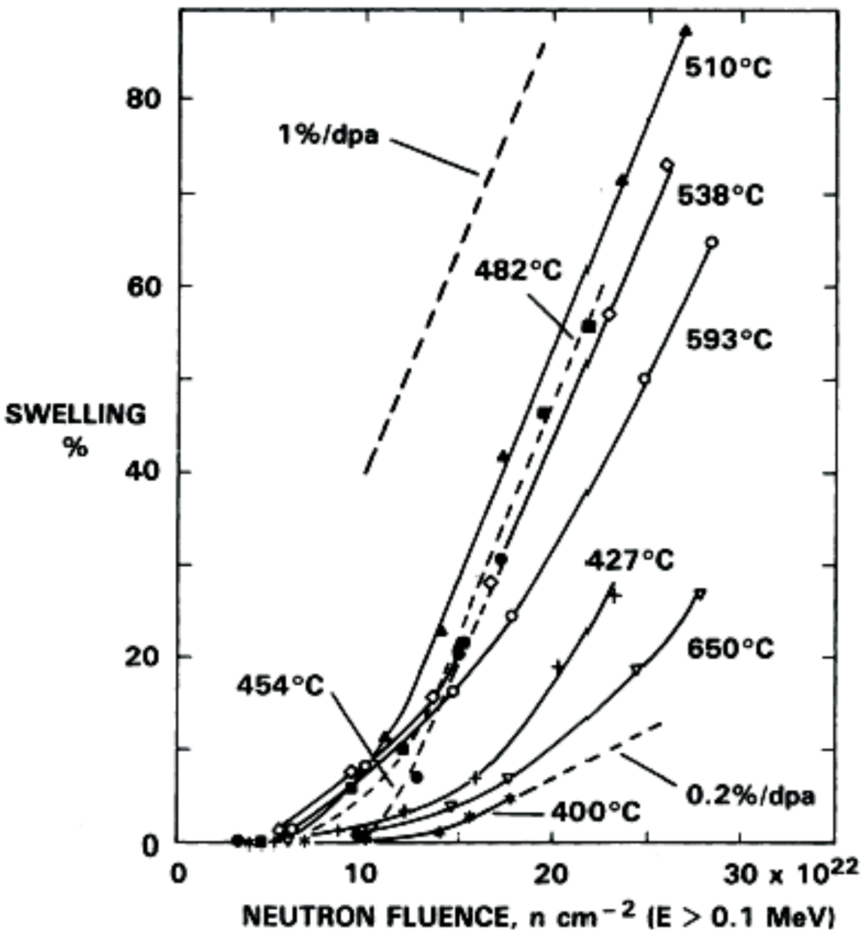
Irradiation Hardening

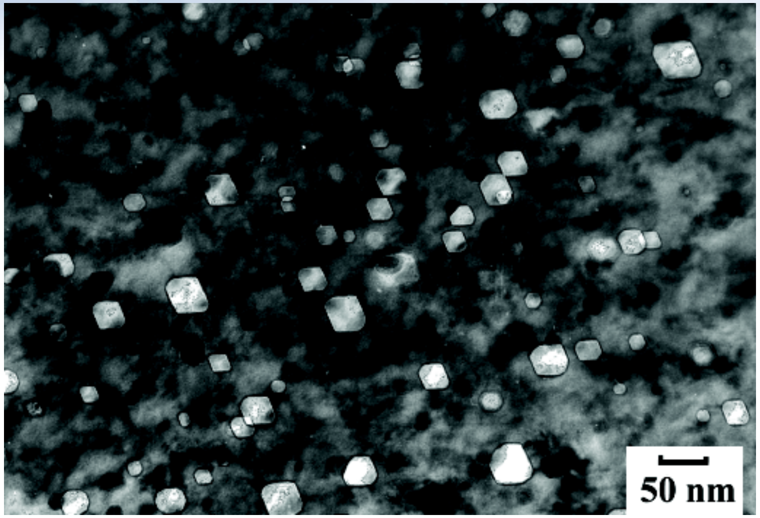




- Dislocations act as sinks for SIA (self interstitial atoms), increasing dislocation density
- Irradiation induced precipitation

