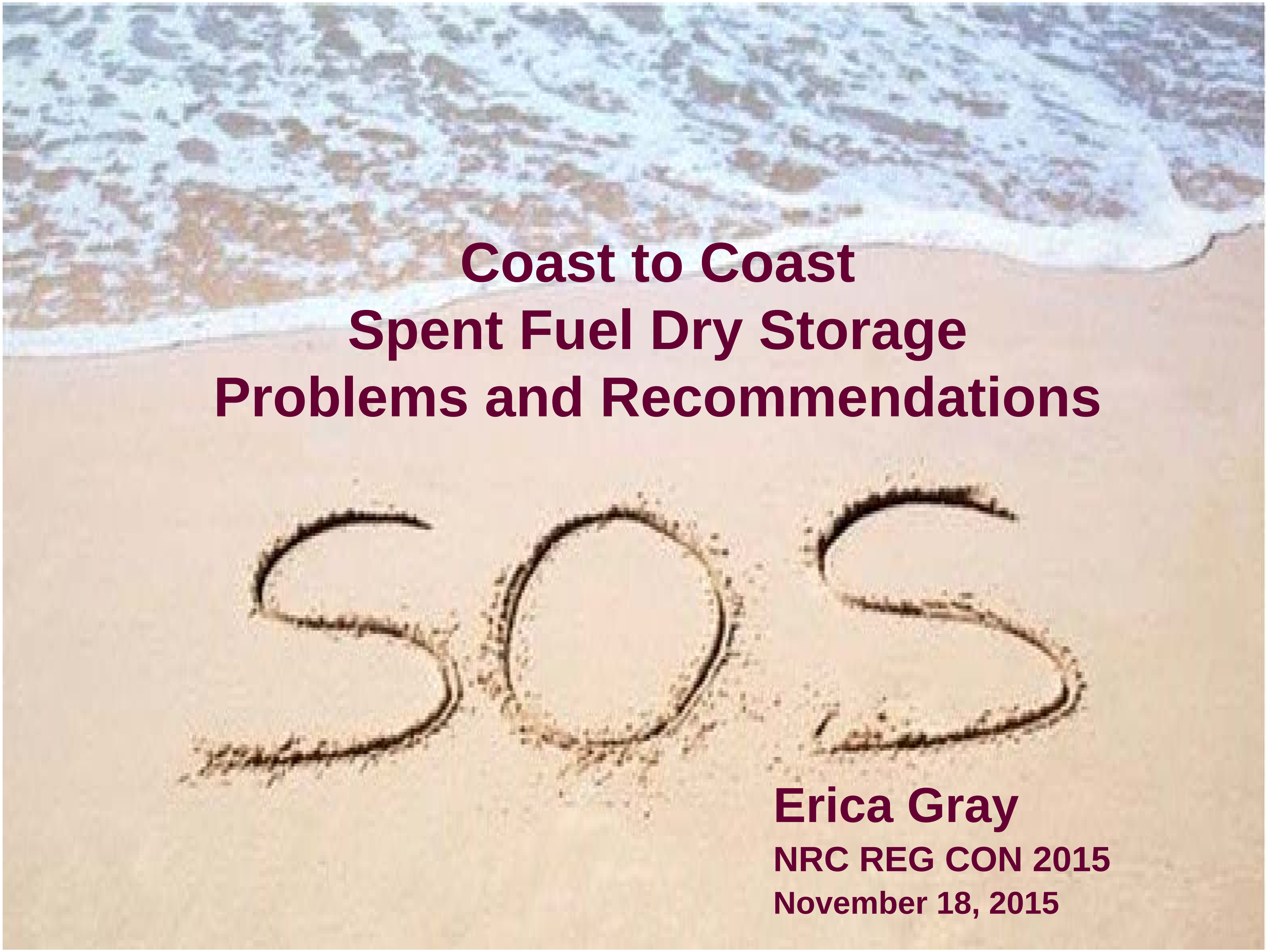


Coast to Coast
Spent Fuel Dry Storage
Problems and Recommendations

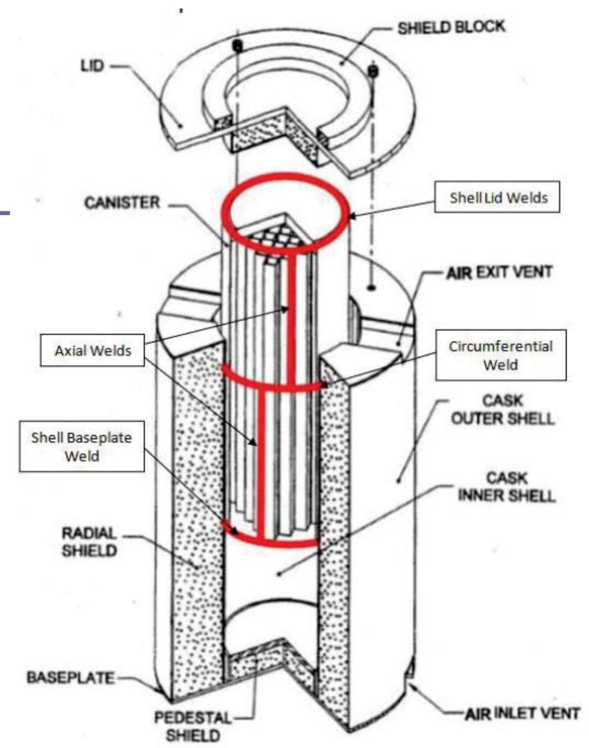
Erica Gray

NRC REG CON 2015

November 18, 2015

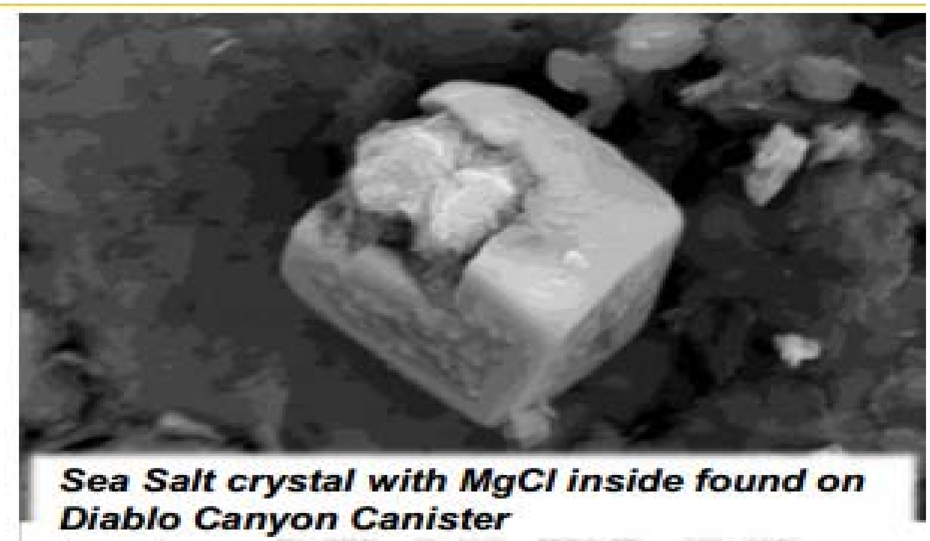
Game Changer: Indefinite on-site storage

