Nuclear Waste Management Strategy for Molten Salt Reactor Systems

Dr. Brian Riley and Dr. John Vienna

Pacific Northwest National Laboratory, USA

15 June 2022
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Meet the Presenters

**Dr. Brian Riley** has a PhD in Materials Science and Engineering from Washington State University. He is a Senior Materials Scientist in the Radiological Materials Group at PNNL and is a Technical Team Leader for the Waste Form Development Team. His research primarily focuses on salt waste form development and salt waste partitioning methods with funding from DOE Office of Nuclear Energy. Recently, Dr. Riley has been performing and leading research on various projects in these areas as well as looking at methods for treating salt wastes from molten salt reactor, as well as developing and testing sorbents for capturing volatile radionuclides such as iodine gas.

Email: brian.riley@pnnl.gov

**Dr. John Vienna** is a Laboratory Fellow in Materials Science at the Pacific Northwest National Laboratory (PNNL). He earned B.S. and M.S. degrees in Ceramics Engineering from Alfred University and a Ph.D. degree in Materials Science from Washington State University. Dr. Vienna joined PNNL in 1993. Throughout his career, has served in numerous technical leadership roles in nuclear waste management, including serving the U.S. Department of Energy’s Office of Nuclear Energy as a technical lead for nuclear waste treatment.

Email: john.vienna@pnnl.gov
Past and Current Collaborators

Funding – US Department of Energy (US DOE)
• DOE Office of Nuclear Energy (USA); K. Gray, S. Kung, B. Robinson
• National Technical Directors (USA) from Nat’l Labs:
  – Patricia Paviet (@PNNL – MSR Campaign)
  – Ken Marsden (@INL – MRWFD and JFCS)

Collaborations
• Oak Ridge National Laboratory (USA) – J. McFarlane, G. DelCul, C. Contescu, K. Myhre, H. Andrews
• Idaho National Laboratory (USA) – S. Frank, K. Marsden, T. Todd
• Argonne National Laboratory (USA) – W. Ebert, S. Stariha
• Rensselaer Polytechnic Institute (USA) – J. Lian
• University of Utah (USA) – M. Simpson
• University of Reno – Nevada (USA) – K. Carlson
• Washington State University (USA) – J. McCloy
• Clemson University (USA) – M. Tang
• Korea Atomic Energy Research Institute (KAERI) (South Korea) – H.S. Park, K. Lee, Y.-Z. Cho
• Australian Nuclear Science and Technology Organisation (Australia) – L. Vance, D. Gregg
• National Nuclear Laboratory (UK) – J. Turner, M. Harrison
• University of Sheffield (UK) – N. Hyatt
Overview of Presentation

1) MSR Overview (High Level)
2) Waste types from MSRs
3) Off-Gas Treatment and Monitoring Examples
4) Waste Form Examples
5) Other Considerations
6) Summary and Conclusions
MSR OVERVIEW
(HIGH LEVEL)
Examples of Salt Compositions for Two-Salt Concepts

• Types
  – Burner reactors vs breeder reactors
  – Thermal spectrum vs fast spectrum

• Salt compositions
  – Fluorides or chlorides are most often discussed but other options exist

• Common abbreviations you might see in the literature
  – FLiBe = $^7\text{LiF-BeF}_2$
  – FLiNaK = LiF-NaF-KF

<table>
<thead>
<tr>
<th>Reactor Type</th>
<th>Neutron Spectrum</th>
<th>Molten Salt Application</th>
<th>Reference Salt Systems</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mole Salt Breeder Reactor</td>
<td>Fast</td>
<td>Secondary coolant</td>
<td>$^7\text{LiF-BeF}_2$, AnF$_4$</td>
</tr>
<tr>
<td>Advanced High Temperature Reactor</td>
<td>Thermal</td>
<td>Primary coolant</td>
<td>$^7\text{LiF-BeF}_2$</td>
</tr>
<tr>
<td>Very High Temperature Reactor</td>
<td>Thermal</td>
<td>Heat transfer coolant</td>
<td>LiF-NaF-KF</td>
</tr>
<tr>
<td>Liquid Salt Cooled Fast Reactor</td>
<td>Fast</td>
<td>Primary coolant, Intermediate coolant</td>
<td>LiCl-NaCl-MgCl$_2$, NaNO$_3$-KNO$_3$</td>
</tr>
</tbody>
</table>