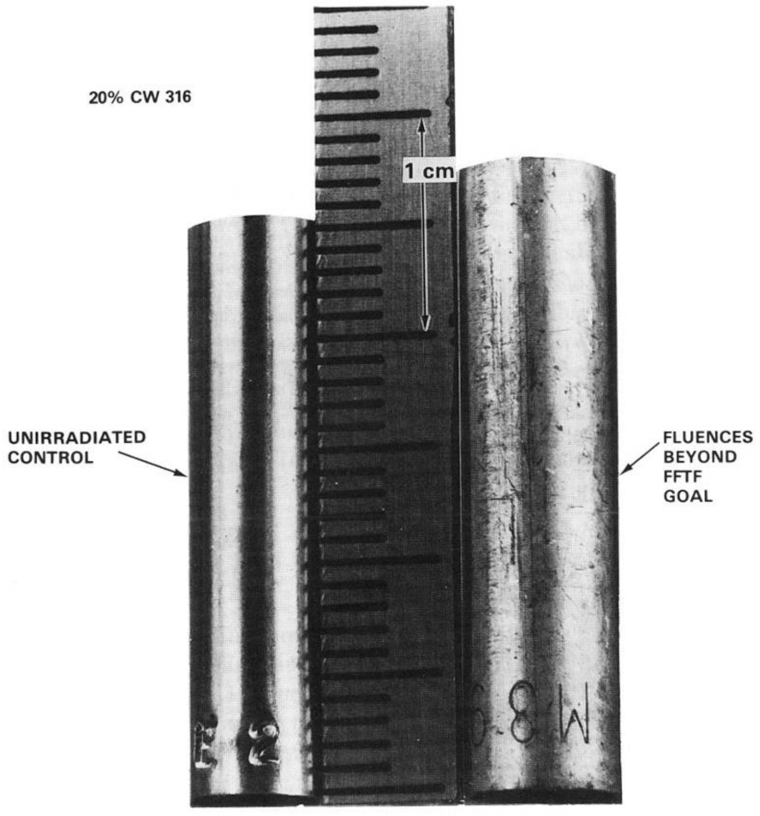
Void Swelling



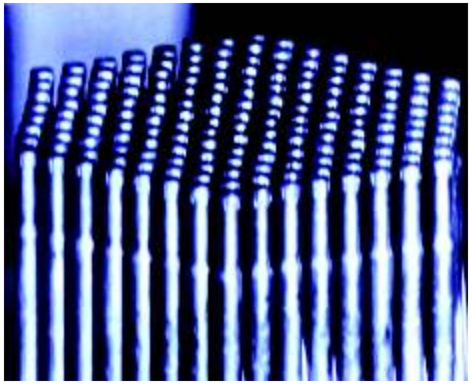


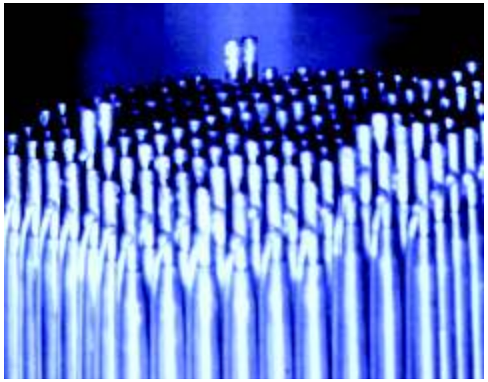
- Coalescence of vacancies at sinks
- Incubation period depends on flux, temperature, composition
- After incubation:
  - Austenitic steels 1%/dpa,
  - Ferritic steels at 0.2%/dpa
- Swelling does not saturate

Swelling



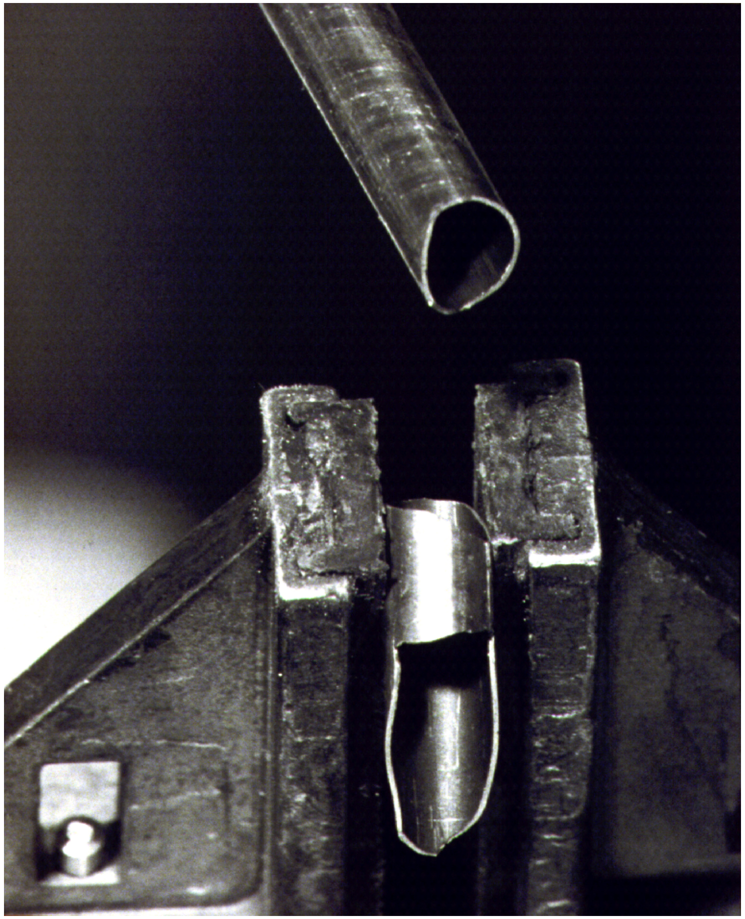
- 316CW, irradiated in EBR-II to 80 dpa at 510ºC resulted in 33 vol.% swelling





- Fuel assemblies irradiated to ~75 dpa
- HT-9 (ferritic) fuel bundle
- D-9 (austenitic) fuel bundle

