Corrosion Costs and Preventative Strategies in the United States – NACE International

Corrosion in the Nuclear Industry

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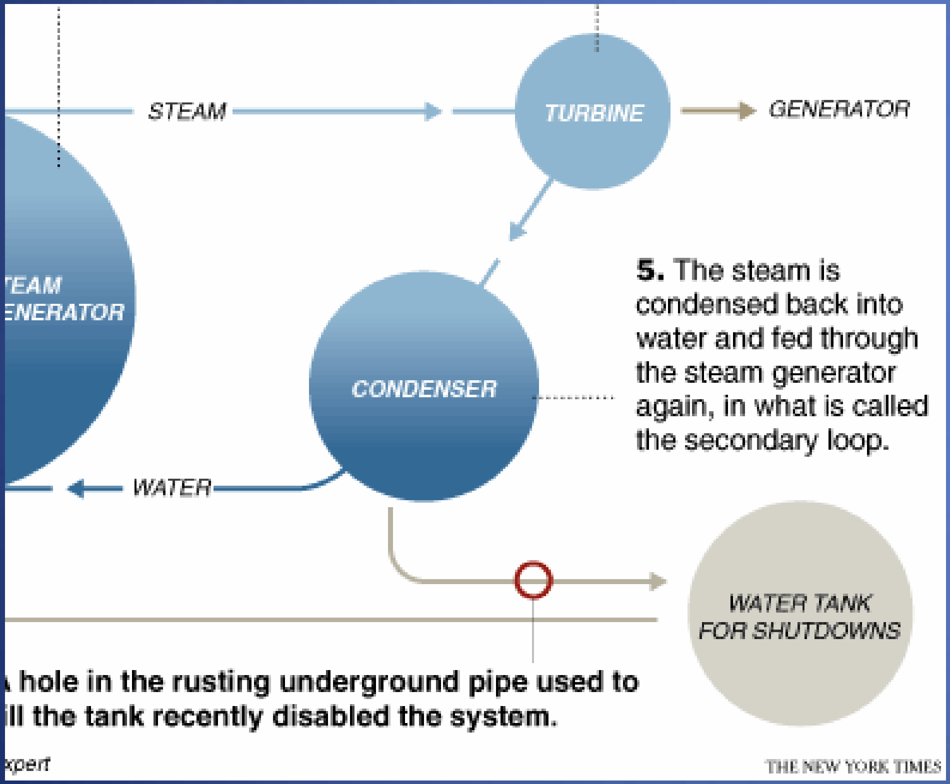
Contents

- Recent examples
- Why are there problems?
- Cost of corrosion
- Types of corrosion
- Materials and environments

Recent Events

- Indian Point nuclear plant
  - 100,000 gallons of water escaped from main cooling system
- Davis-Besse nuclear plant
  - 6” thick reactor head eaten through
- Oyster Creek nuclear reactor
  - 1/3 of steel containment liner eaten through