Courtesy Ted Besmann, MST TWG meeting 21 January 2022
MSR Salt Processing

- Fluorination/chlorination
- UF₆ purification/reduction
- Vacuum distillation
- Reductive extraction (Pa/Bi)
- Hydrofluorination
- Metal transfer process
- Electrolytic oxidation/reduction
- Oxide precipitation
- Selective crystallization
- Electrochemical separations

- Prepare fuel salt
- Separate Pa-233
- Remove fission products
- Remove corrosion products
- Recycle Cl-37
- Recycle Li-7
- Reduce waste volume
- Promote waste form production

WASTE TYPES FROM MSRs
Questions that Require Answers

• What streams should be considered?
• What do we know about the streams?
  – Do we know enough to determine treatment route?
  – Any challenges?
• Are there disposition pathways?
  – Restrictions on stream management (e.g., storage, treatment, packaging, disposal environment)?
• How would effluents be treated and disposed?
• Which streams require research?
  – Determine or estimate characteristics
  – Develop method or treatment of waste form
  – Identify potential restrictions or trade-offs with salt chemistry and processes
  – Generate data for MSR process models
Some of our Work Aimed to Help in These Areas

Identification of Potential Waste Processing and Waste Form Options for Molten Salt Reactors

Nuclear Technology Research and Development

Prepared for
U.S. Department of Energy
MSR Campaign
B. J. Riley(1), J. McFarlane(2),
G.D. DelCu(3), J.D. Vienna(4),
C.J. Contescu(5), L.M. Hay(6), A.V. Savino(7),
H.E. Atkins(8),
(1) Pacific Northwest National Laboratory
(2) Oak Ridge National Laboratory
August 15, 2018
NTRD-MSR-2018-003379, PNNL-27723

Source: https://info.ornl.gov/sites/publications/Files/Pub114284.pdf

Electrochemical Salt Wastef orm Development: A Review of Salt Treatment and Immobilization Options

Brian J. Riley(4)

Source: https://pubs.acs.org/doi/10.1021/acs.iecr.0c01357?ref=pdf

Molten salt reactor waste and effluent management strategies: A review

Brian J. Riley(4), Joanna McFarlane(2), Guillermo D. DelCu(3), John D. Vienna(9), Cristian I. Contescu(5), Charles W. Forsberg(2)

Source: https://doi.org/10.1016/j.nucengdes.2019.02.002

Molten salt reactors and electrochemical reprocessing: synthesis and chemical durability of potential waste forms for metal and salt waste streams

Krista Carlson(3), Levi Gardner(9), Jeremy Moon(4), Brian Riley(2), Jake Amoroso(5) and Dev Chidambaram(8)

Source: https://doi.org/10.1080/09506688.2020.1801229
General Streams – Output from PNNL/ORNL Report

- Decommissioning and Decontamination (D&D)
- Metal
- Off-gas
- Operating
- Carbon
- Spent salt
- Separated salt

Source: https://doi.org/10.1016/j.nucengdes.2019.02.002
Salt Streams: Challenges & Questions

- Halide immobilization is complicated
- $^{36}$Cl and $^{129}$I dose drivers for repository (require fractional release rates of ppm/year)
- Halogen impact on disposal site
- High doses from insanely short cooling
- Salt storage/transportation (radiolysis, dispersibility)
- Uncertain stream compositions and characteristics
- Isotopically enriched $^{37}$Cl and $^7$Li
  - Methods for enrichment
  - Costs of enrichment (favor recycle)
  - Methods for capture/recycle
  - Additional wastes produced?

