SNF Drying Evaluation + Recent Operating Experience

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Disclaimer

NRC staff views expressed herein do not constitute a final judgment or determination of the matters addressed or of the acceptability of any licensing action that may be under consideration at the NRC.

Outline

- Background
  - Regulatory requirements and NRC guidance
- Drying Evaluation
  - Objectives
  - Residual Water
  - Evaluation Constraints
  - Results
- Conclusions
- Recent Operating Experience

Requirements / Guidance

- Fuel-specific:
  - 10 CFR 72.44(c), 72.122(h)(1), 72.122(l)
- Performance/DSS-specific:
  - 10 CFR 72.122(h)(5), 72.124(a), 72.128
- NUREG-1567/ NUREG-1536, Rev. 1
- ISG-1, Rev. 2
- ISG-2, Rev. 2
- ISG-11, Rev. 3

Drying / Residual Water

NUREG-1536, Rev. 1

- ~0.43 gram-mole residual water expected (PNL-6365)
- Maximum cladding temperature of 400 °C [752 °F]
- Drained of as much water as practicable
- ≤ 4.0×10^{-4} MPa [3.0 Torr, 0.058 psi], 30 min
- He gas backfill
- Alternative methods (e.g. FHD) allowed
  - justified cover gas moisture and impurity levels

Drying Evaluation

- Evaluate potential impacts of incomplete drying process
  – Technical support in MAPS Report [20 – 60 yrs]
- Consider uncertainties in potential impacts
  – Assess regulatory bases for extended storage [300-yr timeframe]
- Evaluation considers:
  – residual water
  – environmental factors (temperature and relative humidity)
  – water radiolysis kinetics
  – oxidation kinetics

Residual Water

- Unbound (free)
  - Ice, trapped water, water vapor
- Physisorbed
  - Partial removal during drying process
- Chemisorbed
  - Hydroxides/hydrates (native oxides/corrosion)
  - Complete removal difficult (ASTM C1533-08)
  - More significant contribution

Residual Water

- Water vapor

Backfill Pressure	Cask Volume (3000 L)	Cask Volume (7000 L)
3 Torr (0.06 psi)	0.4 mol (6.7 mL)	1.1 mol (30.3 mL)
15 Torr (0.29 psi)	1.9 mol (33.4 mL)	5.7 mol (101.7 mL)

- Water-logged fuel rods (5-10 mL / breached rod)

Breach Rate	Breached Rods (per 5000)	Residual Water
0.01 %	1	5 – 10 mL
0.1 %	5	25 – 50 mL
1 %	50	250 – 500 mL

Residual Water

- Chemisorbed water
  - Analog estimate based on Al-based cladding
  - Uncertainties in estimates
    - Content/distribution of Zr-hydroxides/hydrates
    - Time/Temperature decomposition fraction
    - Geometrical effects (hairline cracks, pinholes, temperature gradient)
    - Limited stability data under storage conditions
  - Outside of Scope

Evaluation Assumptions

- CASTOR V21, VSC-17
  - 15×15 PWR Fuel (21 assemblies)
  - 2,100 L void volume
- Dried per NUREG-1536
- He-backfilled (1 atm)
- Leak-tight
- Operating experience (in-reactor/wet storage)
  - up to 1.0 % breached rods

