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Nuclear energy is clean and it is safe

US Energy Information Administration
Worldwide use of nuclear energy to generate electricity
The fuel in a light water reactor

- The fuel in a light water reactor are slender rods in a bundle.
- Each rod is a tube filled with ceramic fuel.
- Currently the tube or cladding is a zircaloy alloy (metal) and the fuel is urania (ceramic).
- The current pair zircaloy + urania was born in the late 1940s (unchanged for 70 years).
- The fuel is partially changed in a reactor every ~2 years.

### Alloy for cladding

<table>
<thead>
<tr>
<th>Alloy for cladding</th>
<th>Nominal Composition in mass percent</th>
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<tbody>
<tr>
<td>Zircaloy-2 or R60802</td>
<td>Zr + 1.2/1.7Sn + 0.07/0.20Fe + 0.05/0.15Cr + 0.03/0.08Ni (Fe+Cr+Ni = 0.18-0.38)</td>
</tr>
<tr>
<td>Zircaloy-4 or R60804</td>
<td>Zr + 1.2/1.7Sn + 0.18/0.24Fe + 0.07/0.13Cr (Fe+Cr = 0.28-0.37)</td>
</tr>
<tr>
<td>ZIRLO</td>
<td>Zr + 1Sn + 1Nb + 0.1Fe (Optimized Zirlo has 0.67Sn)</td>
</tr>
<tr>
<td>M5</td>
<td>Zr + 1Nb + 0.14O</td>
</tr>
<tr>
<td>E110</td>
<td>Zr + 1Nb</td>
</tr>
<tr>
<td>E635</td>
<td>Zr + 1.2Sn + 1Nb + 0.35Fe</td>
</tr>
<tr>
<td>Zr-2.5Nb or R60904</td>
<td>Zr + 2.4/2.8Nb</td>
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</tbody>
</table>
The fuel cycle

- The fuel rod first needs to be manufactured, and assembled.
- The design of the fuel rod is for the entire fuel cycle including final disposal or reprocessing.
Degradation of Zirconium alloys during reactor service

**Zirconium Alloys Water Side Degradation**
- General uniform oxidation is understood.
- Nodular corrosion is understood & controlled.
- Hydriding due to corrosion, not a limiting factor.
- Shadow Corrosion - only in BWR, currently rare.
- No classic environmentally assisted stress cracking.
- Crud induced localized corrosion, rare.
- Debris Fretting – the major current cause of fuel rod failure

**Zirconium alloys Fuel Side Degradation**
- Little internal oxidation
- No localized corrosion
- Environmental assisted cracking (PCMI) by iodine – known and controlled.
Uniform OD corrosion/oxidation of Zircaloy tube.
Nodular corrosion and hydriding

Sources: Adamson & Horn/Cheng

circumferential
radial
Shadow corrosion & ID iodine cracking

- Zirconium Alloy: Susceptible Material
- Tensile Stress: Power Ramp
- Aggressive Environment: Iodine, ZrI₂

Channel
- Control Blade Handle
- Control Blade

E_corr shifts under irradiation
- E_corr Ni Alloy
- E_corr Zr Alloy

No irradiation
- Irradiation
Debris Fretting, the current leading mode of failure of LWR fuels
Debris fretting

Debris found in a feedwater heater where a fretting fuel failure occurred

Examples of Debris Fretting Failure perforations
Life Cycle of a Fuel Bundle

1. Reactor Residence ~6/8 years
2. Cooling Pools ~ 5-20 years
3. Dry Cask Storage ~ 100 years
4. Nuclear Waste Geologic Repository ~ 1 Million years
Cooling Pools in Nuclear Power Plants

- Fuel rods stored under water need to survive well for 20 years or more.
- The water in the pools has a precise control of its chemistry.
- The most common parameters specified and monitored regarding water quality include:
  - pH (~7) (in the range 5.5 to 9)
  - Conductivity
  - Water turbidity (from microbial activity)
  - Chemical composition (i.e. Cl\(^-\), F\(^-\), SO\(_4^{2-}\)) (<0.5 or <0.1 ppm Cl\(^-\))
  - Temperature (lowest possible, generally <66°C)
  - Biocide (such as H2O2) to control microbial activity.
- The conditions may vary from plant to plant (country to country).
Cooling pool storage of used fuel

- Source DOE, NRC
  https://www.osti.gov/servlets/purl/7284014/

- There are no obvious degradation mechanisms which operate on the cladding under pool storage conditions at rates which are likely to cause failures in the time frame of probable storage.
Dry Cask Storage System
sources: NRC, DOE

• At some nuclear reactors across the US, spent fuel is kept on site, above ground, in systems basically similar to the ones shown here.
• Once the spent fuel has cooled, it is loaded into special canisters.
• Each canister is designed to hold approximately 2-6 dozen spent fuel assemblies, depending on the type of assembly.
• Water and air are removed. The canister is filled with inert gas, and sealed (welded or bolted shut).
• The principal likely Zircaloy cladding degradation mechanisms are
  - Creep rupture,
  - SCC, and
  - DHC (delayed hydride cracking)
Geologic repository fuel degradation predictions

• The zirconium alloy cladding will be enclosed in the waste package.