Indian Point



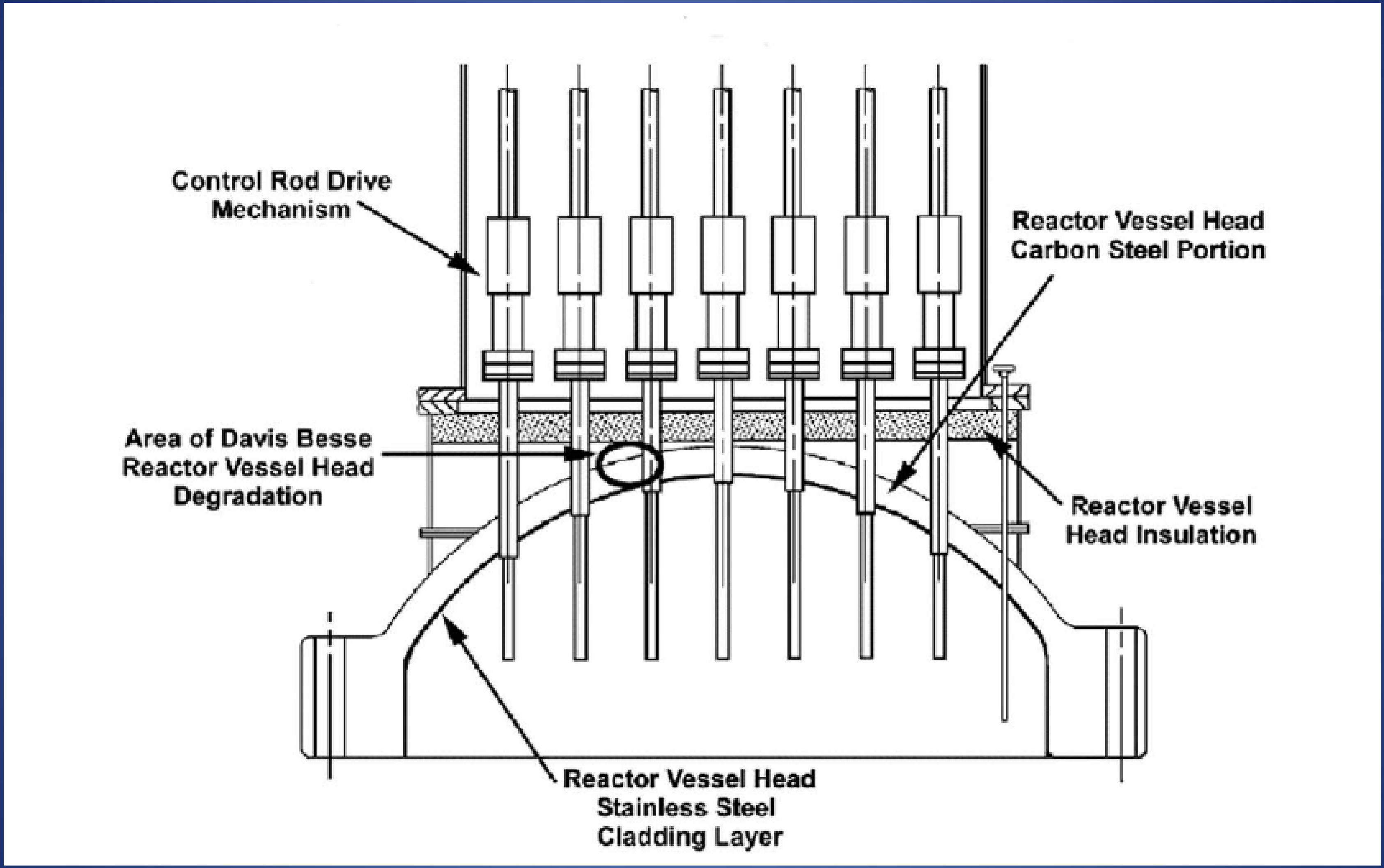
http://www.nytimes.com/2009/05/02/nyregion/02nuke.html

1 ½" hole corroded in underground pipe

Deposits from stagnant water

"underground pipes never been inspected"

Davis-Besse



Davis-Besse Reactor Vessel Head Degradation Lessons'Learned Task Force Report – NRC – 9/20/02