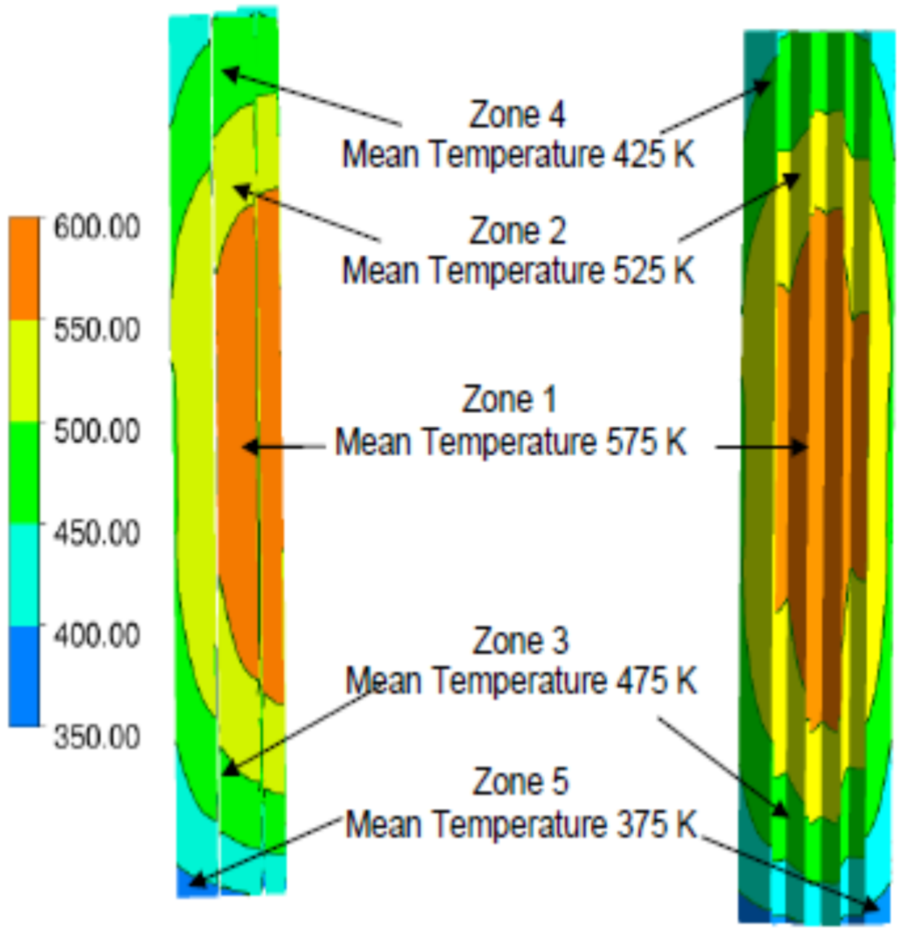
Environmental Conditions

Radiation Dose Rate	Initial Cladding Temperature	Residual Water Amount		
HIGH	HIGH	5.5 moles 0.1 Liter	17.4 moles 0.3 Liter	55 moles 1 Liter
	LOW			
LOW	HIGH			
	LOW			

	Initial Cladding Temperature	Temperature Decay Constant	Radiation Dose Rate [Energy Deposition Rate]
HIGH	208 °C – 400 °C	0.064	10^3 Gy/h [10^{15} eV/g/s]
LOW	102 °C – 302 °C	0.023	10^2 Gy/h [10^{14} eV/g/s]

Temperature Profile

- Cask divided in 5 zones
  - Derived from ANSYS FLUENT CFD for reference cask/fuel
- Mean cladding temperature and RH calculated for each zone over time



Radiolysis

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- Hydrogen/oxygen generation
- Decomposition Rate: $R_D = R_{ED} \times m_{water} \times G_{water}$
- Residual water: $m_{water}(t) = m_0 \exp\left(-\frac{R_{ED} G_{water}}{N_A} t\right)$
- Two dose rates (energy deposition rates, R_{ED}) considered
  - Time constants of 4.8 and 71.6 years
- Recombination considered (20 chemical pathways)
  - Linear decomposition rate
  - Slow collision rate (~ 10^5 < decomposition rate)