Void-Induced Embrittlement



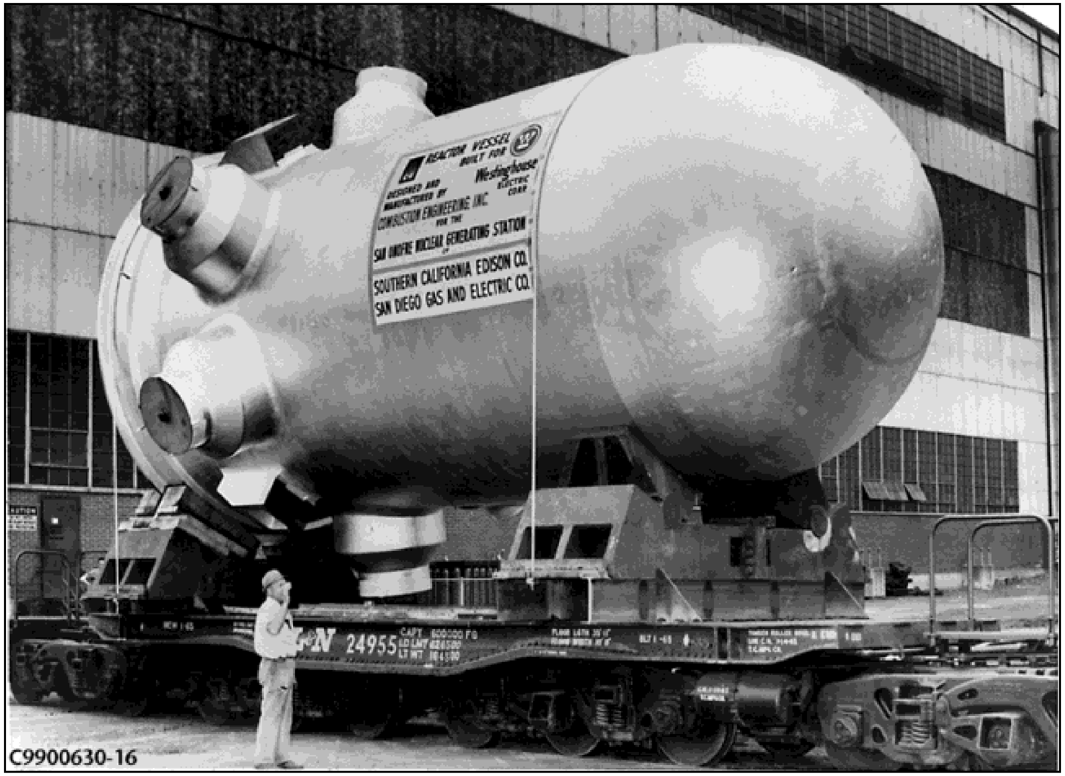
Porter and Garner, 1988

- 14% swelling
- 316 stainless steel irradiated at ~400ºC
- Failure occurred during clamping in a vise at room temperature
- Embrittlement threshold at ~10% swelling

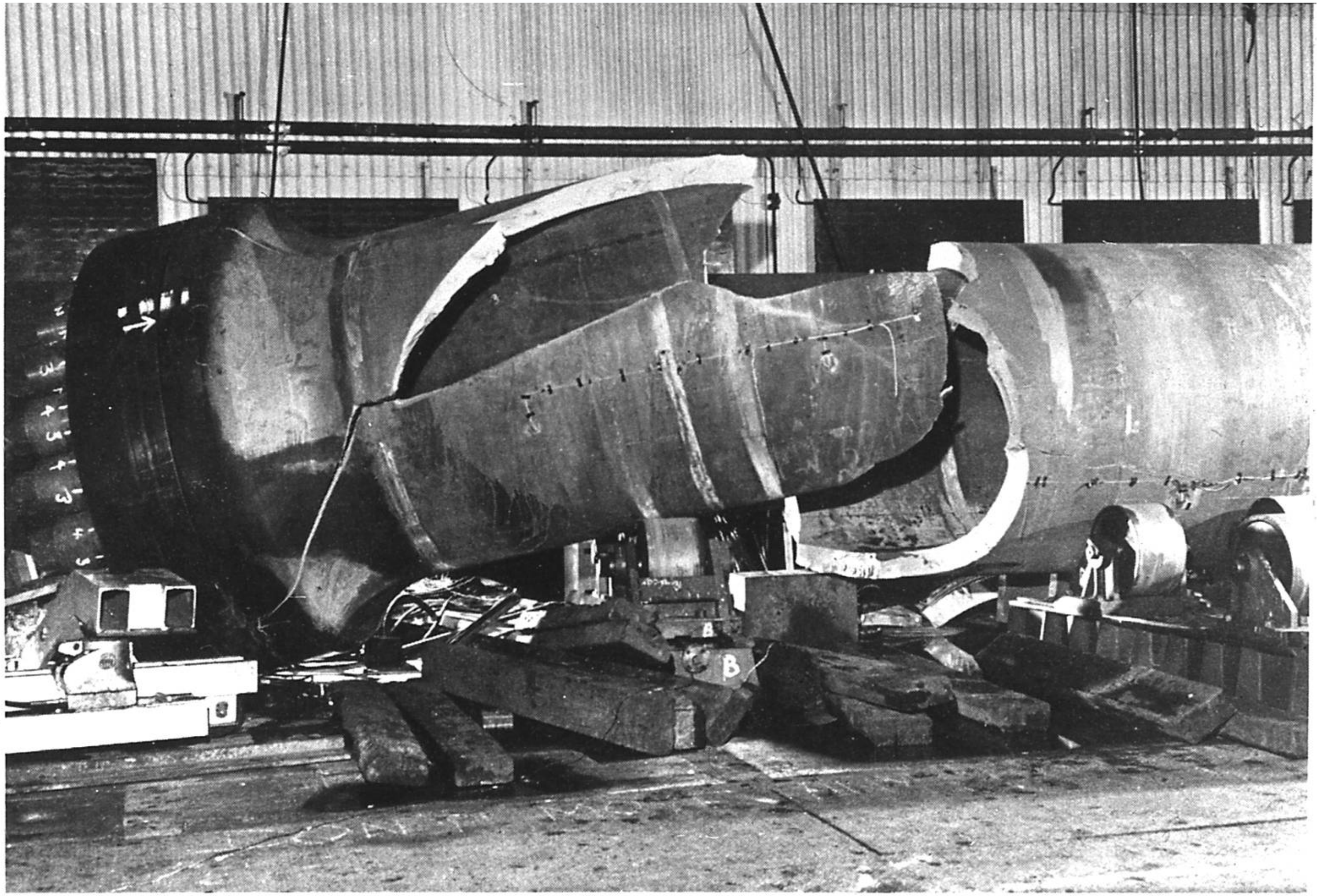
Garner

Manufacturing

- Reactor pressure vessels may weigh up to 800 tons with wall thickness up to ~330mm (~13 in.)
- Materials must:
  - Be obtainable
  - Be manufacturable
  - Be inspectable in service
  - Provide return on investment
  - And most important….