Reactor Head

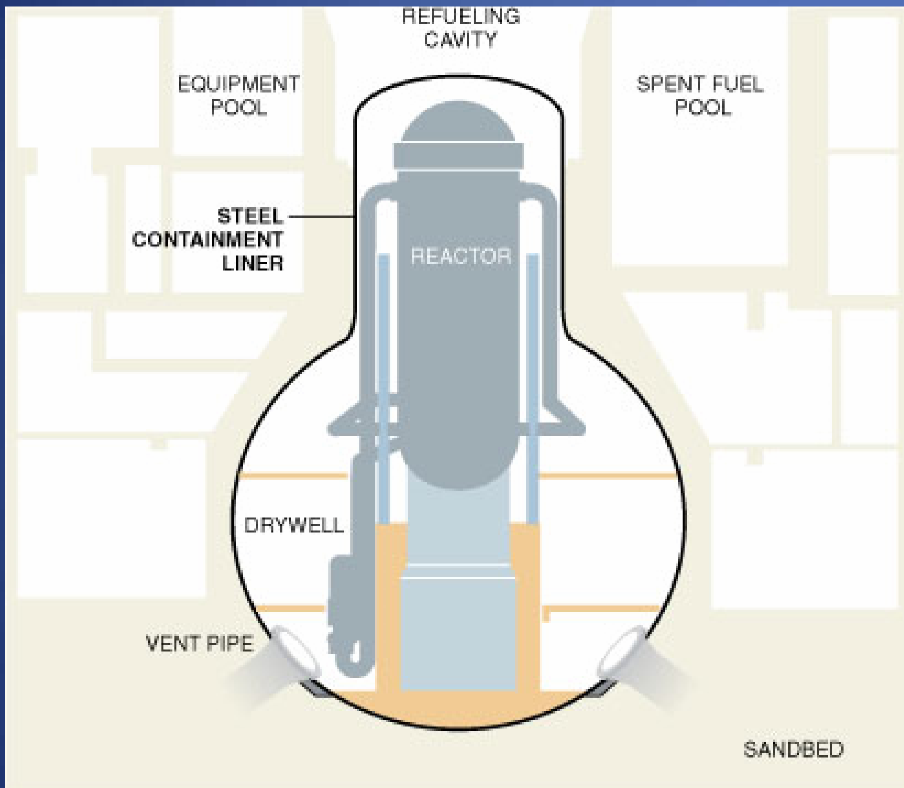
Cracked nozzle allowed boric acid to drip on containment vessel

Left only a ½" liner to support radioactive fluid that can exert up to 2,000 psi

Plant in operation for 25 years with 60 other plants having similar design

http://www.nrc.gov/reactors/operating/ops-experience/vessel-head-degradation.html

Oyster Creek



Safety Concern

Corrosion on a steel containment liner is causing concern at the Oyster Creek nuclear plant. The liner is designed to contain radioactive material in the event of a nuclear accident.

Source: AmerGen The New York Times

http://www.nytimes.com/imagepages/2007/02/08/nyregion/20070208_OYSTER_GRAPHIC.html

Leaking water caused 1/3 of liner to corrode

Pool for spent fuel rods located near the top of reactor building not built to spec – improperly shaped steel bars – earthquake or impact of plane could cause floor of pool to detach from building

Why is this going on?

Nuclear industry is falling behind

- All current reactors should no longer be commissioned in 2056
- To maintain current production rate of 20% over the next 40 years, one new reactor would need to be built every 4-5 months

Earliest new plant will be online is 2018…no currently approved new reactor sites

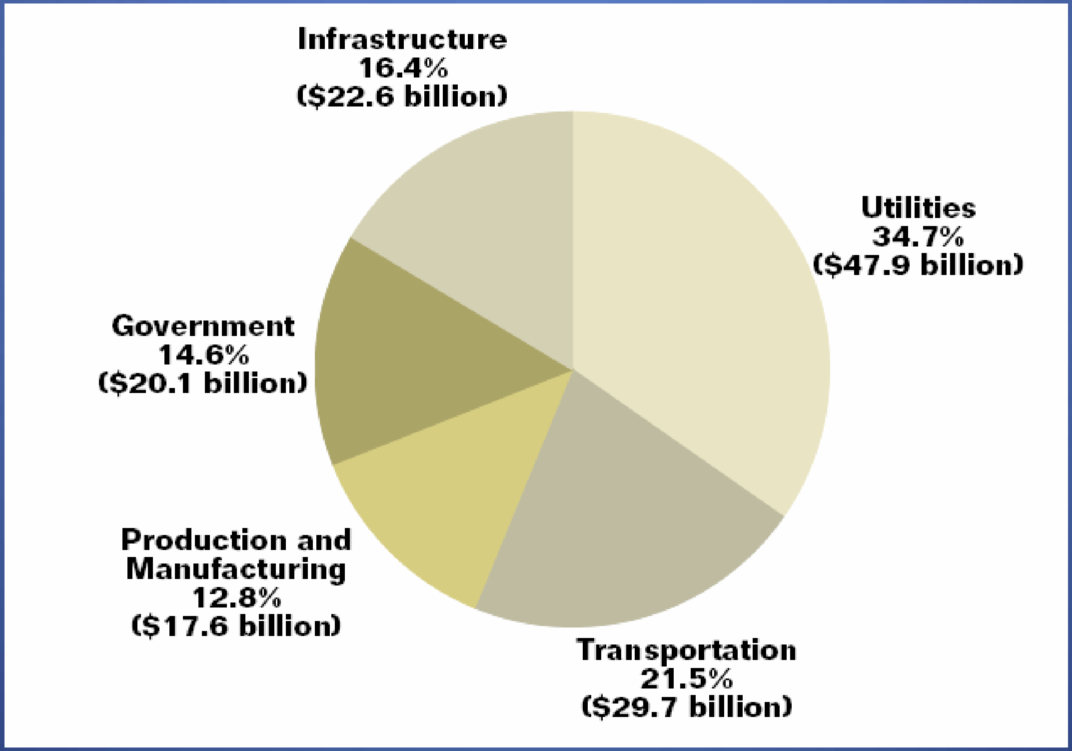
- What is happening
  - Current plants receiving 20 year extensions
  - Current reactors upgraded for increased capacity
  - Future reactors designed for increased capacity