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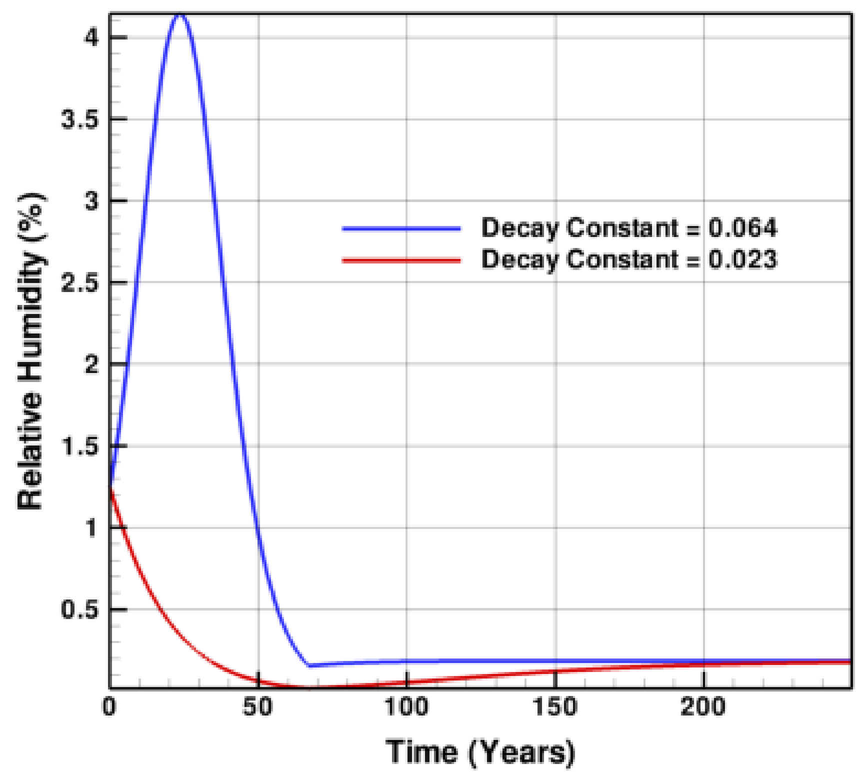
Relative Humidity

- Zone 5 – maximum potential for condensation
- Low RH (< than 5%) for most zone conditions
  - Conducive to cladding/ SNF matrix dry oxidation
- High RH – aqueous corrosion
  - Preferential at high residual water, low temperature, slow radiolysis

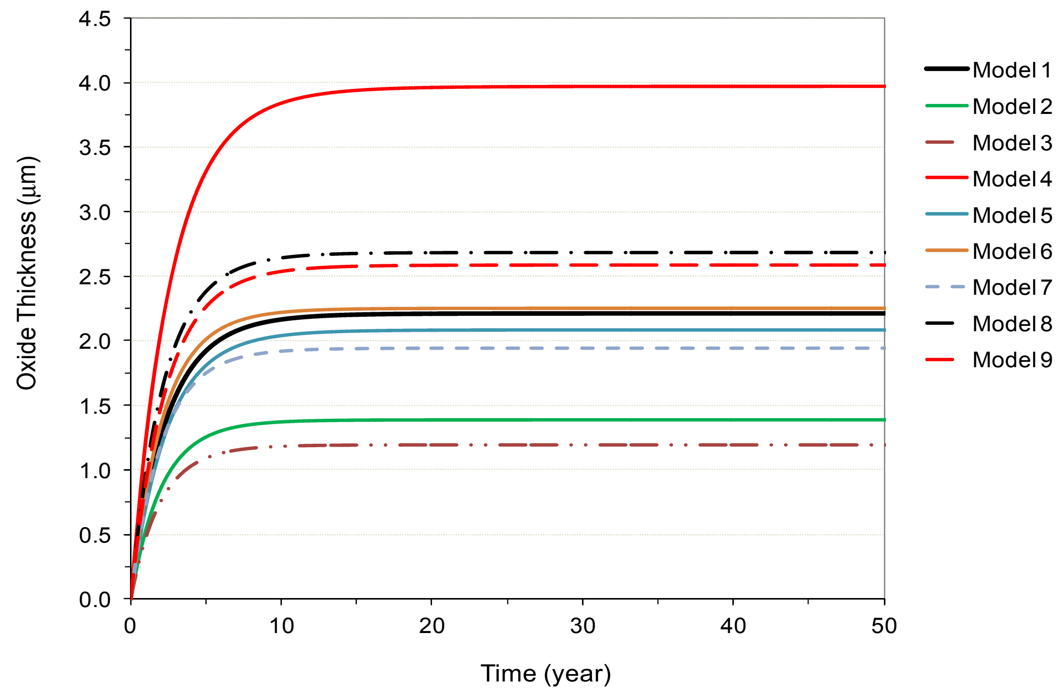


Cladding Oxidation

- 9 models evaluated (unlimited oxygen) varying temperature with time
- Insignificant cladding thinning (< 1%) for all 9 models
- Growth almost stops at ~ 10 years as temperature decreases
- Oxide growth further limited by radiolysis

$$Zr + O_2 = ZrO_2 \text{ (dry air)}$$

$$Zr + 2H_2O = ZrO_2 + 2H_2 \text{ (water/humid air)}$$



SNF Oxidation/Hydration

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- Two-step oxidation of LWR spent fuel: $UO_2 \rightarrow UO_{2.4} \rightarrow U_3O_8$
- Short conversion time to $UO_{2.4}$ or U_3O_8 at high temperatures by grain oxidation

