Dry cask storage issues
Actions needed now

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Game changer
Indefinite on-site storage

- August 26, 2014 NRC approved
  - 60 years (short term) on-site storage
  - 100 years (long term) on-site storage
  - Indefinite on-site storage
- No other storage sites on horizon
- Current U.S. thin steel canister designs inadequate
  - Cannot be inspected or repaired
  - May have stress corrosion cracks
  - No early warning monitoring
- Edison plans to spend $400 million for a thin canister system (~100 canisters) for San Onofre spent fuel
NRC proposed plan inadequate

- NRC revision to NUREG-1927 scheduled for 2015
- NRC plans to require first inspection after 25 years, allowing vendor 5 years to develop inspection technology
- Only requires inspection of one canister per plant
- That same canister to be inspected every 5 years
- NRC to allow up to 75% through-wall crack even though there is no seismic rating for cracked canisters
Two-year old Diablo Canyon canister has conditions for cracking

- NRC assumed it would take over 30 years before temperatures low enough for cracks – proven wrong
- Canister inspected for temperature and salts; no technology exists to inspect for cracks or corrosion
  - Temperature low enough to initiate cracking in marine environment in only two years – under 85°C (185°F)
  - Salts found on canister can trigger corrosion and cracking
## Thin Canisters vs. Thick Casks

<table>
<thead>
<tr>
<th>Safety Feature</th>
<th>Thin Canisters</th>
<th>Thick Casks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thick walls</td>
<td>1/2” to 5/8”</td>
<td>Up to 20”</td>
</tr>
<tr>
<td>Won’t crack</td>
<td></td>
<td>✓</td>
</tr>
<tr>
<td>Ability to repair</td>
<td></td>
<td>✓</td>
</tr>
<tr>
<td>Ability to inspect</td>
<td></td>
<td>✓</td>
</tr>
<tr>
<td>Early warning monitor</td>
<td></td>
<td>✓</td>
</tr>
<tr>
<td>ASME canister or cask certification</td>
<td></td>
<td>✓</td>
</tr>
<tr>
<td>Defense in depth</td>
<td></td>
<td>✓</td>
</tr>
</tbody>
</table>
Thick casks designed for longer storage

- Market leader internationally
- No stress corrosion cracking
- Can inspect casks
- Thick casks body -- forged steel or thicker ductile cast iron up to 20”
- Early warning before radiation leak (remote lid pressure monitoring)
- Double bolted thick steel lids allow reloading without damaging cask
- Cask protects from all radiation, unlike thin steel canisters. No concrete overpack required. Stored in concrete building for additional protection
- Both a storage and transport cask
- Parts (seals, lids) can be replaced, if needed
- ASME & international manufacturing cask certifications
- Defense in depth – damaged fuel sealed for radiation protection
- Not currently licensed in U.S. (18 to 30 month process)
- Vendors won’t request license unless they have customer
Sandia Labs: Ductile cast iron performs in an exemplary manner

- ...studies cited show DI [ductile iron] has sufficient fracture toughness to produce a containment boundary for radioactive material transport packagings that will be safe from brittle fracture.

- ...studies indicate that even with drop tests exceeding the severity of those specified in 1 OCFR7 1 the DI packagings perform in an exemplary manner.

- Low temperature brittle fracture not an issue. The DCI casks were tested at -29°C and -49°C exceeding NRC requirements.

- Conclusions shared by ASTM, ASME, and IAEA.

Germany interim storage

Transport and storage casks in the interim storage facility of Gorleben

Photo: GNS
Problems with thin stainless steel canisters

- Cannot inspect exterior or interior for cracks
- Cannot repair cracks
- No warning BEFORE radiation leaks
- Canisters not ASME certified
- No defense in depth
- Unsealed damaged fuel cans
- Early stress corrosion cracking risk
- No adequate plan for failed canisters
- Inadequate aging management plan
Thin canisters not what they’re cracked up to be

- Condition of existing canisters unknown
  - No technology exists to inspect these canisters
  - Canisters in use less than 30 years (1986)
  - *Won’t know until after leaks radiation*