- NRC 2014: 100+ years on-site
  - No other sites on horizon
- Thin canisters not maintainable
  - May crack and leak in 20+ years
  - Some may already have cracks
  - Cannot inspect or repair
  - Not transportable with cracks
- No solution for cracked canisters
- No warning until AFTER radiation leaks



Diablo Canyon canister has *conditions* for cracking in 2-year old canister

- **Canister temperatures low enough to dissolve salt on canister (EPRI)**
  - **Triggers corrosion and chloride-induced stress corrosion cracking (CISCC)**
- **Other triggers for cracking not investigated**


Sea Salt crystal with MgCl inside found on Diablo Canyon Canister

After CRACK starts, thin canisters can LEAK in 16 years, NRC*

- **U.S. has almost 2000 thin canisters loaded****
- **Examples** **1st loaded**
  - **Oconee, SC** **1990**
  - **Calvert Cliffs, MD** **1993**
  - **Davis Besse, OH** **1995**
  - **Maine Yankee** **2002**
  - **San Onofre, CA** **2003**
  - **North Anna, VA** **2008**

***NRC Summary of August 5, 2014 Public Meeting** with the Nuclear Energy Institute on Chloride Induced Stress Corrosion Cracking Regulatory Issue Resolution Protocol http://pbadupws.nrc.gov/docs/ML1425/ML14258A081.pdf

**1989 is earliest thin canister in use (Robinson, H.B., SC). Failure Modes and Effects Analysis (FMEA) of Welded Stainless Steel Canisters for Dry Cask Storage Systems, EPRI, Final Report, December 2013, Table 2-2

Koeberg container LEAKED in 17 years

- **Koeberg South Africa container is considered comparable to thin canisters. Cracked and leaked in 17 years from corrosive environment.[1]**
  - **Frequent salt & high moisture from on-shore winds, surf, & fog**
  - **Higher risk for chloride-induced stress corrosion cracking (CISCC)**
- **Koeberg steel tank crack deeper than thickness of most U.S. thin canisters (0.61” vs. 0.50”)**
- **Nuclear industry EPRI[2] report cherry-picked data[3]**
  - **Ignored 17-year Koeberg tank failure**
  - **Ignored 2-year old Diablo Canyon canister conditions for cracking**
  - **Ignored frequent salt & high moisture, on-shore winds, surf & fog**

[1] Power Plant Operating Experience with SCC of Stainless Steel, Slide 9, NRC, D. Dunn, August 5, 2014 *http://pbadupws.nrc.gov/docs/ML1425/ML14258A082.pdf*

[2] Electric Power and Research Institute (EPRI)

[3] Critique: EPRI Flaw Growth and Flaw Tolerance Assessment for Dry Cask Storage Canisters, D. Gilmore, May 7, 2015

https://sanonofresafety.files.wordpress.com/2013/06/epri-critiqueandkoebergplant2015-05-17.pdf

Inspecting thin canisters “not a now thing” – NRC Mark Lombard

- **Thin canisters can crack. The ability to detect cracks or the depth of cracks is “not a now thing.”**

  Mark Lombard, NRC Director of Spent Fuel Management Division, speaking at October 6, 2015 California Coastal Commission meeting. https://youtu.be/QtFs9u5Z2CA

- **NRC approves licenses & renewals with only vendor promises of future solutions**

Not feasible to REPAIR thin canisters – Kris Singh, Holtec canister vendor

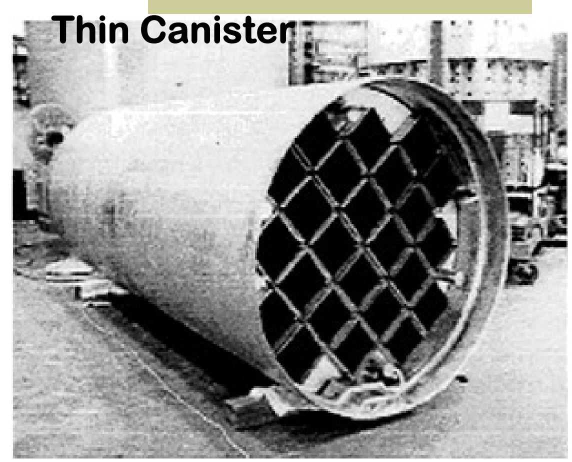
"if that canister were to develop a leak, let's be realistic; you have to find it, that crack, where it might be, and then find the means to repair it. You will have, **in the face of millions of curies of radioactivity coming out of canister**; we think it's not a path forward…A canister that develops a microscopic crack (all it takes is a microscopic crack to get the release), to precisely locate it…

And then **if you try to repair it (remotely by welding)…the problem with that is you create a rough surface which becomes a new creation site for corrosion down the road**. ASME Sec 3. Class 1 has some very significant requirements for making repairs of Class 1 structures like the canisters, so I, as a pragmatic technical solution, I don't advocate repairing the canister." **10/14/2014 Edison Community Engagement Panel https://youtu.be/euaFZt0YPi4**