Corrosion?

- Plants are already closing in on their 40 year lifespan
- Preliminary testing was unable to properly simulate working environment
- Corrosion problems were not predicted - minimal inspection procedures in place

Cost of Corrosion

$276 billion per year for all industries



http://events.nace.org/publicaffairs/images_cocorr/ccsupp.pdf

Electric Utilities

FACILITY	REASON FOR CORROSION COST	CORROSION COST PER YEAR ($ x billion)
Nuclear	O&M	2.013
	Depreciation	1.546
	Forced Outage	0.670
	SUBTOTAL	**$4.229**
Fossil Fuel	O&M	0.698
	Depreciation	1.214
	Forced Outage	0
	SUBTOTAL	**$1.912**
Hydraulic & Other Products	O&M	0.075
	Depreciation	0.066
	Forced Outage	0
	SUBTOTAL	**$0.141**
Transmission & Distribution	O&M	0
	Depreciation	0.607
	Forced Outage	0
	SUBTOTAL	**$0.607**
	TOTAL	**$6.889 billion**

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Effect on Upfront Costs

Costs associated only with corrosion prevention

CATEGORY	PLANT COST %	CORROSION EFFECT, % OF PLANT COST	WEIGHTED % OF CORROSION EFFECT
Property	0.5	0	0.0
Structures, inc. Containment	26.3	2	0.5
Reactor Vessel & Reactor Core System	18.5	20	3.7
Reactor Auxiliary Systems	9.0	20	1.8
Turbine Generator	19.5	20	3.9
Heat Exchangers & Piping	7.0	15	1.1
Electric Power & Instrumentation, and Controls	11.5	5	0.6
Misc. Power Plant Equipment	7.7	2	0.2
TOTAL	**100%**		**11.8%**

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Common Forms of Corrosion

- Stress corrosion cracking – combination of corrosive environment and tensile stress
  - – influenced heavily by radiation
- Flow assisted corrosion
- General corrosion
- Microbiologically

History of Stress Corrosion Cracking

Component and mode of failure	Alloy	Time period
Fuel cladding, irradiation-assisted SCC	304	1960s
Furnace-sensitized safe ends, IGSCC	304, 182, 600	↓
Weld-sensitized small diameter piping, IGSCC	304	
Weld-sensitized large diameter piping, IGSCC	304	
Furnace-sensitized weldments and safe ends, IGSCC	182/600	
Low-alloy steel nozzles, thermally induced vibration	A508	1980s
Crevice-induced cracking	304L/316L	
Jet pump beams, IGSCC	X750	↓
Cold work induced IGSCC of "resistant" alloys	304L	
Low-alloy steel pressure vessel, TGSCC	A533B/A508	
Irradiated core internals, IASCC	304, 316	
IGSCC/IASCC of low-carbon and stabilized stainless steels	304L, 316L, 321, 347	2000s

SCC, stress-corrosion cracking; IGSCC, intergranular stress-corrosion cracking; TGSCC, transgranular stress-corrosion cracking; IASCC, irradiation-assisted stress-corrosion cracking