- Other welded stainless steel items at nuclear plants failed in 11 to 33 years at ambient temperatures ~20°C (68°F)

- Crack initiation unpredictable
  - Cracks more likely to occur at higher end of temperature range up to 80°C (176°F) instead of ambient temperatures
  - Canister temperatures above 85°C will not crack from marine air – salts won’t stay and dissolve on canister

- Crack growth about *four times faster* at 80°C (176°F) in “wicking” tests compared with 50°C (122°F)
Thin canisters cannot be inspected

- No technology to detect surface cracks, crevice and pitting corrosion in thin canisters filled with nuclear waste
  - Canister must stay inside concrete overpack/cask due to radiation risk, so future inspection technology may be limited
  - Thin canisters do not protect from gamma and neutrons
  - Microscopic crevices can result in cracks
- Thick casks can be inspected
  - Provide full radiation barrier without concrete
  - Surfaces can be inspected
  - Not subject to stress corrosion cracking
Thin canisters not repairable

- No current technology to repair canisters filled with nuclear waste
  - Canisters must be repaired under water
  - Holtec Dr. Singh: should not attempt repair
    - Surface must be completely smooth to avoid imperfections that can initiate cracks

- **No seismic rating for a cracked canister**

- No plan for replacing canisters or casks
  - Funds not budgeted
  - NRC allows pools to be destroyed, removing only method for replacing canisters and casks
  - Vendor proposal to transport cracked canister in transport cask is unsafe and not NRC approved
Thin canisters not designed to be replaced

- Welded lid not designed to be removed
- Lid must be unwelded under water
- Fuel transfer from damaged canister to new canister must be done under water
- No spent fuel has ever been reloaded into another thin canister
- Thick casks are designed to remove and reload fuel
No warning before radiation leaks from thin canisters

- No pressure or helium monitoring
- Remote temperature monitoring not early warning
- No remote or continuous canister radiation monitoring
  - Workers “periodically” walk around canisters with portable radiation monitors
- Thick casks have continuous remote pressure monitoring – alerts to early helium leak
- Thick casks have continuous remote radiation monitoring
Thin canisters not ASME certified

- Canisters do not have independent quality certification from American Society of Mechanical Engineers (ASME)
- NRC allows exemptions to some ASME standards
- No independent quality inspections
- ASME has not developed standards for spent fuel stainless steel canisters
No defense in depth in thin canisters

- Thin stainless steel canisters do not protect from gamma or neutron radiation
  - Unsealed concrete overpacks/casks required for gamma and neutron protection
- Damaged fuel placed in vented cans provide no radiation protection
- High burnup fuel can damage protective Zirconium cladding in dry storage
- Technology to examine fuel assemblies for damage is limited
- We’re only 1/2” to 5/8” away from a radiation disaster
Recommendations

- NRC needs to act now
  - Freeze procurement of thin canisters
  - Set higher dry storage standards
  - Evaluate thick cask technology used internationally
    - Review Sandia Labs report to dispel myth of ductile cast iron embrittlement
  - Don’t approve removal of empty pools until DOE takes waste
- Base standards on longer term storage needs
  - Not on limitations of thin canister technology
  - Not on vendor promises of future solutions
- Be proactive – take a leadership role
- Utilities need to evaluate thick cask technology
References

- Diablo Canyon: conditions for stress corrosion cracking in two years, D. Gilmore, October 23, 2014

- Top Ten Reasons to Buy Thick Casks, D. Gilmore, October 14, 2014

- Dry Cask Storage Issues, D. Gilmore, September 23, 2014

- Additional references: SanOnofreSafety.org
Additional Slides
Fukushima thick casks