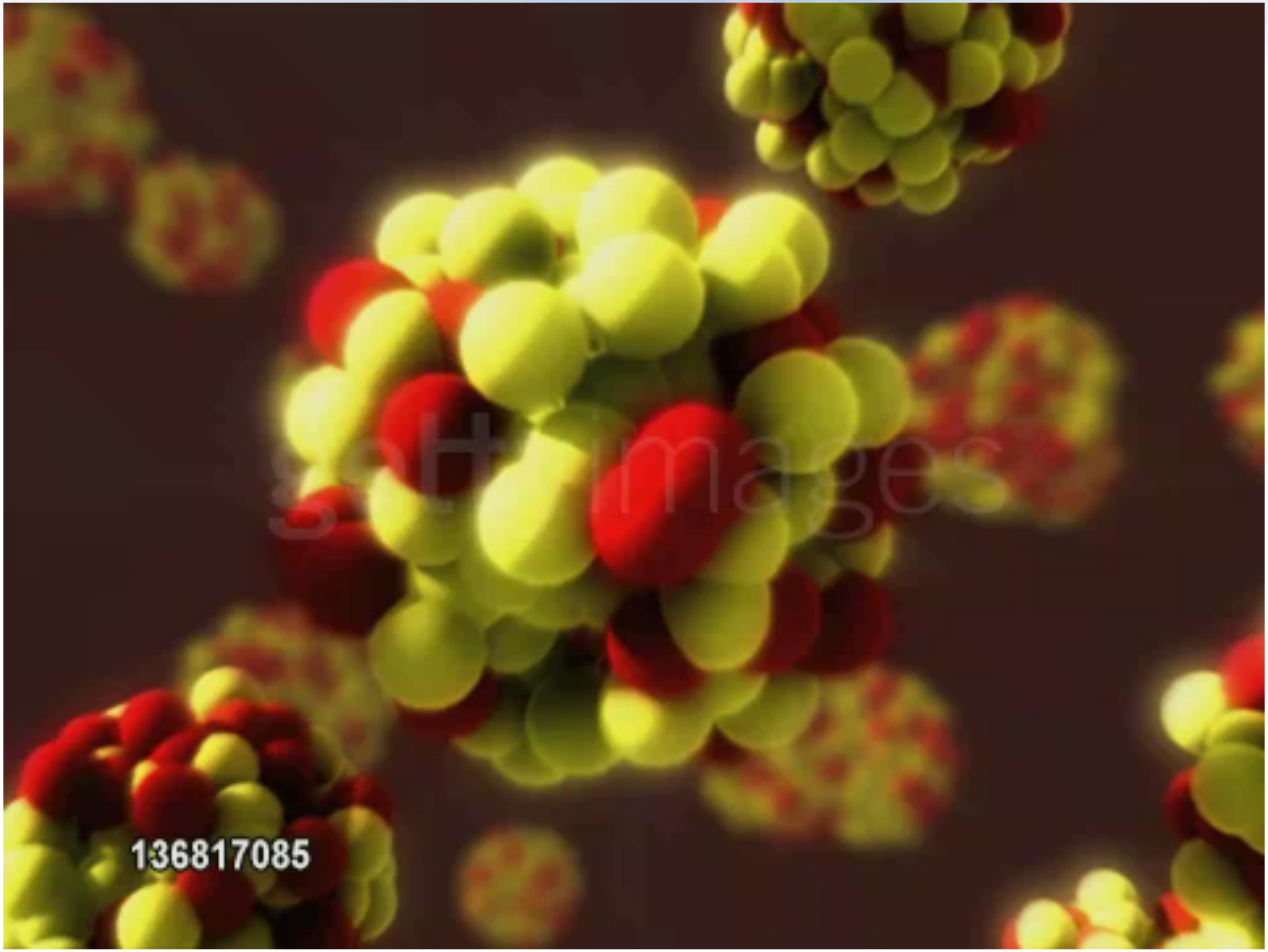


…and be reliable



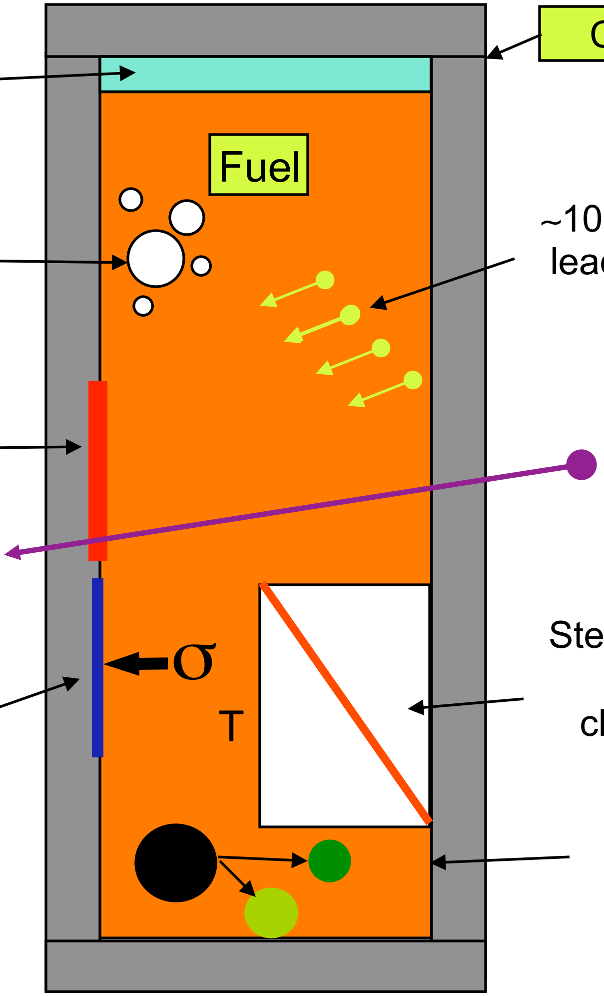
CATASTROPHIC FAILURE OF PRESSURE VESSEL DURING HYDROSTATIC
TESTING; DUE TO IMPROPER POSTWELD HEAT TREATMENT