Temperature	Relative Humidity	Primary Phase Considered
T ≥ 230 °C (T ≥ 446 °F)	Independent	U_3O_8
150 ≤ T < 230 °C (302 ≤ T < 446 °F)	RH < 40%	$UO_{2.4}$
	RH > 40%	U_3O_8
T <150 °C (T < 302 °F)	RH < 40%	$UO_{2.4}$
	RH > 40%	$UO3 \bullet xH_2O$ (x < 2)

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ISG-1, Rev. 2 (2007)

- **Damaged SNF**: any fuel rod or assembly that cannot fulfill its fuel-specific or system-related functions
- **Undamaged SNF**: can meet all fuel-specific and system-related functions
  - <u>Intact SNF</u>: not breached
  - <u>Breached SNF rod</u>:
    - *Pinhole leak or hairline crack*: not permit significant release of particulate matter
    - *Grossly-breached SNF rod*: any cladding breach greater than 1 mm [0.0394 in] in width

SNF Oxidation

- Increased hoop stresses due to 36% volume expansion from UO_2 to U_3O_8
- Threshold criterion:
  - 3.5 cm crack – propagation > 6.5% strain for 100% conversion to U_3O_8 (Einziger and Cook, 1985)
  - Pellets within a linear zone (3 cm beyond both ends) may oxidize to U_3O_8

SNF Oxidation

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- Estimated strains induced by different U_3O_8 conversion fractions assuming:
  - 3.5 cm (long) x 1 mm (wide) crack
  - a sphere shape of grain and isotropic dimensional change
- Linear increase in radius based on the grain size model

Conversion Fraction to U_3O_8, δ (no unit)	Volume Increase, ΔV (%)	Radius Increase (=Strain Induced), Δr (%)
1.00	36.0	10.8 (6.5 for LWR)
0.86	31.0	9.4
0.58	20.9	6.5
0.50	18.0	5.7 (2 for LWR)
0.25	9.0	2.9
0.20	7.2	2.3 (1 for LWR)
0.15	5.4	1.8

SNF Oxidation

Integrated Quantitative Model

- Estimate in each zone (temperature, RH):
  - Number of SNF rods and cladding surface area
  - Number of breached rods in each zone
  - Number of exposed SNF pellets and total surface area
    - Grain model (HIGH)
    - Fragment model (LOW)
- Divide storage time into time steps

SNF Oxidation

Integrated Quantitative Model

- Estimate in each time step:
  - Temperature
  - Amounts of oxygen and water consumed
    - Radiolysis kinetics (exponential / linear)
    - Oxidation kinetics
      - Cladding
      - Exposed pellets
  - Relative Humidity

SNF Oxidation

Integrated Quantitative Model

- Evaluated 5 cases - altering parameter values

Parameter	Value
SNF/cladding initial temperature	HIGH/LOW
Initial cladding failure	0.1, 0.01%
Radiolysis kinetics	Exponential or linear decomposition for either 4.77 or 71.62 years
Residual water amount	5.5, 17.4, 55 moles
Thermal decay constant	HIGH/LOW
Mode of oxygen contacting the fuel	Through grain boundaries or fragment surface