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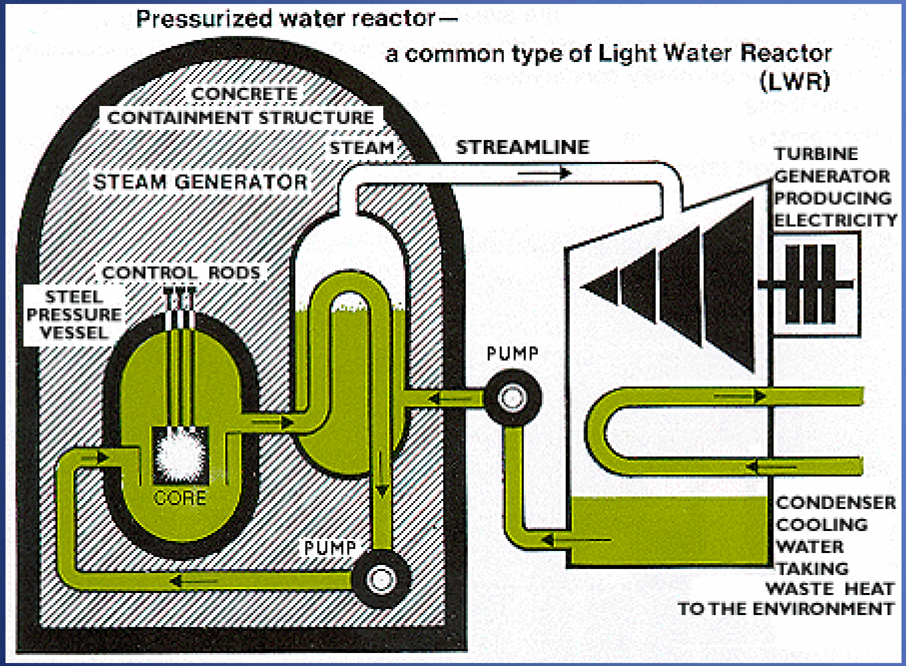
Common Materials of Reactor Components

- Nickel alloys – tubing for steam generators
- Stainless steels – components that hold radioactive water
- Zirconium alloys – cladding of control rods
- Copper alloys
- Titanium alloys – components exposed to salt water

Pressure Vessels

Designed based on fracture mechanics



http://www.world-nuclear.org/info/inf32.html

Mainly ASTM grade steels designed specifically for reactors – high resistance radiation and high fracture toughness

Effects of Radiation on Materials

- Irradiation
  - Swelling: increase in volume of the material without an increase in density – can increase 20-30%
  - Irradiation-creep: deformation of material at lower stresses than the yield strength
  - Embrittlement: increase in hardness and strength but a decrease in ductility – yield strength can reach up to 5X the unirradiated value