Nuclear Fission



Focus on the large fission fragments

Nuclear fuel operating conditions



Cladding: stainless steel or Zircaloy

Gas pressurization of cladding tube

Fission gas bubbles (Xe, Kr) cause fuel swelling

~100 MeV heavy fission fragments lead to very high defect densities, very fast diffusion

Fuel-clad chemical interaction as a result of fuel and fission products

Neutrons cause cladding damage

Fuel-clad mechanical interaction results from fuel swelling

Steep temperature gradient can lead to large difference in chemical potential and drive constituent migration

Solid fission products cause fuel swelling, change in composition (oxygen potential in $TRUO_x$)

- **Fuel irradiation testing is extremely important!**

Fission Fragment Damage

WADCO
CORPORATION
Richland, Washington 99352

STRUCTURE EVOLUTION IN AN OXIDE FUEL PIN

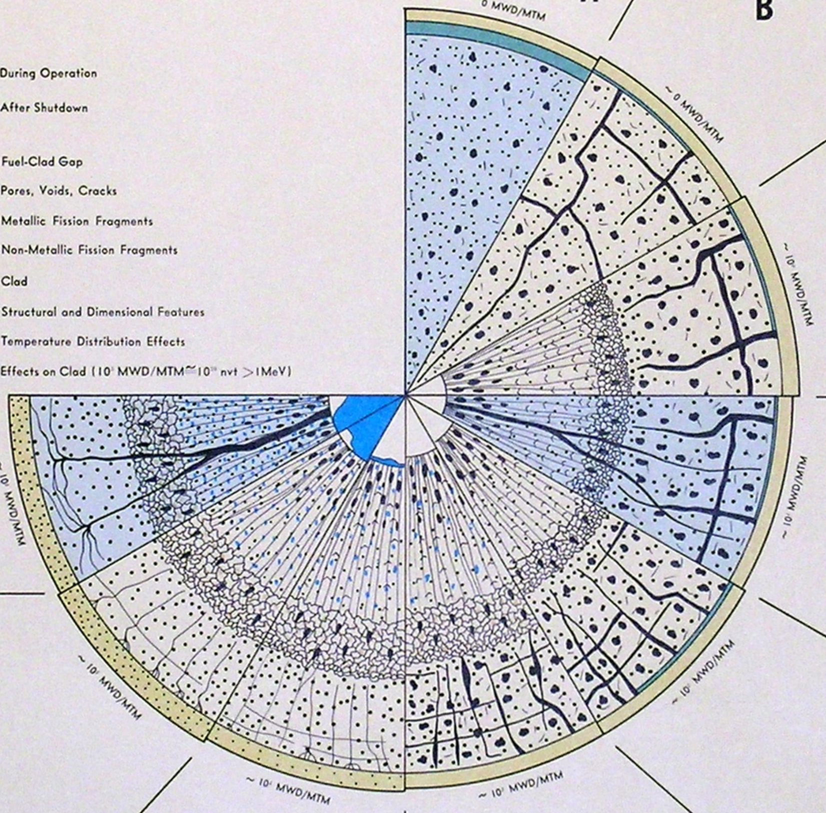
NOMINAL HEAT RATING=~13 kw/FT THROUGHOUT LIFE

WHAN-PR-4

J. A. Christensen
WADCO Corporation
Richland, Washington
for the U.S.A.E.C.
under contract no. AT(45-1)-2170

▷ During Operation
▷ After Shutdown

▨ Fuel-Clad Gap
■ Pores, Voids, Cracks
🟦 Metallic Fission Fragments
▨ Non-Metallic Fission Fragments
▭ Clad
● Structural and Dimensional Features
■ Temperature Distribution Effects
▲ Effects on Clad (10[illegible] MWD/MTM ≅ 10[illegible] nvt > 1MeV)



A

- ● Small (~ 10μ) Equiaxed Grains
- ● Equilibrium Pores to 50μ
- ● Large Voids, ~ 200μ
- ● Small Cracks, Crevices, etc.
- ● Gap Large (~ 3 mil) and Uniform, He Filled

B

- ● ■ Radial and Circumferential Cracks from Thermal Shock
- ● Startup Cracks Taper Inward
- ● ■ Gap Partly and Irregularly Closed from Thermal Expansion and Cracking; He Contaminated by Desorbed Gases.
- ■ Reduction in Thermal Conductivity Because of Cracks

C

- ● ■ Columnar Grain Formation by Lenticular Pore Migration
- ● ■ Central Void Formed from Pores Displaced from Columnar Grain Region
- ● ■ Some Equiaxed Grain Growth, Pores Move to Grain Boundaries
- ● Large Stable Central Pores — Increase in Size and Density Toward Center
- ● Small Migrating Spherical Pores
- ● ■ Crack & Hole Healing to Beyond Grain Growth Region
- ● ■ Gap Unchanged from "B" (or Perhaps Enlarged by Sintering or Closed by "Bloating")
- ▲ Grain Boundary Carbide Precipitate Concentration Reaches Limiting Value with 1100°F Na Outlet Temperature

D

- ● New Family of Cracks Which Taper Outward Formed During Shutdown
- ● ■ Gap Opens Some Compared with "C" but Not to Condition in "A" Because Thermal Expansion Strains (cracks) Remain and are Partially Redistributed Toward Center
- ■ Thermal Conductivity Increased Because of Porosity Depletion in Higher Temperature Regions
- ▲ Observable Grain Boundary σ Phase with 1100°F Na Outlet Temperature