Source: https://doi.org/10.1016/j.nucengdes.2019.02.002
Reactor Off-Gas Streams: Challenges/Questions

• Current U.S. regulations require $^{85}\text{Kr}$ capture and storage
  – $^{85}\text{Kr}$ gas storage is point source, high rad, high pressure, corrosive daughters
  – $^{85}\text{Kr}$ immobilization is expensive, low loading
• Acid gas capture in inert gas
• Salt mist/entrainment
• High-dose streams require holdup for decay (e.g., Xe)
• Recycle He back into the reactor
• Need to deal with $^3\text{H}$ partitioning and transportation (permeation through metallic reactor components)

Source: https://doi.org/10.1016/j.nucengdes.2019.02.002
Metal and Carbon Streams: Challenges/Questions

- Salt impregnation
- Deep penetration of radionuclides at equipment end of life
- High dose (from salt, gas penetration)
- Large portion could be GTCC*/HLW* due to activation products and embedded actinide salts
- Treatment options are challenging (metals) or impractical (graphite)
- Untreated durabilities questionable to poor (both graphite and many metals)
- Graphite recycle options might be plausible (next slide)

GTCC*: greater than class C
HLW*: high-level waste

Source: https://doi.org/10.1016/j.jnucmat.2013.05.043

Source: https://doi.org/10.1016/j.nucengdes.2019.02.002

5-metal (Mo+Pd+Rh+Ru+Tc) epsilon phase

Crum et al. (2016)
Potential for Carbon Recycle

- It is possible to recycle used graphite moderators from MSRs
- This could significantly reduce the carbon waste from graphite moderators
- Graphite will likely be very radioactive, complicating handling
- Eventually, at reactor end-of-life, it would have to be disposed

Burchell and Pappano
(ORNL/TM-2010/00169)

Source: https://doi.org/10.1016/j.nucengdes.2019.02.002
D&D and Operating Wastes: Challenges/Questions

- Potentially high doses (significant fractions GTCC)
- Potential for mixed LLW and mixed GTCC
- High volumes/masses
- Uncertain characteristics and amounts (mixed wastes?)
- Salt contaminated wastes challenge to dispose

Source: https://doi.org/10.1016/j.nucengdes.2019.02.002
Primary Gaps Identified – Proposed Next Steps

- Need more information on mass balances and compositions of expected wastes
- Need to develop initial functional and operational requirements (FOR) for MSR wastes
- Initiate off-gas treatment technology testing
- Investigate waste form options for salt-based waste streams
- Evaluate treatment options of contaminated carbon-based materials (i.e., graphite)

Some of this work is already being done through the US Department of Energy Office of Nuclear Energy (DOE-NE) Campaigns including:

- Material Recovery and Waste Form Development (MRWFD) (NE-4)
- Molten Salt Reactor (MSR) (NE-5)

Source: https://doi.org/10.1016/j.nucengdes.2019.02.002
OFF-GAS TREATMENT & MONITORING EXAMPLES
Molten Hydroxide Scrubber

- Potential non-aqueous scrubber option to remove halides, particulates, mists, and aerosols from process gas stream
- Would include delay bed for high-activity noble gases (e.g., neutronics poisons)
- Purge gas could be cleaned and sent back to the reactor

Source: https://doi.org/10.1016/j.nucengdes.2019.02.002

Concept by Bill Del Cul (ORNL)
Iodine Capture and Immobilization

- Solid sorbent systems utilizing chemisorption
  - Metal-impregnated zeolites for iodine (e.g., Ag, Bi, Cu)
  - Metal-impregnated silica-based gels (e.g., Ag, Bi, Cu)
- Fate after capture – they can be hot pressed into waste forms

**IPS I-loaded Ag⁰-aerogel**

**HIPed I-loaded sodalite**

**HIPed I-loaded AgZ (mordenite)**

*Work by:*
- Matyas, et al. (PNNL)
- Chong, et al. (PNNL) | Bruffey (ORNL)
- Bruffey (ORNL)