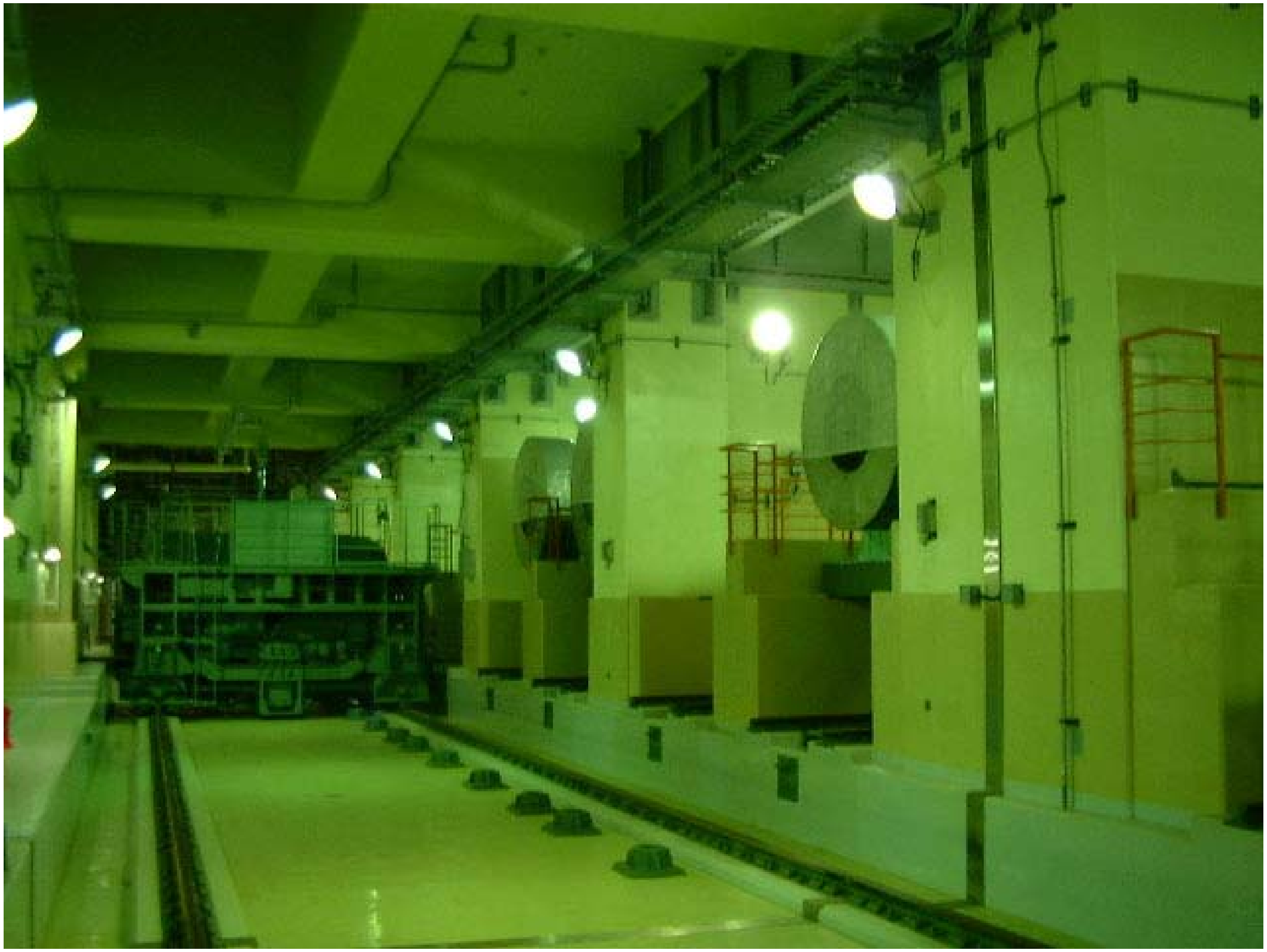
Note: Holtec warrants for UMAX thin canister system for 10 years on the concrete base and 25 years for the thin canister.

North Anna reduced safety with change from thick casks to thin canisters

Safety features	Thin canister NUHOMS 32PTH	Thick cask TN-32
Thick walls	1/2”	10”
Won’t crack		√
Maintainable		√
Repairable (replace seals)		√
Inspectable		√
Early leak detection		√
Defense in depth		√
Gamma/neutron barrier	with vented concrete overpack	√
Transportable design	Not if cracked; Requires thick cask	√
Retrievable fuel (bolted lid)	welded lid	√