E

- ● ■ Gap Closes Further
- ● ■ New Cracks Heal — Associated Void Redistributes Toward Center
- ■ Gap Conductance Decreases from Xe and Desorbed Gas Contamination
- ● "Stable" Residual Crack Pattern Achieved After several Cycles
- ● ■ Grain Growth Proceeds; Columnar Grain Growth "Temperature" Decreases Continuously During Life
- ● ■ Central Void Diameter Increases Continuously During Life

F

- ● ■ Gap Closed by Crack-Ratcheting After Several Cycles or Accelerated Fission Gas Swelling at Intermediate Temperatures (1300-1500°C)
- ▲ Clad Strain from Mechanical Interaction with Fuel on Cycling
- ● Residual Cracks Narrower Because of Clad Restraint and Swelling Accommodation
- ■ Slight Irradiation Decrease in Thermal Conductivity
- ▲ Ductility Decreased Because of He in Grain Boundaries (~ 1 PPM He/10[illegible]nvt)

G

- ■ Gap Conductance Reaches Maximum, Steady--State Value
- ▲ 1% Swelling from Voids; He at Grain Boundaries Reduces Ductility to ~ ½ Pre-Irradiation Value
- ▲ Grain Boundary Carbide Precipitation with 900°F Na Outlet Temperature Reaches Limiting Concentration
- ▲ Recrystallization with 1100°F Na Outlet Temperature
- ▲ Observable Grain Boundary σ Phase with 900°F Na Outlet Temperature

H

- ■ Heat Rating Reduced by Fissile Depletion
- ● ■ Largest Holes and Old Cracks Replaced by Fine (< 1μ) Gas Bubbles and Inclusions
- ● ■ Extensive Fission Product and Clad Derived Inclusions
- ● Fission Product Oxides in Equiaxed Grains; Fission Product Metals in Columnar Grains Concentrated Near Edge
- ▲ Localized Clad Strain Near Cracks
- ■ ▲ Clad Swelling Severe (~ 10%, May Cause Gap to Reopen?), Maximum Pin Diameter
- ▲ Ductility Decreased to Zero
- ■ Maximum Impurity and Irradiation Effect on Thermal Conductivity and Melting Point

- ● Bubble Steady State Achieved in Warmer Portions
- ● ■ Large Voids and Old Cracks Begin to Close from Swelling
- ● Fission Fragments and Clad Derived Inclusions Appear
- ■ Thermal Conductivity Further Decreased

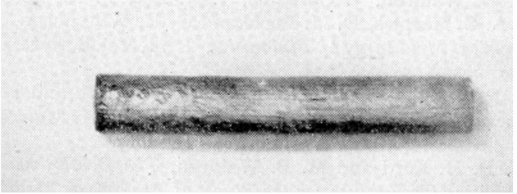
I

- ● As H but with Family of New Cracks Formed on Shutdown
- ● Retains large voids formed Early in Life in Columnar Grains
- ● ■ Pore Size Refined Beyond Columnar Grains (Fission Gas Bubbles)
- ● ■ No Gap Reopening for Large Hg (< ~ 2000 BTU/HR-FT^2 °F)
- ▲ Voids Between 75 and 1000 Å Depending on Clad Temperature; Void Density Increases with Burnup; Void Size Increases with Temperature; Uniform Void Distribution with Slight Grain Boundary Denudation
- ▲ Dislocation Loops Commensurate with Atoms Displaced from Void Sites
- ▲ Possible Recrystallization with 900°F Na Outlet Temperature
- ▲ Grain Boundary σ Phase Concentration Saturated at 5-7%

Example: Pu-Zr alloy Irradiation Data

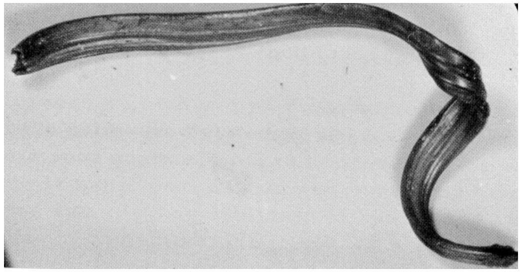
Waldren, et. al. (1958)

- δ-phase Pu-35Zr, cast/extruded
- 500°C, 0.83% burnup (all atoms)
- Swelling = 6.5% per at% burnup
- ρ = 10.25 g/cm^3, ρ_{Pu} = 6.7 g Pu/cm^3