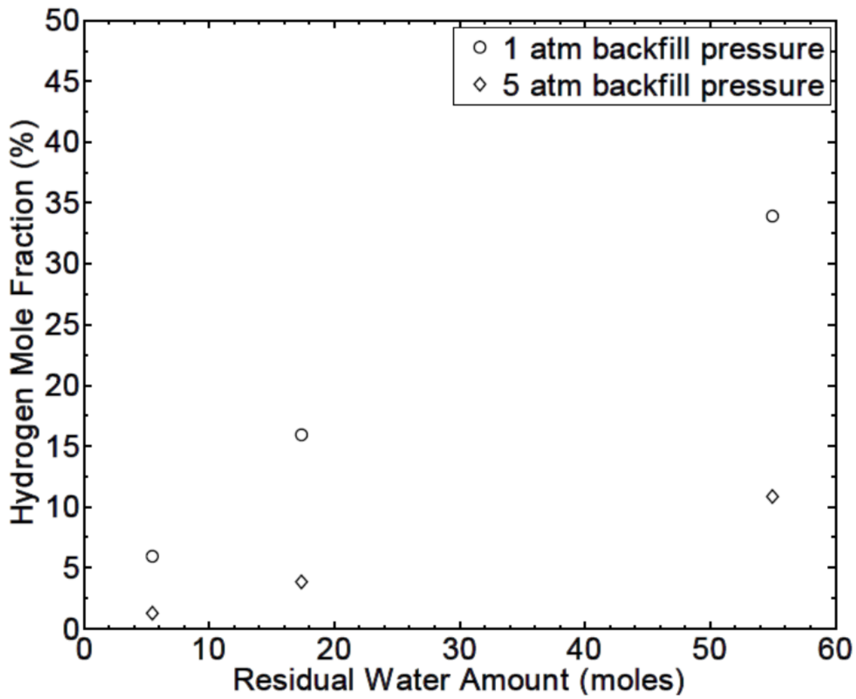
SNF Oxidation

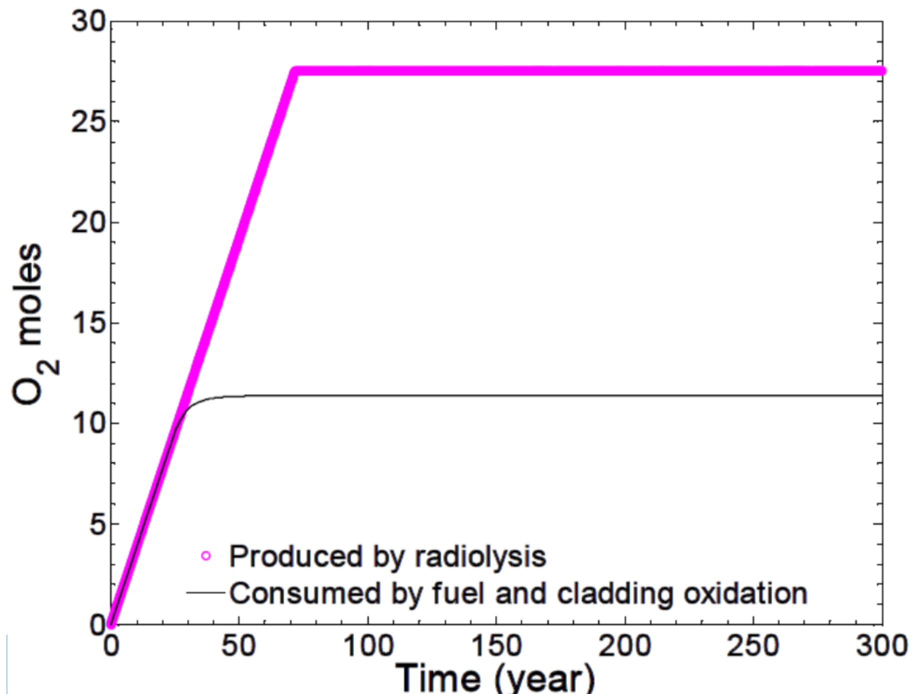
Results

- High Dose Rate (10^3 Gy/h)
  - Fast radiolysis kinetics (time constant, τ, 4.77 yrs)
  - Potential 100% U_3O_8 conversion (cladding unzipping) HIGH/LOW cladding temperatures (5.5, 17.4, 55 moles)
- Low Dose Rate (10^2 Gy/h)
  - Slow radiolysis kinetics (time constant, τ, 71.6 yrs)
  - Potential 100% U_3O_8 conversion (cladding unzipping) HIGH/LOW cladding temperatures (17.4, 55 moles)

Hydrogen Flammability

- NUREG-1609 – volume fraction flammable gases < 5%
- Oxygen partially consumed by cladding/SNF during first few decades
- Generated molecular hydrogen unreactive