Source: [https://doi.org/10.1016/j.jnucmat.2020.152222](https://doi.org/10.1016/j.jnucmat.2020.152222)


HIP = hot isostatic pressing; SPS = spark plasma sintering
Noble Gas Capture

- Metal-Organic Frameworks (MOFs) can be used to separate Xe and Kr
  - Many MOFs have high Xe/Kr selectivities (>10×); very few have Kr/Xe selectivities
  - Separate MOFs can be used to pull out Xe in bed-1 followed by Kr in bed-2
- Cryogenic distillation can also be used for noble gas capture
In-Situ Off-Gas Monitoring

• Online monitoring can be used to track the species and concentrations in the off-gas streams
• Spectroscopic tools include
  – Raman
  – UV-VIS-NIR – ultraviolet-visible-near infrared
  – LIBS – laser-induced breakdown spectroscopy
• Analysis in gas phase, liquid phase, molten salt, etc.
• Species include $I_2(g)$, ICl, Xe, and hydrogen isotopes

Sources:
https://doi.org/10.1021/acs.est.0c06137
https://doi.org/10.1117/12.2557555
https://doi.org/10.1021/acs.jpca.0c07353

Work led by:
Lines, Bryan, et al. (PNNL)
McFarlane, Andrews, Myhre, et al. (ORNL)
WASTE FORM EXAMPLES
Waste Form Definitions

• Dehalogenation – halides are removed, salt cations are converted to another form (e.g., oxides, phosphates)

• Waste loading (WL) – mass fraction of waste in the waste form
  1) Full salt – direct immobilization of entire salt
  2) Salt cation loading – normalized parameter to compare waste forms on this basis despite how they are processed
  3) Salt cation oxide loading – mass of salt cation oxides in WF

• Storage volume – volume of final waste form required to immobilize starting salt mass

• Density – mass/volume; this affects storage volume of final waste form; effected by porosity

• Porosity – open/closed voids; some waste forms have porosity (e.g., GBS-CWF)

• Chemical durability – leach rate(s) in standardized accelerated leaching tests (e.g., PCT, C1308)
### Waste Form Types

- **Single-phase waste forms** – glass or crystalline material (e.g., REPO$_4$)
- **Multi-phase waste forms** – cermet (ceramic-metal), halmet (halide-metal), glass-bonded ceramic (e.g., glass-bonded sodalite), glass ceramic