### Specification of Dry Casks

<table>
<thead>
<tr>
<th></th>
<th>Large type</th>
<th>Medium type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weight (t)</td>
<td>115</td>
<td>96</td>
</tr>
<tr>
<td>Length (m)</td>
<td>5.6</td>
<td>5.6</td>
</tr>
<tr>
<td>Diameter (m)</td>
<td>2.4</td>
<td>2.2</td>
</tr>
<tr>
<td>Assemblies in a cask</td>
<td>52</td>
<td>37</td>
</tr>
<tr>
<td>Number of casks</td>
<td>5</td>
<td>2</td>
</tr>
<tr>
<td>Fuel type</td>
<td>8 x 8</td>
<td>8 x 8</td>
</tr>
<tr>
<td>Cooling-off period (years)</td>
<td>&gt; 7</td>
<td>&gt; 7</td>
</tr>
<tr>
<td>Average burn-up (MWD/T)</td>
<td>&lt;24,000</td>
<td>&lt;24,000</td>
</tr>
</tbody>
</table>

Additional 11 casks are being prepared for installation.
Fukushima cask building
Higher Burnup = Higher Cladding Failure

Higher oxide thickness results in higher cladding failure. Argonne scientists reported high burn-up fuels may result in fuel rods becoming more brittle over time, “…insufficient information is available on high burnup fuels to allow reliable predictions of degradation processes during extended dry storage.” U.S. Nuclear Waste Technical Review Board Evaluation of the Technical Basis for Extended Dry Storage and Transportation of Used Nuclear Fuel, December 2010, Burnup Chart Page 56
Stress Corrosion Cracking
Background Information

- 304 and 316 Stainless steels are susceptible to chloride stress corrosion cracking (SCC)
  - Sensitization from welding increases susceptibility
  - Crevice and pitting corrosion can be precursors to SCC
  - SCC possible with low surface chloride concentrations
- Welded stainless steel canisters have sufficient through wall tensile residual stresses for SCC
- Atmospheric SCC of welded stainless steels has been observed
  - Component failures in 11-33 years
  - Estimated crack growth rates of 0.11 to 0.91 mm/yr

2/3 of the requirements for SCC are present in welded stainless steel canisters
Power Plant Operating Experience with SCC of Stainless Steels

<table>
<thead>
<tr>
<th>Plant</th>
<th>Distance to water, m</th>
<th>Body of water</th>
<th>Material/Component</th>
<th>Thickness, or crack depth, mm</th>
<th>Time in Service, years</th>
<th>Est. Crack growth rate, m/s</th>
<th>Est. Crack growth rate, mm/yr</th>
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</thead>
<tbody>
<tr>
<td>Koeberg</td>
<td>100</td>
<td>South Atlantic</td>
<td>304L/RWST</td>
<td>5.0 to 15.5</td>
<td>17</td>
<td>$9.3 \times 10^{-12}$ to $2.9 \times 10^{-11}$</td>
<td>0.29 to 0.91</td>
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<tr>
<td>Ohi</td>
<td>200</td>
<td>Wakasa Bay, Sea of Japan</td>
<td>304L/RWST</td>
<td>1.5 to 7.5</td>
<td>30</td>
<td>$5.5 \times 10^{-12}$ to $7.9 \times 10^{-12}$</td>
<td>0.17 to 0.25</td>
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<tr>
<td>St Lucie</td>
<td>800</td>
<td>Atlantic</td>
<td>304/RWST pipe</td>
<td>6.2</td>
<td>16</td>
<td>$1.2 \times 10^{-11}$</td>
<td>0.39</td>
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<tr>
<td>Turkey Point</td>
<td>400</td>
<td>Biscayne Bay, Atlantic</td>
<td>304/pipe</td>
<td>3.7</td>
<td>33</td>
<td>$3.6 \times 10^{-12}$</td>
<td>0.11</td>
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<tr>
<td>San Onofre</td>
<td>150</td>
<td>Pacific Ocean</td>
<td>304/pipe</td>
<td>3.4 to 6.2</td>
<td>25</td>
<td>$4.3 \times 10^{-12}$ to $7.8 \times 10^{-12}$</td>
<td>0.14 to 0.25</td>
</tr>
</tbody>
</table>