• The environment inside the waste package will be non-corrosive, dry and low temperature.

• Creep and delayed hydride cracking may be possible but unlikely.

• Thousand of years may pass before the external environment corrodes through the external waste package.

• Zircaloy cladding would be the last barrier for the environment to degrade before the environment reaches the toxic waste.

Red line = temperature
Summary and Conclusions

• The fuel of light water reactors includes urania pellets inside zirconium alloy tubes.

• The degradation of the fuel cladding can be separated in four steps during the fuel cycle
  • Reactor residence, shortest time but harshest environment
  • Pool residence, wet and mild environment
  • Dry cask, second longest time, dry and mild
  • Repository conditions, longest time and mild environment inside the container.

• Most of corrosion issues inside the reactor have been understood and solved.

• No problems in wet pool storage.

• No current issues on dry cask storage.
Materials in a light water power reactor
Structural Materials in the Nuclear Power Industry. Same materials used in plants for over 60 years.

Source: R. W. Staehle
Energy Accidents – Hydrocarbon Casualties

- More than 100,000 coal miners died in accidents in the last century.
- 19 May 1902: 216 miners were killed in the Fraterville Mine Disaster in Fraterville, Tennessee.
- 06 December 1907: 362 miners died in the Monongah Mining Disaster in Monongah, WV.
- 19 December 1907: 239 workers died, including children in the Darr Mine Disaster in Pennsylvania.
- In 1907 alone; 3,200 coal miners died around the globe.
- 21 December 1910: 344 men and boys lost their lives in an explosion in the Pretoria Pit Disaster in Lancashire, UK.
- 05 November 1930: 82 miners died in the Millfield Mine disaster in Dover Township, Athens County, in Ohio.
Energy Accidents – Hydroelectric casualties

• In 1952 the electric power generation Banqiao Dam on the Ru river was finished in China.
• In August 1975 the Banqiao Dam collapsed due to excessive rainfall – more than 3 m of rain in three days, from Typhoon Nina.
• Up to 230,000 deaths due to the dam collapse, which produced a stream of 10 km wide and 7 m high wall of water.
Energy Accidents – Hydrocarbon Casualties

• 06-July 1988: An explosion and fire on a North Sea oil production platform Piper Alpha kills 167 men.

• On 06-July-2013 a rail disaster happened when 63 cars of a 72-car train carrying Bakken crude oil derailed, causing fire and explosions in downtown Lac-Mégantic, Quebec Canada. 47 people were killed and 30 buildings were burned to the ground. Most or the surviving buildings had to be demolished due to contamination.

Infrared image taken by NASA's Suomi NPP satellite shows the fire that followed the derailment: on the left, taken two days before; on the right, taken about two hours after the explosions.
# Energy Accidents – Nuclear Power Casualties

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<th>Commercial Nuclear Accident</th>
<th>What Happened?</th>
<th>Direct human casualties (&amp; delayed, estimated)</th>
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<tbody>
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<td>Three Mile Island, 1979</td>
<td>Partial meltdown of the PWR Unit 2 reactor due to a loss of coolant in the primary circuit caused by a valve stuck open. Cause, human error, &amp; lack of training.</td>
<td>0 (0)</td>
</tr>
<tr>
<td>Chernobyl, 1986</td>
<td>Steam explosion followed by open air graphite fire of the light water graphite moderated RBMK Unit 4 reactor during a test to simulate a station black out. The fire burned for 9 days releasing fission products to the atmosphere. Cause, operator error, negligence &amp; lack of training or knowledge.</td>
<td>30 (134 up to 1996, maybe a total of 4000 due to leukemia &amp; cancer)</td>
</tr>
<tr>
<td>Fukushima Daiichi, 2011</td>
<td>Hydrogen gas explosions because of loss of coolant due to station black out caused by a tsunami wave. Release of radioactive products to the atmosphere from BWR Units 1, 2, and 3. Cause, failure of operator to meet basic safety requirements.</td>
<td>2 drowned (~1600 elderly early deaths related to evacuation, not to radiation)</td>
</tr>
</tbody>
</table>

The Fukushima plant blackout was a result of a major natural disaster, a magnitude 9 earthquake and a tsunami that killed nearly 20,000 people and still nobody died at the 6000 employee site due to radiation.
Crisis Creates New Opportunities

Crisis = wēi jī

Danger + Opportunity

Character wēi
Incipient moment; crucial point, when something begins or changes.

Character jī

The Fukushima accident was a catalyst or changing point for nuclear power materials.