Fukushima thick casks survived earthquake and tsunami

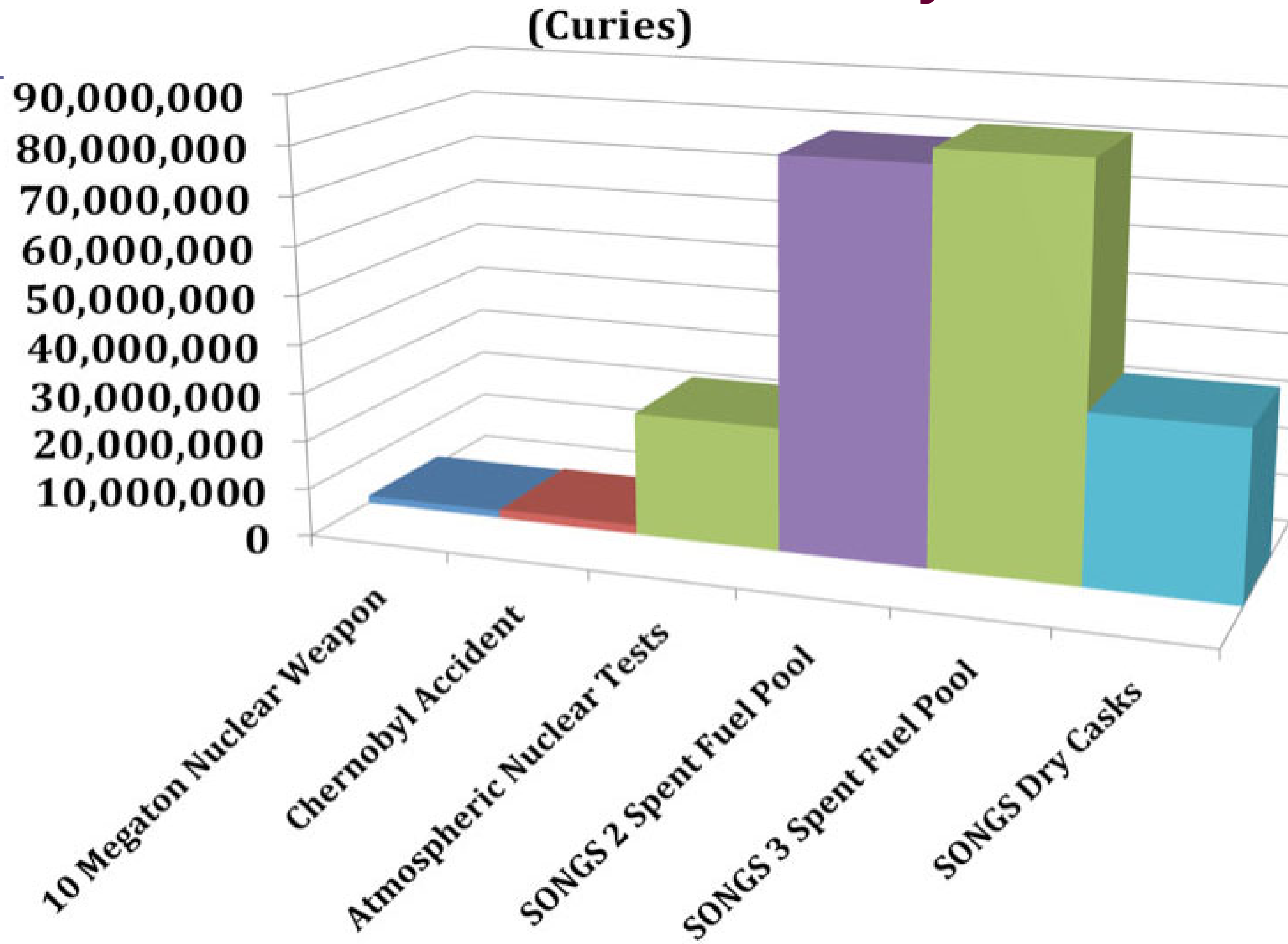


German interim storage provides additional environmental protection

NRC initial license excludes aging Renewal based on vaporware

- **Ignores issues that may occur after initial 20 year license, such as cracking and other aging issues**
- **Refuses to evaluate thick casks unless vendor applies**
- **NRC NUREG-1927 Rev 1 draft for license renewal:**
  - **Requires first canister inspection after 25 years**
    - Allowing **5 years** to develop inspection technology
  - **Requires inspection of only one canister per plant**
    - That same canister to be inspected **once every 5 years**
  - **Allows up to a 75% through-wall crack**
- **No seismic rating** for cracked canisters & **not transportable**
- **No viable repair or replacement plan for cracked canisters**
  - Approves destroying fuel pools after emptied
  - No money allocated for replacing canisters. (Minimum $1.5 million per canister. Includes $1 million canister + $200,000 disposal + $300,000 load and unload). http://www.gpo.gov/fdsys/pkg/FR-2012-04-04/html/2012-8114.htm

More Cesium-137 than Chernobyl release



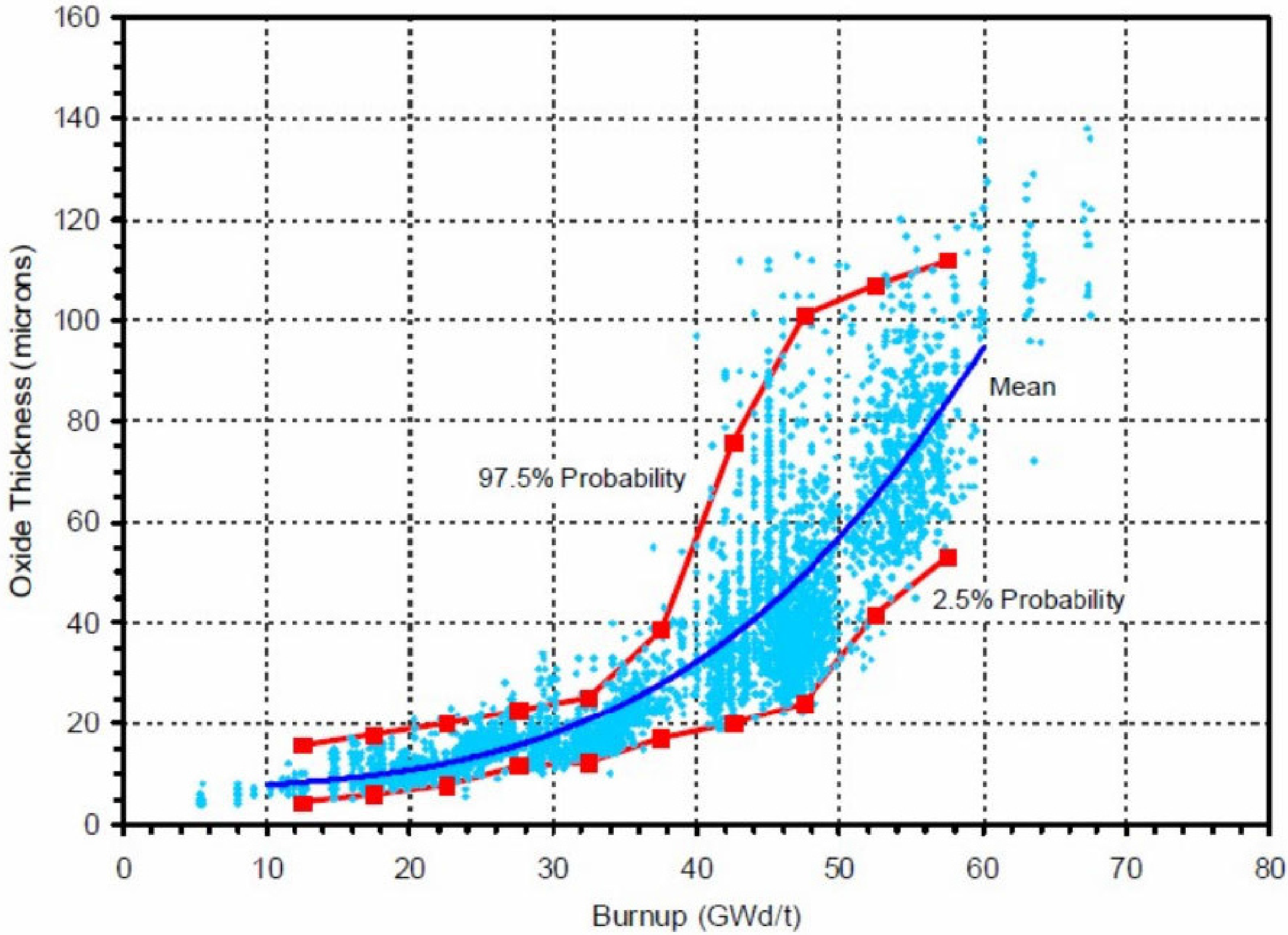
http://libcloud.s3.amazonaws.com/93/22/3/3024/SONGS_Spent_Fuel_FINAL.pdf

High burnup fuel cladding continues to degrade after dry storage

"the trend of the data generated in the current work **clearly indicates that failure criteria for high-burnup cladding need to include the embrittling effects of radial-hydrides for drying-storage conditions that are likely to result in significant radial-hydride precipitation**...A strong correlation was found between the extent of radial hydride formation across the cladding wall and the extent of wall cracking during RCT [ring-compression test] loading."