**Source:** https://doi.org/10.1016/j.nucengdes.2019.02.002
## Types of Applicable Crystalline Matrices

<table>
<thead>
<tr>
<th>Mineral</th>
<th>Name</th>
<th>Halides</th>
<th>Alkalis</th>
<th>Alkaline Earths</th>
<th>Rare Earths</th>
<th>Actinides</th>
<th>Reference(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Fluorapatite</td>
<td>F</td>
<td>–</td>
<td>Ca</td>
<td>–</td>
<td>–</td>
<td>Lu et al. (2013)</td>
</tr>
<tr>
<td></td>
<td>BeF-apatite</td>
<td>F</td>
<td>Na</td>
<td>Be</td>
<td>–</td>
<td>–</td>
<td>Engel and Fischer (1990)</td>
</tr>
<tr>
<td></td>
<td>LiF-BeF₂ apatite</td>
<td>F</td>
<td>Li</td>
<td>Be, Ca</td>
<td>–</td>
<td>–</td>
<td>Lexa (1999)</td>
</tr>
<tr>
<td></td>
<td>Chlorapatite</td>
<td>Cl</td>
<td>–</td>
<td>Ca</td>
<td>–</td>
<td>–</td>
<td>Lu et al. (2013)</td>
</tr>
<tr>
<td></td>
<td>Iodoapatite</td>
<td>I</td>
<td>–</td>
<td>Ca</td>
<td>–</td>
<td>–</td>
<td>Cao et al. (2017)</td>
</tr>
<tr>
<td>Perovskite</td>
<td>Sn-Cl perovskite</td>
<td>Cl</td>
<td>Cs</td>
<td>–</td>
<td>RE</td>
<td>An</td>
<td>Scott et al. (2018)</td>
</tr>
<tr>
<td></td>
<td>Ca-Ti Perovskite</td>
<td>–</td>
<td>–</td>
<td>L</td>
<td>L</td>
<td>L</td>
<td>Vance et al. 2006)</td>
</tr>
<tr>
<td>Phosphate</td>
<td>Spodiosite</td>
<td>Cl, F</td>
<td>–</td>
<td>Ca</td>
<td>–</td>
<td>–</td>
<td>Donald (2010)</td>
</tr>
<tr>
<td></td>
<td>RE-Monazite</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>RE</td>
<td>–</td>
<td>Boatner et al. (1980)</td>
</tr>
<tr>
<td></td>
<td>An-Monazite</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>An</td>
<td>Van Emden et al. (1997)</td>
</tr>
<tr>
<td></td>
<td>Xenotime</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>RE</td>
<td>An</td>
<td>Van Emden et al. (1997)</td>
</tr>
<tr>
<td>Sodalite</td>
<td>Chlorosodalite</td>
<td>Cl</td>
<td>Li→K</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>Riley et al. (2017)</td>
</tr>
<tr>
<td></td>
<td>Wadalite</td>
<td>Cl</td>
<td>–</td>
<td>Ca</td>
<td>–</td>
<td>–</td>
<td>Mihajlovic et al. (2004)</td>
</tr>
<tr>
<td></td>
<td>Iodosodalite</td>
<td>I</td>
<td>Na</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>Chong et al. (2017)</td>
</tr>
<tr>
<td>Nesosilicate</td>
<td>Rondorfite</td>
<td>Cl</td>
<td>–</td>
<td>Ca, Mg</td>
<td>–</td>
<td>–</td>
<td>Mihajlovic et al. (2004)</td>
</tr>
<tr>
<td></td>
<td>Cancrinite</td>
<td>Cl</td>
<td>Na, K</td>
<td>Ca</td>
<td>–</td>
<td>–</td>
<td>Bonaccorsi et al. (1994)</td>
</tr>
<tr>
<td>Titanate</td>
<td>Zirconolite</td>
<td>–</td>
<td>–</td>
<td>L</td>
<td>L</td>
<td>L</td>
<td>Vance et al. (2006)</td>
</tr>
<tr>
<td></td>
<td>Perovskite</td>
<td>–</td>
<td>–</td>
<td>L</td>
<td>L</td>
<td>L</td>
<td>Vance et al. (2006)</td>
</tr>
<tr>
<td></td>
<td>Hollandite</td>
<td>–</td>
<td>L</td>
<td>L</td>
<td>L</td>
<td>L</td>
<td>Vance et al. (2006)</td>
</tr>
</tbody>
</table>

- “L” denotes that species could likely be incorporated (but not necessarily documented yet)
- “–” denotes that these species are unlikely to incorporate
- Primary issue is that salt must meet target stoichiometry of the crystal or additional reagents are needed

More information provided and original references provided here: [https://doi.org/10.1016/j.nucengdes.2019.02.002](https://doi.org/10.1016/j.nucengdes.2019.02.002)
Waste Form (WF) Graphical Representations

storage volume and waste loading

different ways to think about WL

Goals: maximize waste loading and minimize WF volume

Source: https://doi.org/10.1080/09506608.2020.1801229
Options for Partitioning to Remove Different Salt Components

- Full salt immobilization
- Salt partitioning options
- Immobilization of separate partitions