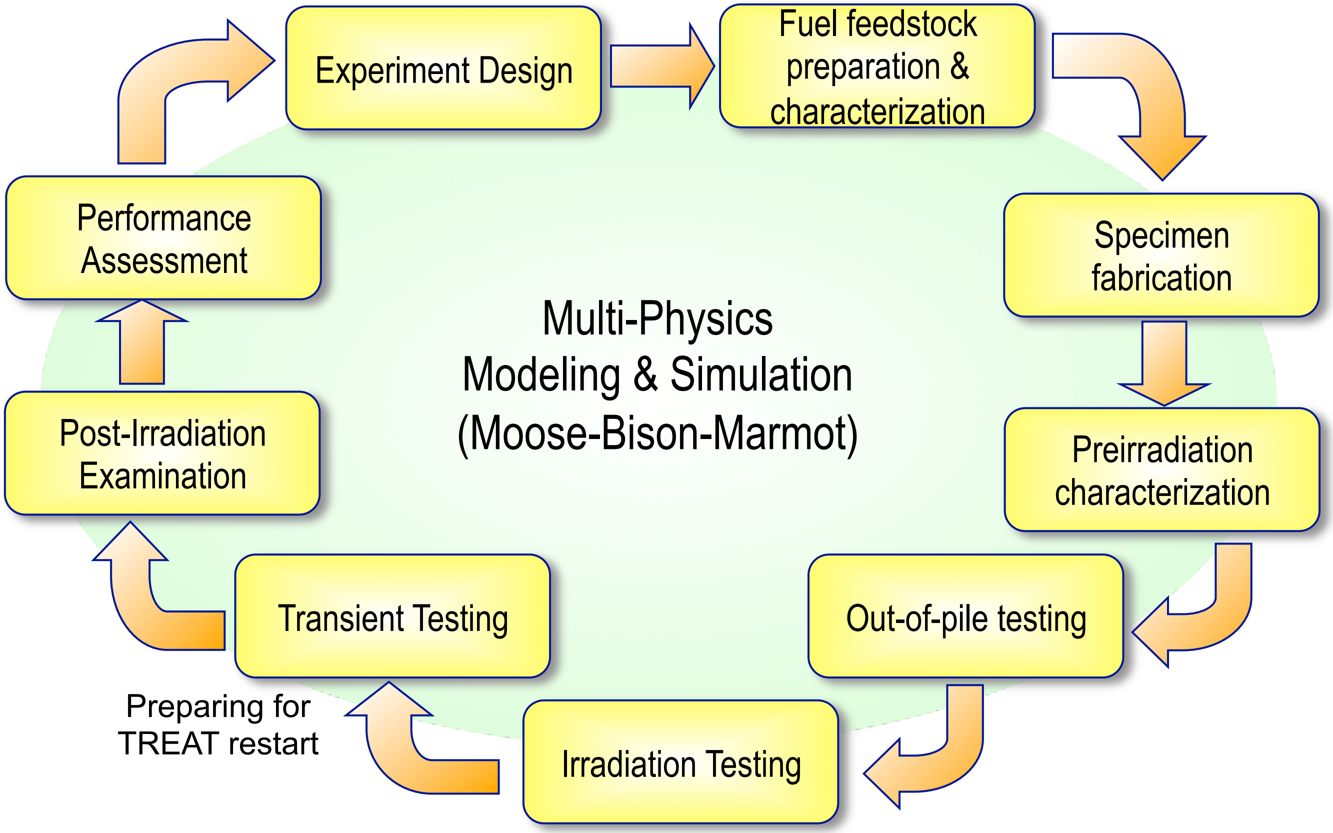
Horak, et. al. (1962)

- α-Zr phase Zr-5Pu, rolled
- 530°C, 0.9% burnup (all atoms)
- Swelling = 3.3% per at% burnup
- Extreme growth



Fuel irradiation behavior of fuel can be sensitive to composition, crystal structure, crystallographic texture, etc.

Nuclear fuel and material R&D cycle



Experiment Design

Fuel feedstock preparation & characterization

Specimen fabrication

Preirradiation characterization

Out-of-pile testing

Irradiation Testing

Transient Testing

Preparing for TREAT restart

Post-Irradiation Examination

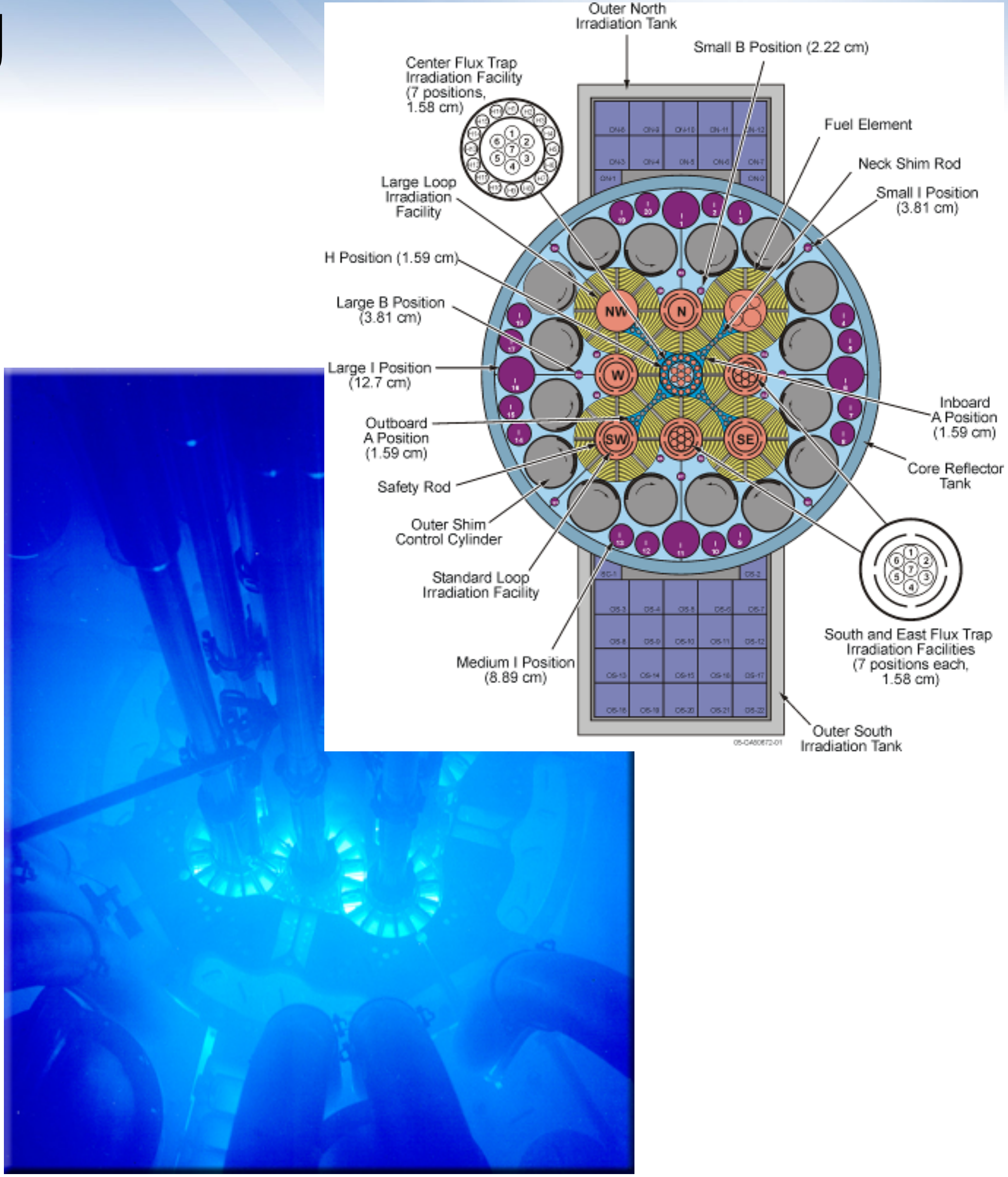
Performance Assessment

Multi-Physics Modeling & Simulation (Moose-Bison-Marmot)