Ductile-to-Brittle Transition Temperature for High-Burnup Zircaloy-4 and ZIRLO™ Cladding Alloys Exposed to Simulated Drying-Storage Conditions M.C. Billone, T.A. Burtseva, and Y. Yan, Argonne National Laboratory September 28, 2012.
http://pbadupws.nrc.gov/docs/ML1218/ML12181A238.pdf

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

Recommendations

CASTOR® - Type V/19 cask

- Stop procurement of thin steel canisters
- Don’t buy vendor promises of future capabilities (vaporware)
- Obtain bids from thick cask vendors
  - Vendors won’t request NRC license unless they have customer
  - NRC licensing takes 18 to 30 months and costs millions of dollars
- Require best technology available internationally
  - Maintainable, inspectable, repairable, no cracking, replaceable parts.
  - Continuous early warning monitoring prior to radiation leaks
  - Redundant systems, defense in depth, transportable
  - Store in hardened concrete buildings
- Cost-effective for longer term storage and transport
- Require empty pool to retrieve fuel assemblies to transfer to new casks or replace failed canister/cask
- Require on-line radiation monitoring with public access

More Information and Sources

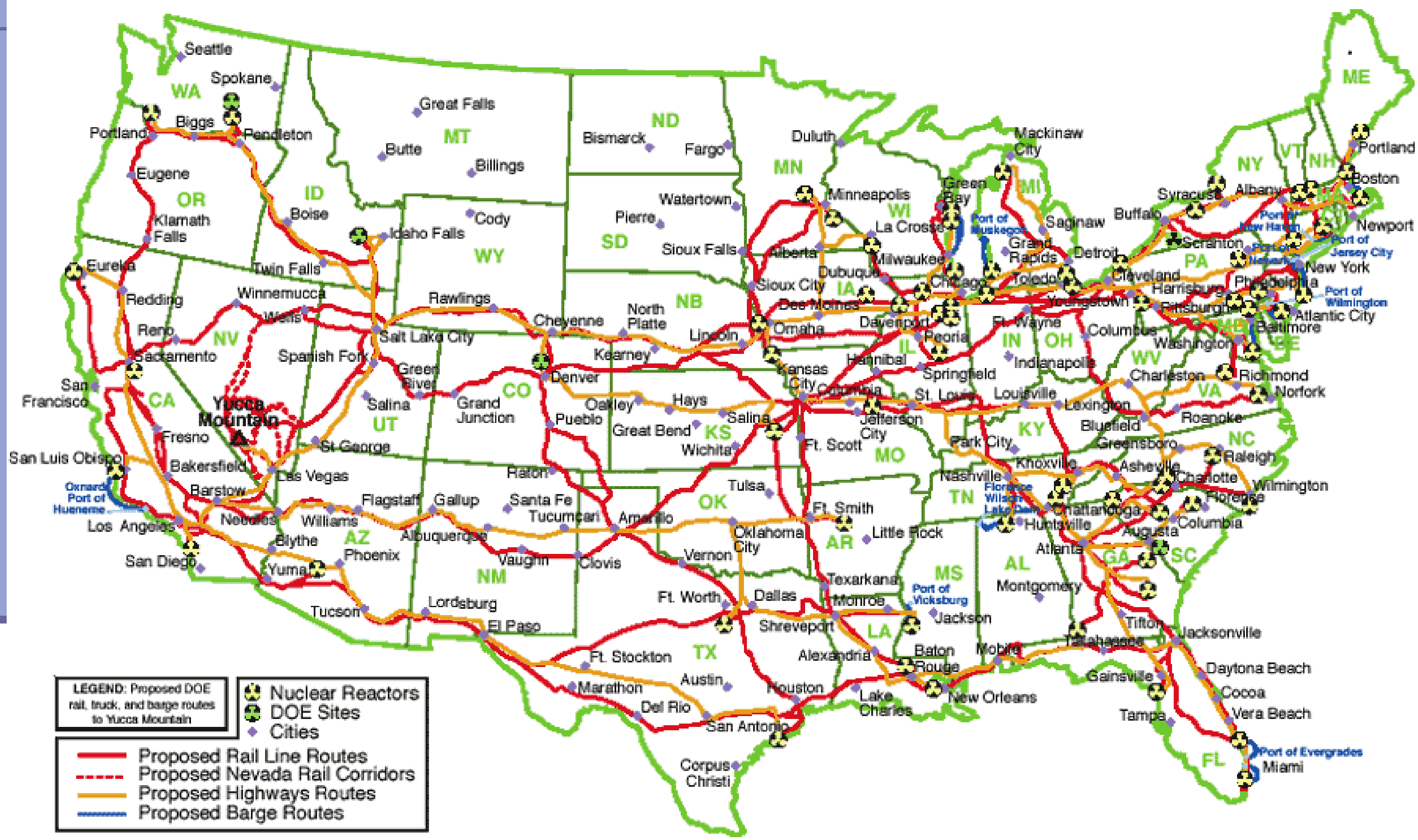
- Erica Gray veggielady@yahoo.com
- Donna Gilmore dgilmore@cox.net
- SanOnofreSafety.org

Additional Slides

Roadblocks to transporting waste

- **Transport problems:** Infrastructure issues, no funding, existing canisters may be cracking, daily accident risks, no adequate emergency plans for accidents, high burnup fuel unstable in transport
- **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 hotter, unstable & more radioactive high burnup fuel
  - Numerous technical, legal and political issues unresolved
  - No other geological sites being considered by Congress
- **Interim storage sites unlikely for decades, if ever**
  - No funding source, technical, legal & political challenges
  - Communities do not want the waste; tried numerous times before and failed
  - U.S. military, California & other states do not want the waste
- **No safe waste solutions & broken promises**
  - WIPP repository leaked in 15 years, currently closed; broken promises to New Mexico
  - Hanford, Savannah River, Nevada Nat. Security & other sites leak – broken promises
  - No state authority over problems; cheaper rather than safer solutions
  - Waste creep – more waste & waste types stored than promised
  - Fuel assemblies damaged after storage may not be retrievable
  - Identification of damaged fuel assemblies imperfect

Proposed rail, highway and barge routes to Yucca Mountain (2002)



No warning before radiation leaks from thin canisters

- **No early warning monitoring**
  - Remote temperature monitoring not early warning
  - No pressure or helium monitoring
  - Thick casks have continuous remote pressure monitoring – alerts to early helium leak
- **No remote or continuous canister radiation monitoring**
  - Workers walk around canisters with a “radiation monitor on a stick” once every 3 months
  - Thick casks have continuous remote radiation monitoring
- **After pools emptied, NRC allows**
  - **Removal of all radiation monitors**
  - **Elimination of emergency planning to communities** – no radiation alerts
  - **Removal of fuel pools** (assumes nothing will go wrong with canisters)

Condition of existing canisters unknown

- **No technology exists to inspect canisters for cracks**
  - Most thin canisters in use less than 20 years
- **Won't know until AFTER leaks radiation**
- Similar steel components at nuclear plants **failed in 11 to 33 years** at ambient temperatures ~20°C (68°F)
- **Crack growth rate about four times faster** at higher temperatures
  - 80ºC (176°F) in "wicking" tests compared with 50°C (122°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 – chloride salts won't stay and dissolve on canister
- **Many corrosion factors not addressed**. NRC focus is chloride-induced stress corrosion cracking (CISCC).