<table>
<thead>
<tr>
<th>Waste</th>
<th>Partially dehalogenated salt (e.g., REOCI)</th>
<th>Fully dehalogenated salt (e.g., REO₃)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Processes</td>
<td>a) phosphate process</td>
<td>b) USHYZ process</td>
</tr>
<tr>
<td></td>
<td>a) USHYZ process</td>
<td>c) LABS process</td>
</tr>
<tr>
<td>Wastefoms</td>
<td>a) Pb-Te-O glass</td>
<td>b) LABS glass</td>
</tr>
<tr>
<td></td>
<td>a) Pb-Te-O glass</td>
<td>b) LABS glass</td>
</tr>
<tr>
<td></td>
<td>a) Pb-Te-O glass</td>
<td>b) LABS glass</td>
</tr>
<tr>
<td></td>
<td>a) Pb-Te-O glass</td>
<td>b) LABS glass</td>
</tr>
</tbody>
</table>

**Partitioning process**
- a) vacuum distillation
- b) melt crystallization
- c) zone freezing/refining

**Final product(s)**
- a) CsCl (FP) removal
- b) ER electrolyte (LiCl) removal
- c) ER electrolyte (LiCl) removal

- a) vacuum distillation
- b) oxidative precipitation (Λ₅CO₃)
- c) reactive distillation (Λ₅PO₃)

- a) BaCl₂ remains
- b) (Ba, Sr)CO₃ precipitation

- a) REOCI/REO₃ mixtures
- b) REOCI/REO₃ mixtures
- c) REPO₄ mixtures

- a) An²⁺ (reduced at the cathode)
- b) AnCl₂ can be removed
- c) actinides dissolved in a solvent

- a) phosphate process
- b) USHYZ process
- c) SAP/U-SAP

- a) dehalogenated phosphate glass
- b) alkali-loaded Y-zeolite
- c) Li₃PO₄ droplets in silica-rich glass

Figure 1. Summary of partitioning processes and final products targeting alkalis (A⁺), alkaline earths (AE²⁺), rare earths (RE³⁺), actinides (An³⁺), and halides (Ha⁻) where the product(s) listed are those resulting from the partitioning process. These are described in more detail in subsequent sections.

Source: https://dx.doi.org/10.1021/acs.iecr.0c01357
Glass-Bonded Sodalite Ceramic Waste Form (GBS-CWF)

- Made from salt (no pre-partitioning of the salt), zeolite 4A, & glass binder
- Contains some porosity due to pressureless sintering process used for synthesis

Source: http://dx.doi.org/10.1016/j.jnucmat.2017.03.041
Source: https://doi.org/10.1007/s00269-020-01124-4
Iron Phosphate Waste Forms

• Salt is dehalogenated prior to WF fabrication
• Phase distribution upon slow-cooling is complex
• Low release rates during durability experiments

Quenched DPF WFs

Source: https://doi.org/10.1016/j.jnucmat.2019.151949
Iron Phosphate Waste Forms (continued)

- Five-zone furnace
- Cl is removed and collected as NH₄Cl in the off-gas system
- It is likely that this process could be used for defluorination of fluoride-salts
Ultrastable H-Y Zeolite Process (Dechlorination)

- Developed by Simpson, Bagri, Wasnik (Univ. Utah) and Carlson (UNR)
- Chloride salts are reacted with H-Y zeolite, Cl reacts with H to produce HCl, resulting product is immobilized in glass-bonded waste form
- Reaction times of 120 hours at 625°C estimated to yield 99% dechlorination

Source: https://pubs.acs.org/doi/10.1021/acs.iecr.9b02577

USHY zeolite particulates
(45-90 µm)

Dehalogenated particles

Fired pellets of products

Figure 5. Ion-exchanged samples (45–90 µm) at different times of ion exchange in the increasing order of reaction time from 0 to 6 h.