- CISCC growth rates of 0.11 to 0.91 mm/yr for components in service
  - Median rate of $9.6 \times 10^{-12}$ m/s (0.30 mm/yr) reported by Kosaki (2008)
- Activation energy for CISCC propagation needs to be considered
  - 5.6 to 9.4 kcal/mol (23 to 39 kJ/mol) reported by Hayashibara et al. (2008)
## Data Gap Summarization

<table>
<thead>
<tr>
<th>Gap</th>
<th>Priority</th>
<th>Gap</th>
<th>Priority</th>
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<tbody>
<tr>
<td>Thermal Profiles</td>
<td>1</td>
<td>Neutron poisons – Thermal aging</td>
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<tr>
<td>Stress Profiles</td>
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<td>Moderator Exclusion</td>
<td>8</td>
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<tr>
<td>Monitoring – External</td>
<td>2</td>
<td>Cladding – Delayed Hydride Cracking</td>
<td>9</td>
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<tr>
<td>Welded canister – Atmospheric corrosion</td>
<td>2</td>
<td>Examination of the fuel at the INL</td>
<td>10</td>
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<tr>
<td>Fuel Transfer Options</td>
<td>3</td>
<td>Cladding – Creep</td>
<td>11</td>
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<tr>
<td>Monitoring – Internal</td>
<td>4</td>
<td>Fuel Assembly Hardware – SCC</td>
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<tr>
<td>Welded canister – Aqueous corrosion</td>
<td>5</td>
<td>Neutron poisons – Embrittlement</td>
<td>11</td>
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<tr>
<td>Bolted casks – Fatigue of seals &amp; bolts</td>
<td>5</td>
<td>Cladding – Annealing of radiation damage</td>
<td>12</td>
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<tr>
<td>Bolted casks – Atmospheric corrosion</td>
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<td>Cladding – Oxidation</td>
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<tr>
<td>Bolted casks – Aqueous corrosion</td>
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<td>Neutron poisons – Creep</td>
<td>13</td>
</tr>
<tr>
<td>Drying Issues</td>
<td>6</td>
<td>Neutron poisons – Corrosion</td>
<td>13</td>
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<tr>
<td>Burnup Credit</td>
<td>7</td>
<td>Overpack – Freeze-thaw</td>
<td>14</td>
</tr>
<tr>
<td>Cladding – Hydride reorientation</td>
<td>7</td>
<td>Overpack – Corrosion of embedded steel</td>
<td>14</td>
</tr>
</tbody>
</table>

*Imminent need*  
*Immediate to facilitate demonstration early start*  
*Near-term High or Very High*  
*Long-term High*  
*Near-term Medium or Medium High*  
*Long-term Medium*
San Onofre Cesium-137
Safety Complaints to NRC from all External Sources*
Non-Operating U.S. Nuclear Power Reactors
January 2009 to August 2013

San Onofre – worst safety complaint record in the nation!

* Nuclear Regulatory Commission (NRC) refers to these complaints as “Allegations from External Sources” (all sources external to the NRC). Majority of complaints are from employees & other on-site sources. These are reports of impropriety or inadequacy of NRC-related safety or regulatory concerns. Includes all non-operating U.S. operating nuclear power plants & reactors. One allegation report may contain multiple allegations. However, the NRC counts it as one allegation in these statistics. A complaint about a safety-conscious work environment (SCWE) problem is important. However, a Notice of Violation cannot be issued, because there is no applicable NRC regulation. Source: www.nrc.gov/about-nrc/regulatory/allegations/statistics.html
Waste is not going anywhere

- **Yucca Mountain geological repository issues unresolved**
  - DOE plan: Solve water intrusion issue 100 years AFTER loading nuclear waste
  - Inadequate capacity for all waste
  - Not designed for high burnup fuel

- **Congress limited DOE to consider only Yucca Mountain**
  - Funding of storage sites unresolved
  - Communities do not want the waste

- **Poor track record for finding safe waste solutions**
  - New Mexico WIPP repository leaked within 15 years
  - Washington Hanford repository leaking containers
  - Other storage sites leaked

- **Inadequate transport infrastructure & potential for accidents**

- **High burnup fuel over twice as radioactive, hotter, and unstable**
  - Zirconium cladding more likely to become brittle and crack -- eliminates key defense in depth. Radiation protection limited to the thin stainless steel canister. Concrete overpack/cask only protects from gamma and neutrons.