Thick cask advantages


CASTOR® - Type V/19 cask

- **Market leader internationally**
- **Maintainable**
  - No cracking or significant corrosion*
  - Inspectable, repairable, replaceable parts (metal seals, lids, bolts)
  - 40 years in service with insignificant material aging*
  - Thick cask body − steel up to 10” or DCI* up to 20”
  - ASME & international quality cask certifications for storage & transport*
- **Redundancy – no single point of failure**
  - Two independently bolted thick steel lids, each with double seals*
  - Can reload fuel without destroying cask
- **Early warning before radiation leak**
  - Continuous remote lid pressure monitoring
- **Permanent storage option with added welded lid***
- **Thick casks protect from all radiation, reducing cost & handling**
  - No concrete overpacks required
  - No steel transfer and transport casks required
  - Used for both storage and transportation (with transport shock absorbers)
- **Store in concrete building for additional protection**
- **Vendors won’t request NRC license unless they have customer**
  - NRC license requires 18 to 30 month and millions of dollars

* Ductile cast iron (DCI)

Fukushima thick casks

Specification of Dry Casks

	Large type	Medium type	
Weight (t)	115	96	
Length (m)	5.6	5.6	
Diameter (m)	2.4	2.2	
Assemblies in a cask	52	37	
Number of casks	5	2	2
Fuel type	8 x 8	8 x 8	New 8 x 8
Cooling-off period (years)	> 7	> 7	> 5
Average burn-up (MWD/T)	<24,000	<24,000	<29,000

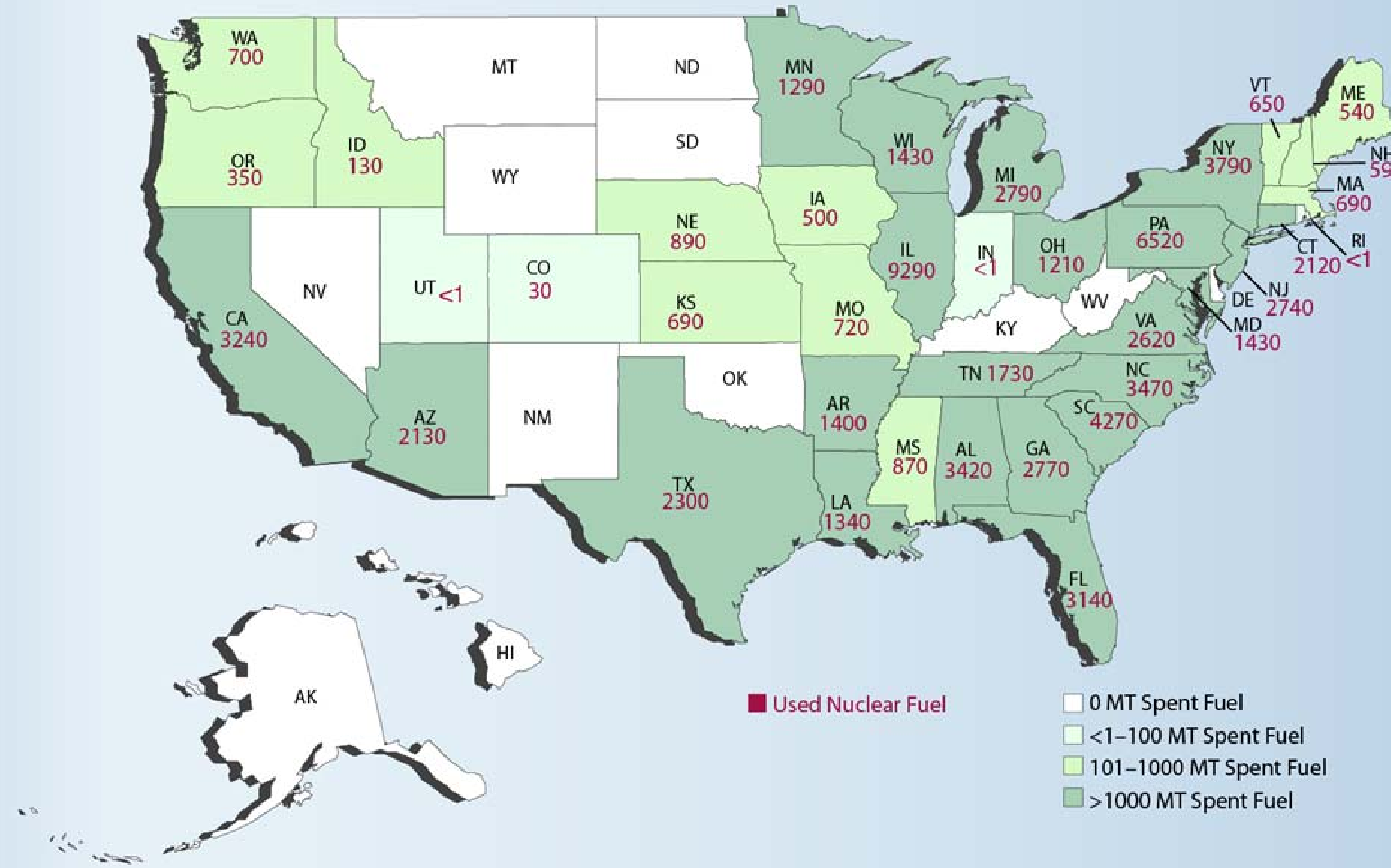
Additional 11casks are being prepared for installation.