Current Reactors vs. Next Gen Reactors

3X higher temperatures and radiation levels

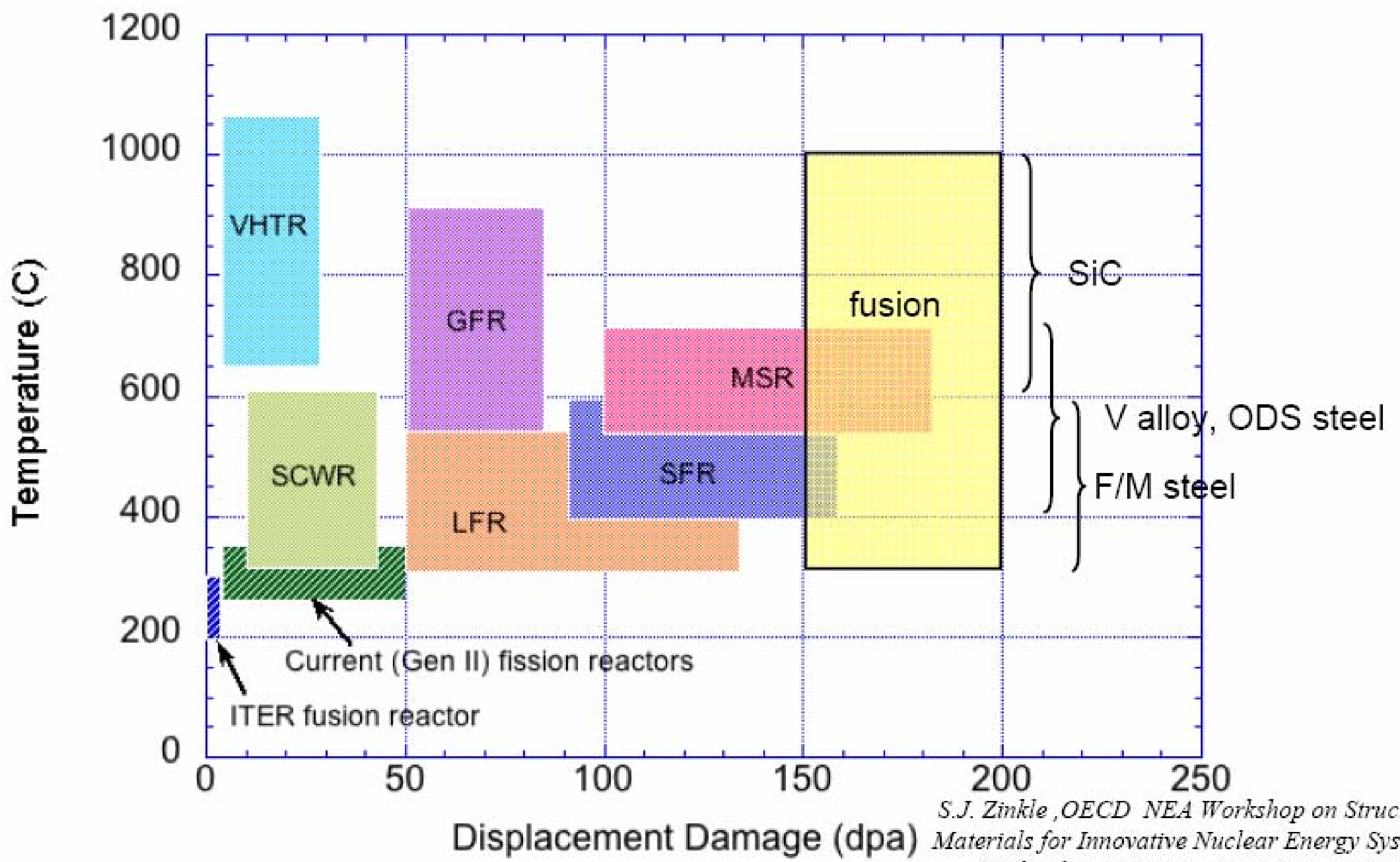
Max outlet temp of Gen II reactor: 350 C
Max outlet temp of Gen IV reactor: 1100 C