- **Fuel assemblies damaged after storage may not be retrievable**

- **Inspection of damaged fuel assemblies is imperfect**
Introduction: Circumferential and Radial Hydrides in HBU Cladding

As-Irradiated

Drying-Storage

660 wppm H

After

650 wppm H

200 μm

320 wppm H

350 wppm H
Summary of Results

- Susceptibility to Radial-Hydride Precipitation
  - Low for HBU Zry-4 cladding
  - Moderate for HBU ZIRLO™
  - High for HBU M5®

- Susceptibility to Radial-Hydride-Induced Embrittlement
  - Low for HBU Zry-4
  - Moderate for HBU M5®
  - High for HBU ZIRLO™

- DBTT Values for HBU Cladding Alloys
  - Peak drying-storage hoop stress at 400°C: 140 MPa → 110 MPa → 90 MPa → 0 MPa
  - DBTT for HBU M5® after slow cooling: 80°C → 70°C → <20°C → <20°C
  - DBTT for HBU ZIRLO™ after slow cooling: 185°C → 125°C → 20°C → <20°C
  - DBTT for HBU Zry-4 after slow cooling: 55°C → <20°C → >90°C
    - Embrittled by circumferential hydrides: 615±82 wppm 520±90 wppm 640±140 wppm
    - HBU Zry-4 with 300±15 wppm was highly ductile at 20°C
### Container Degradation Mechanisms
**Base Metal, Welds, Bolts, and Seals**

<table>
<thead>
<tr>
<th>Stressor</th>
<th>Degradation Mechanism</th>
<th>Influenced by VLTS or Higher Burnup</th>
<th>Additional Data Needed</th>
<th>Priority of R&amp;D</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal and Mechanical</td>
<td>Embrittlement of elastomer seals</td>
<td>Yes</td>
<td>Yes</td>
<td>Low</td>
</tr>
<tr>
<td></td>
<td>Thermomechanical fatigue of seals and bolts</td>
<td>Yes</td>
<td>Yes</td>
<td>Medium</td>
</tr>
<tr>
<td>Radiation</td>
<td>Embrittlement of elastomer seals</td>
<td>Yes</td>
<td>Yes</td>
<td>Low</td>
</tr>
<tr>
<td>Chemical</td>
<td>Atmospheric Corrosion (Including Marine Environment)</td>
<td>Yes</td>
<td>Yes</td>
<td>High</td>
</tr>
<tr>
<td></td>
<td>Aqueous Corrosion: general, localized (pitting, crevice), SCC, galvanic</td>
<td>Yes</td>
<td>Yes</td>
<td>High</td>
</tr>
</tbody>
</table>
Background information

- CoCs/licenses for high burn-up fuel storage to be renewed over next few years
  - 2012 Prairie Island-TN-40HT, Calvert Cliffs-NUHOMS\(^1\)
  - 2015 Transnuclear-NUHOMS 1004
  - 2020 NAC-UMS; Holtec-Hi-STORM

- Storage of high burn-up fuel is relatively recent
  - 9 years – Maine Yankee\(^2\) (since 2003) up to 49.5 GWh\(\text{MTU}\)
  - 7 years – Robinson (since 2005) up to 56.9 GWh\(\text{MTU}\)
  - 6 years – Oconee (since 2006) up to 55 GWh\(\text{MTU}\)
  - <4 years for most – up to 53.8 GWh\(\text{MTU}\)

- ~ 200 loaded-casks contain high burn-up fuel

- Most fuel in pools for future loading is high burn-up

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1) Since 1992, allowable burn-up to 47 GWh\(\text{MTU}\), since 2010, up to 52 GWh\(\text{MTU}\)
2) All high burn-up fuel is in damaged fuel cans
High Burnup Fuel Approval

June 1992
Up to 60 GWd/MTU (60 MWD/kg)
Used Nuclear Fuel in Storage
(Metric Tons, End of 2013)