Sandia Labs: Ductile cast iron performs in an exemplary manner

- **Safe from brittle fracture in transport**
  - …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.
- **Exceeds drop test standards**
  - …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**.**
- **Exceeds low temperature requirements**
  - 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**
  - *Fracture Mechanics Based Design for Radioactive Material Transport Packagings Historical Review*, Sandia Labs, SAND98-0764 UC-804, April 1998 http://www.osti.gov/scitech/servlets/purl/654001

Used Nuclear Fuel in Storage

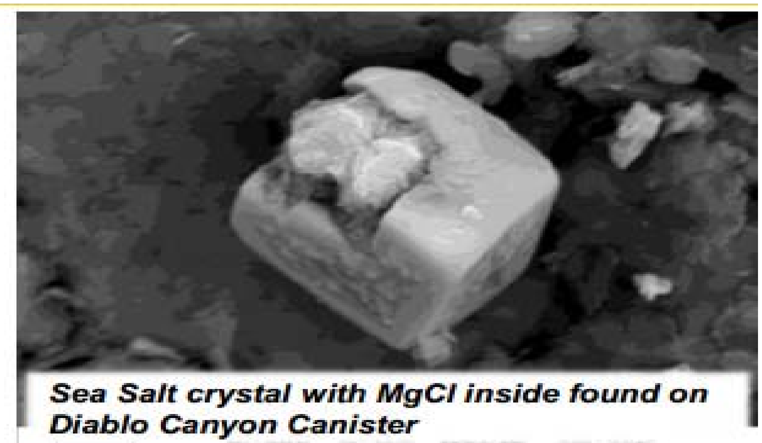
(Metric Tons, End of 2013)



NEI
NUCLEAR ENERGY INSTITUTE

Two-year old Diablo Canyon Holtec canister has conditions for cracking

- **Temperature low enough to initiate cracks in 2 years <85°C (185°F)**
- **Moisture dissolves sea salt – trigger for corrosion and cracking**
- **Only small surface area of two canisters sampled Jan 2014**
  - Sampled temperature and part of surface for salt and other surface contaminants, due to limited access via concrete air vents
- **Canisters not repairable & millions of curies of radiation would be released from even a microscopic crack**
  - Holtec CEO Dr. Singh,10/14/2014 http://youtu.be/euaFZt0YPi4
- **No plan in place to replace cracked canisters**



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
- Potential problem unloading fuel from a dry storage canister or cask into a pool with existing fuel

No defense in depth in thin canisters

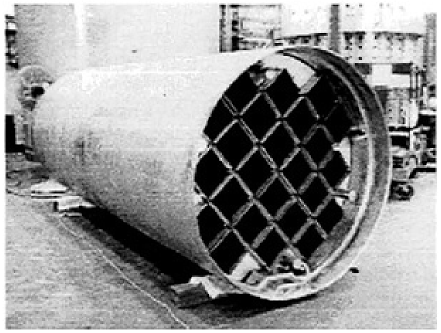
- **No protection** from gamma or neutron radiation in thin canister
  - **Vented** concrete overpack/cask required for gamma & neutrons
  - **No other type of radiation protection if thin canister leaks**
  - Thick steel overpack transfer cask required to transfer from pool
  - Thick steel overpack transport cask required for transport
- **High burnup fuel (HBF)** (>45 GWd/MTU)
  - Burns longer in the reactor, making utilities more money
  - Over twice as radioactive and over twice as hot
  - Damages protective Zirconium fuel cladding even after dry storage
  - Unstable and unpredictable in storage and transport
- **Limited technology** to examine fuel assemblies for damage
- **Damaged fuel cans** vented so no radiation protection
  - Allows retrievability of fuel assembly into another container

Thin canisters not ASME certified

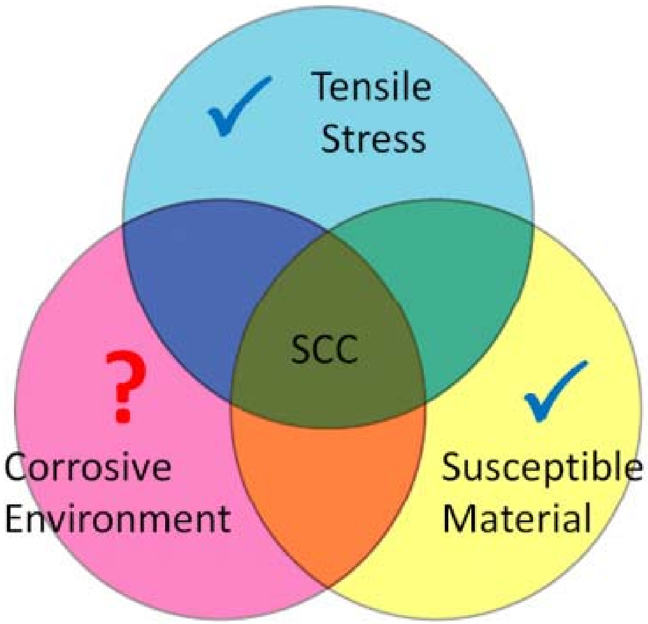
- Canisters do not have independent quality certification from American Society of Mechanical Engineers (ASME)
- NRC allows exemptions to some ASME standards
- No independent quality inspections
- ASME has not developed standards for spent fuel stainless steel canisters
- Quality control has been an issue with thin canisters

Problems with thin stainless steel canisters

- **Not maintainable**
  - Cannot inspect exterior or interior for cracks
  - Cannot repair cracks
  - Not reusable (welded lid)
- **No warning BEFORE radiation leaks**
- **Canisters not ASME certified**
- **NRC allows exemptions from ASME standards**
- **No defense in depth**
  - Concrete overpack vented
  - Unsealed damaged fuel cans
  - No adequate plan for failed canisters
- **Early stress corrosion cracking risk**
- **Inadequate aging management plan**



Stress Corrosion Cracking Background Information



2/3 of the requirements for SCC are present in welded stainless steel canisters

- 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

Power Plant Operating Experience with SCC of Stainless Steels

U.S.NRC
United States Nuclear Regulatory Commission
Protecting People and the Environment

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

- CISCC growth rates of 0.11 to 0.91 mm/yr for components in service
  - Median rate of 9.6×10^{-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)