Irradiation

Neutrons bombard the surface of materials

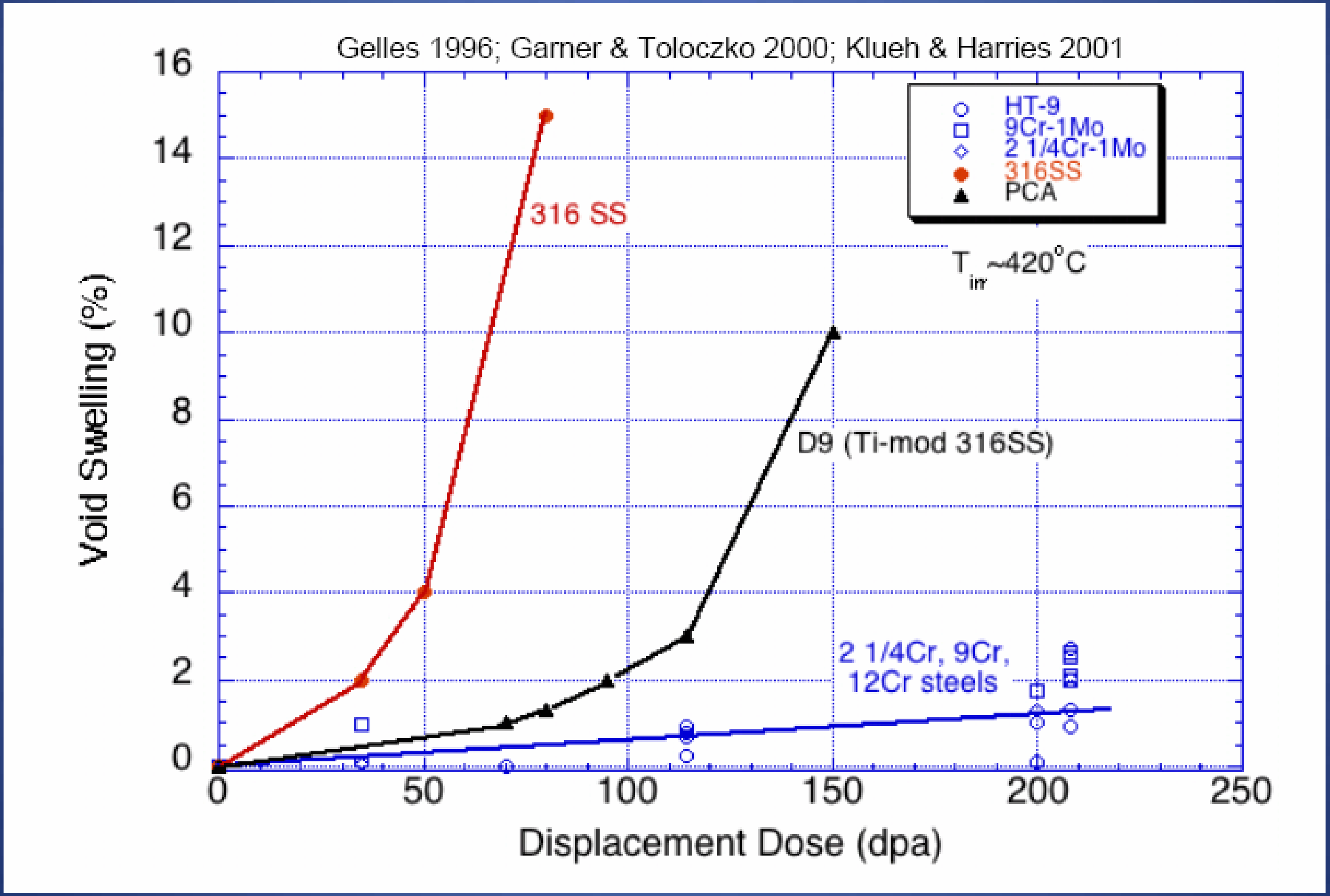
Atoms in the crystal structure get displaced – amount of displacement and likelihood of recombination determine effect on material – measured in displacement per atom or dpa

Displacement Data and Temperatures of Reactors



S.J. Zinkle ,OECD NEA Workshop on Structural Materials for Innovative Nuclear Energy Systems, Karlsruhe, Germany, June 2007, in press

Void Swelling of Various Steels



Nuclear Waste

- Temporary storage currently used
  - Wet or dry containers on-site
- Permanent storage in development at Yucca Mountain

Radioactive material estimated to remain radioactive for 10,000 years – longer exposure to materials than while in use

Yucca Mountain

CONSTRUCTION PHASE		NUMBER OF YEARS	HISTORICAL (1983-2002) ($ x million)	FUTURE COST WITHOUT CONTINGENCY (1999-2116) ($ x million)	CONTINGENCY COST ($ x million)	TOTAL (1999-2116) ($ x million)	AVERAGE COST PER YEAR ($ x million)
Development and Evaluation	1983-2002	20	4,910	990	-	990	49.5
Licensing	2002-2005	4	-	670	90	760	190.0
Pre-Emplacement Construction	2005-2010	6	-	2,460	490	2,950	491.7
Emplacement Operations	2010-2041	32	-	13,580	2,310	15,890	496.6
Monitoring	2041-2110	70	-	2,590	630	3,220	46.0
Closure and Decommissioning	2110-2116	7	-	330	70	400	57.1
		TOTAL	**$4,910**	**$20,620**	**$3,590**	**$24,210**	

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20% for materials/components that have no other function but corrosion prevention