Conclusions

- Cladding thinning (dry oxidation) is insignificant
- No significant over-pressurization from oxygen and hydrogen generated per studied residual water range
- Molecular hydrogen not significantly absorbed by SNF and internals – potential for accumulation depending on residual water
- Uncertainties in amount of residual water post-drying
  - SNF oxidation
  - Hydrogen/oxygen accumulation
- No immediate safety concerns – DOE HBU Fuel RPC

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Recent Operating Experience

Fuel Classification / Selection

- Ensure compliance with:
  - License / CoC Technical Specifications
  - 10 CFR 72.122(h)(1): *…spent fuel cladding must be protected during storage against degradation that leads to gross ruptures or the fuel must be otherwise confined… This may be accomplished by canning of consolidated fuel rods or unconsolidated assemblies or other means as appropriate*.
  - 10 CFR 72.122(l): *Storage systems must be designed to allow ready retrieval of spent fuel, . . . for further processing or disposal.*

Fuel Classification / Selection

ISG-1, Rev. 2 (2007)

An acceptable examination for a gross breach is a visual examination that has the capability to determine the fuel pellet surface may be seen through the breached portion of the cladding.

Alternatively, review of reactor operating records may provide evidence of the presence of heavy metal isotopes indicating that a fuel rod is grossly breached.

Fuel Classification / Selection

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- Fuel Qualification Testing
  - Visual inspection (PWR, BWR)
  - In-mast sipping (PWR)
  - Telescope sipping (BWR, PWR)
  - Mast sipping (PWR)
  - Vacuum can sipping (BWR, PWR)
  - Individual-rod (in-bundle) ultrasonic testing (UT) (PWR, BWR)
  - Individual-rod eddy current (EC)
  - Power suppression testing (BWR in-core)

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Fuel Classification / Selection

- Method reliability/accuracy for identifying gross ruptures
  - Licensees determine acceptability of testing method based on operating experience
- Arkansas Nuclear One (2014)
  - Noble gas release during drying
  - Visual Inspection/ UT/ In-Mast Sipping
  - GTRF cycles/ in-mast sipping not routine at defueling
  - Violation / Exemption Request
  - 10 CFR 71 implications

Fuel Classification / Selection

Additional noble gas releases:

- Standard Vacuum Drying
  - Surry (2008)
  - Millstone (2015)
  - Calvert Cliffs (2014, 2015)
- Forced Helium Dehydration
  - Arkansas Nuclear One
    - 2014 – Exemption Request
    - 2015

Fuel Classification/Selection

- Information Notice (Winter 2016)
  - Discuss operating experience and licensee-specific follow-up actions
  - Importance of fuel selection records
    - Reactor operating records
      - GTRF prevalent cycles
      - Data reliability/accuracy (QA program)
    - Assess need for secondary characterization
    - Assess need to limit acceptable testing methods
- ISG-1 Revision (NUREG-1536/NUREG-1567)

Acronyms

- Al: Aluminum
- ANSYS FLUENT CFD: thermal computer code
- ASTM: American Society for Testing and Materials
- atm: atmosphere
- BWR: boiling water reactor
- CASTOR V/21: dry storage system design
- CFR: *Code of Federal Regulations*
- cm: centimeter
- CoC: Certificate of Compliance
- EC: eddy current
- eV: electron volt
- FHD: forced helium dehydration
- g: gram
- GTRF: grid-to-rod fretting
- G_{water}: G-value of water (decomposition)
- Gy: Gray
- h: hour
- ISG: Interim Staff Guidance
- L: Liter
- LWR: light water reactor
- MAPS: Managing Aging Processes in Storage
- mL: milliliter
- mm: millimeter
- M_{water}: mass of water
- N_A: Avogadro's number
- NRC: Nuclear Regulatory Commission
- psi: pounds per square inch
- QA: Quality Assurance
- R_D: decomposition rate
- R_{ED}: rate of energy deposition
- RH: relative humidity
- s: second
- SNF: spent nuclear fuel
- t: time
- T: temperature
- UT: ultrasonic testing
- VSC: Ventilated Storage Cask
- Zr: Zirconium
- PWR: Pressurized Water Reactor

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