Used Fuel Disposition

Data Gap Summarization

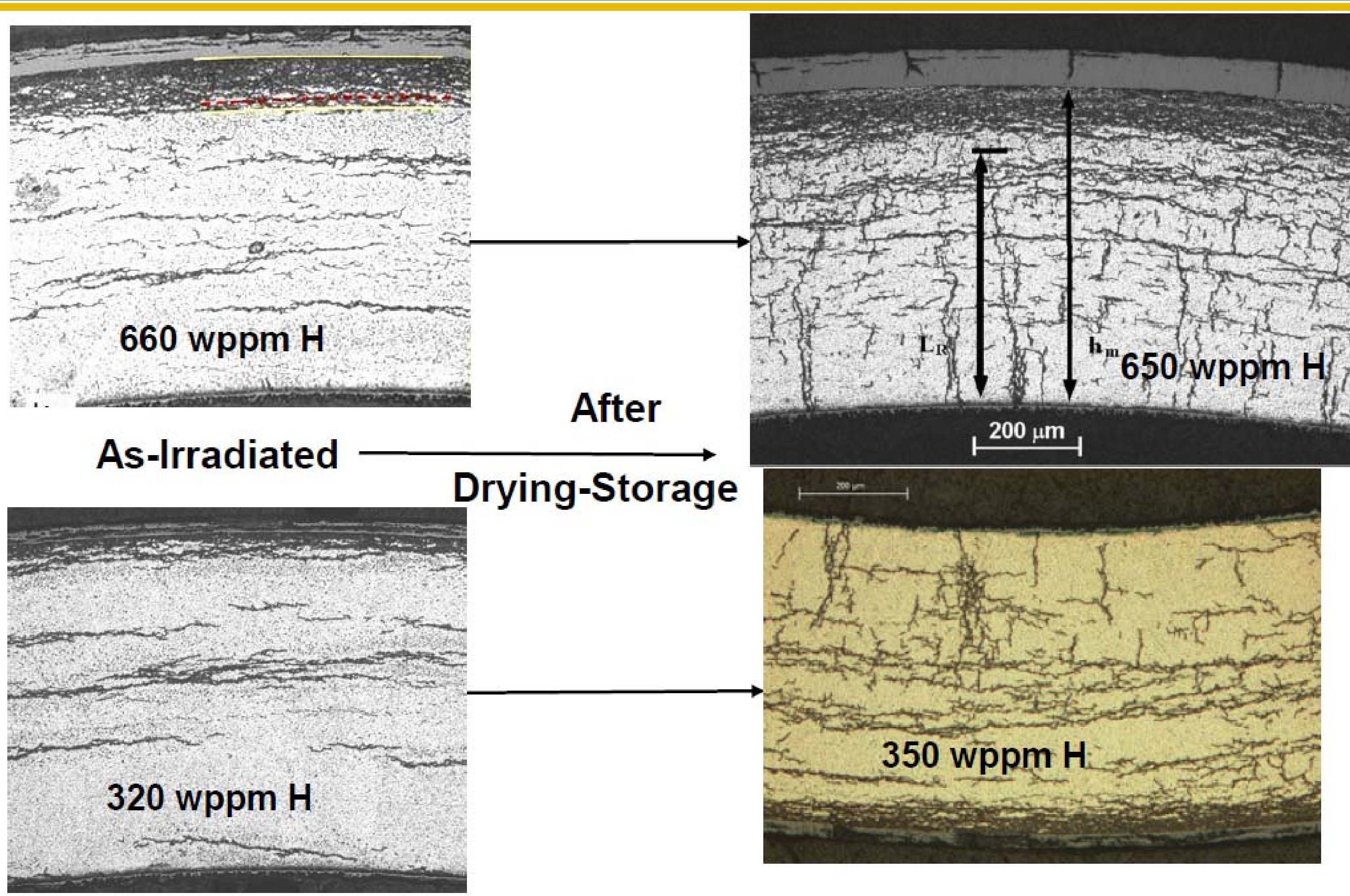
Gap	Priority	Gap	Priority
Thermal Profiles	1	Neutron poisons – Thermal aging	7
Stress Profiles	1	Moderator Exclusion	8
Monitoring – External	2	Cladding – Delayed Hydride Cracking	9
Welded canister – Atmospheric corrosion	2	Examination of the fuel at the INL	10
Fuel Transfer Options	3	Cladding – Creep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

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

U.S. DEPARTMENT OF ENERGY

Nuclear Energy

Introduction: Circumferential and Radial Hydrides in HBU Cladding



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

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 GWd/MTU
  - 7 years – Robinson (since 2005) up to 56.9 GWd/MTU
  - 6 years – Oconee (since 2006) up to 55 GWd/MTU
  - <4 years for most – up to 53.8 GWd/MTU
- ~ 200 loaded-casks contain high burn-up fuel
- Most fuel in pools for future loading is high burn-up

1) Since 1992, allowable burn-up to 47 GWd/MTU, since 2010, up to 52 GWd/MTU
2) All high burn-up fuel is in damaged fuel cans

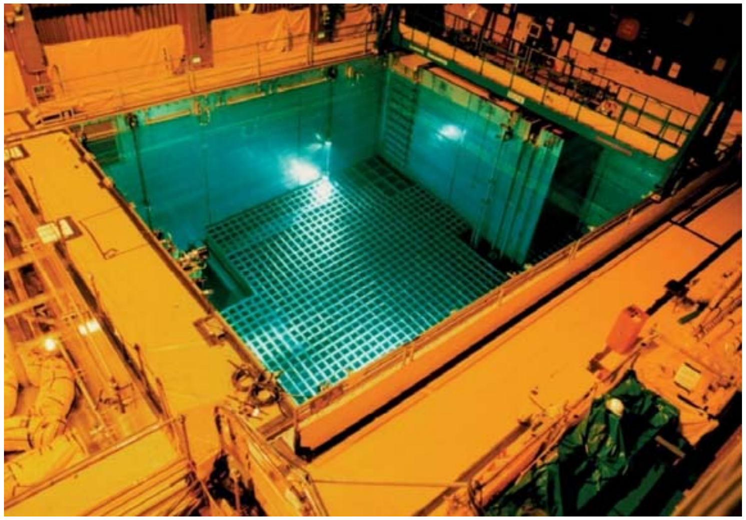
Thin canisters cannot be inspected

- **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
  - Air pollution can trigger corrosion & cracking
  - Microscopic scratches from insects & rodents
- **Thick casks can be inspected**
  - Provide full radiation barrier without concrete
  - Surfaces can be inspected
  - Not subject to stress corrosion cracking


Collecting dust samples at Diablo Canyon

Pools are needed to retrieve fuel assemblies and to replace casks/canisters

- **Pools are only method to replace failed canister**
  - Dry transfer systems not available
  - Nesting failed canisters (like Russian dolls) does not fix problem, is expensive & not NRC approved
- **Pools already destroyed at some decommissioned plants**
- **No funds to replace pools**



SCE wants over $1 billion for new thin canister system at San Onofre

- **Holtec UMAX underground system is experimental**
- **Never used anywhere in world**
  - 2008 Humboldt Bay underground system **not** similar, yet water intrusion despite no vents
- **Not NRC approved**
  - Needs seismic evaluation
- **NRC license ignores aging over 20 years**
- **Known problems with underground systems (corrosion, moisture, limited inspection)**
  - Higher corrosion from ground chemicals and moisture
  - Higher corrosion in marine environments
  - Inspection & repair technology limited or not possible
  - Flooding and moisture risks
  - More likely to overheat in low or no wind conditions