Source: https://pubs.acs.org/doi/10.1021/acs.iecr.9b02577

Wasnik, et al. (2019)
Tellurite Glass – A Potential Full Salt Option

- Most of the work at PNNL in this area has revolved around the 78%TeO$_2$-22%PbO (mass) glass system for different salt compositions:
  - KCl-LiCl + FPs
  - LiCl-Li$_2$O + FPs
  - RECl$_3$
  - REOCl
  - SrCl$_2$
- High-LiCl glasses show poor durability
- High-RE glasses show good durability
- Glasses are expensive to make (high cost of TeO$_2$)

RE = rare earth; FP = fission product(s)

Sources:
http://dx.doi.org/10.1016/j.jnucmat.2017.08.037
https://dx.doi.org/10.1021/acs.iecr.0c01357
Tellurite Glass – Full Salt Option

Most work done at 78/22 TeO\textsubscript{2}/PbO comp.

Phase separation at higher salt loadings

Leached layer increasing with time

Source: http://dx.doi.org/10.1016/j.jnucmat.2017.08.037
Fluoride Salt Waste Forms – Glass-Bonded CaF$_2$

- FLiNaK salt mixed with fission product simulant (alkali and alkaline earth nitrates, Sb$_2$O$_3$, MoO$_3$)
- Salt added to H$_3$BO$_3$, Al(NO$_3$)$_3$, Ca(OH)$_2$, and colloidal silica
- Mixed/heated to dry at 110°C and dried powder was calcined at 600°C
- Calcined powder was milled
- This product was cold pressed and sintered or processed with a hot isostatic press (HIP)
- Product has good chemical durability

- Most of the F partitions to CaF$_2$
- Some is left in the glass phase
- Fluoride loadings up to 7.2 mass% demonstrated
- Full waste loadings of 17-21 mass% achieved

Source: [https://doi.org/10.1111/jace.17293](https://doi.org/10.1111/jace.17293)

Work by: Gregg, Vance, et al. (ANSTO)
OTHER CONSIDERATIONS
Options for $^{37}\text{Cl}$ Recycle

- $^{37}\text{Cl}$ recycle is important to prevent neutron activation of natural $^{35}\text{Cl}$ to $^{36}\text{Cl}$ ($t_{1/2} = 3 \times 10^5$ years)
- $\text{Cl}$ can be removed from $\text{Cl}$-based salts using dechlorination processes
  - Reactions with ammonium phosphates (e.g., ADP, DHP) $[{\uparrow \text{NH}_4\text{Cl}}]$
  - Reactions with $\text{H}_3\text{PO}_4$ $[{\uparrow \text{HCl}}]$
  - Reactions with USHY zeolite $[{\uparrow \text{HCl}}]$

$\text{ADP} = \text{NH}_4\text{H}_2\text{PO}_4$
$\text{DHP} = (\text{NH}_4)_2\text{HPO}_4$
$\text{USHY zeolite} = \text{ultrastable H-Y zeolite}$
Minimizing Tritium Production

• Tritium can be produced through activation of $^6$Li or $^{19}$F
• This can be reduced by using $^7$Li-enriched salts

$$^6\text{LiF} + n \rightarrow ^4_2\text{He} + ^3_1\text{HF}$$

$$^{19}_9\text{F} + n \rightarrow ^{17}_8\text{O} + ^3_1\text{H}$$

Source: https://doi.org/10.1016/j.nucengdes.2019.02.002
Technology Readiness Levels (TRLs)

• Most waste form technologies have low TRL values
• Most are only conducted at small-scale with nonradiological salt compositions
• More work is needed to further these technologies towards higher TRLs
• Some TRL jumps are extremely expensive
SUMMARY AND CONCLUSIONS
Summary and Conclusions

• High-level takeaway: the waste problem is solvable...

• Starting points exist for technology development in all these topic areas

• Several waste form options exist for most waste streams, but most are at low TRLs

• Options demonstrated for Cl-based salts might work for F-based salts

• Some WF and salt treatment options are better than others (e.g., cost, waste loading, storage volume, simple vs multiple process steps)

• Several opportunities exist for research in development in each of these areas

• Potential for component recycle (e.g., $^{37}$Cl, $^7$Li, graphite)
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