Each iteration of this cycle requires 2 – 5 years

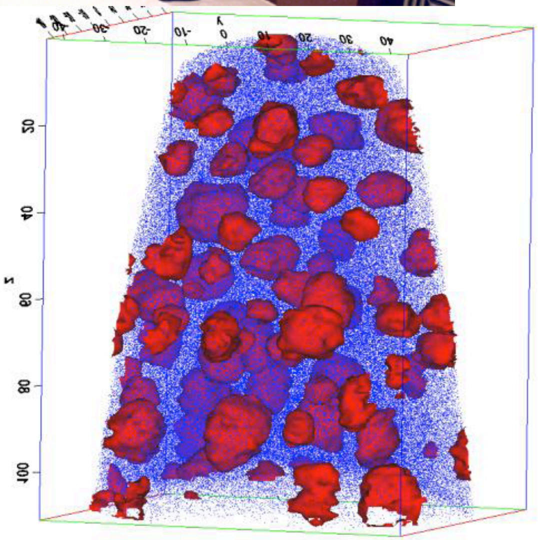
Irradiation testing

- Ion irradiation can provide screening data
  - Many universities offer this service
- ‘Rabbit’ testing provides a mechanism for evaluation at low neutron dose
- Static capsules allow for higher neutron dose under ‘nominal’ conditions
- Instrumented tests allow temperature and load control
- Loop tests provide prototypic light water reactor environment
- ATR National Scientific User Facility provides cost free access
  - Google ‘ATR NSUF’



Postirradiation examination

- Many examinations conducted remotely
- Careful test design allows contact handling
  - Sample size
  - Choice of materials
  - Small specimen size
  - Cooling time
- Access to many analysis methods for materials
  - SEM, TEM
  - Mechanical testing
  - Atom probe
  - Light source (APS) and neutron scattering (LANSCE) facilities



Where do we want to be?

Mission

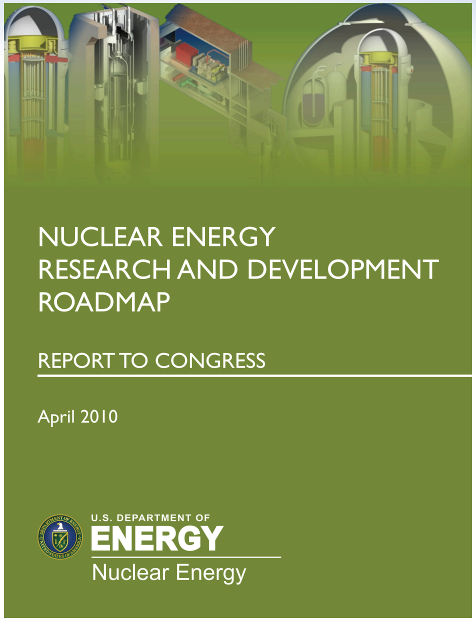
Advanced Nuclear Energy Technologies

R&D Objectives

- Sustain Current Fleet
- Improvements in Affordability
- Sustainable Fuel Cycles
- Reduced Proliferation Risk

Enabling Technologies

- Structural Materials
- Nuclear Fuels
- Reactor and Fuel Cycle Systems
- Instrumentation and Controls
- Power Conversion Systems
- Process Heat Transport Systems
- Dry Heat Rejection
- Separation Processes
- Waste Forms
- Risk Assessment Methods
- Nuclear Fuel Resources
- Computational Modeling & Simulation



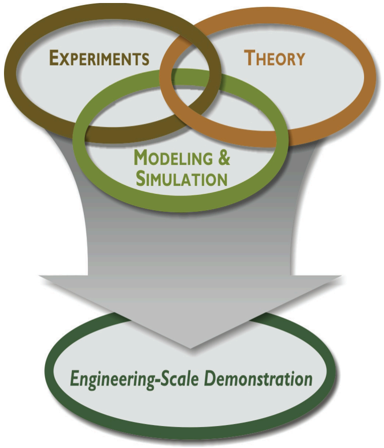
NUCLEAR ENERGY RESEARCH AND DEVELOPMENT ROADMAP

REPORT TO CONGRESS

April 2010

U.S. DEPARTMENT OF ENERGY

Nuclear Energy



How do we get there?

- Incremental improvements to materials used in existing plants
    - Surface modification to cladding and materials?

- Consistent long-term approach to developing new materials for future applications
    - Intelligent choices for candidate technologies that consider entire nuclear fuel cycle and how it may evolve
    - Early testing in relevant environments
    - Down-selection at appropriate development stages

- Reasonable expectations for total development time (20 years) with defined
    - Contact with industry and regulators at appropriate time

Our objective this week

- Find common ground
  - Develop an approach that focus on 2-3 areas/issues
  - Develop a path forward

- Near term opportunities
  - NEET (Nuclear Energy Enabling Technologies) funding opportunity (www.nuclear.gov)

  - ATR NSUF (Advanced Test Reactor National Scientific User Facility (atrnsuf.inl.gov)