INL/MIS-21-63682-Revision-0

Task 2: Radiolytic Gas Generation due to ASNF Corrosion Layers (Public Talk)

August 2021

Changing the World's Energy Future

Gregory P Horne

Idaho National Laboratory

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Task 2: Radiolytic Gas Generation due to ASNF Corrosion Layers (Public Talk)

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Task 2: Radiolytic Gas Generation due to ASNF Corrosion Layers

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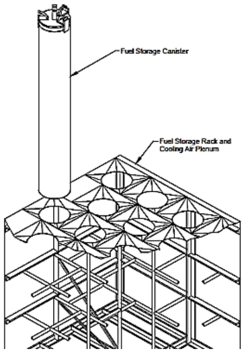
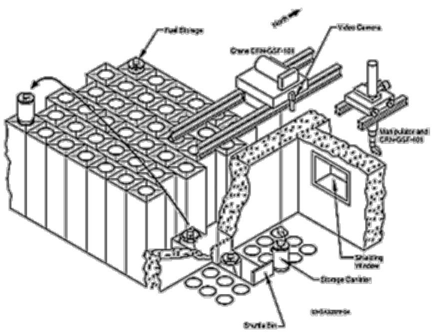
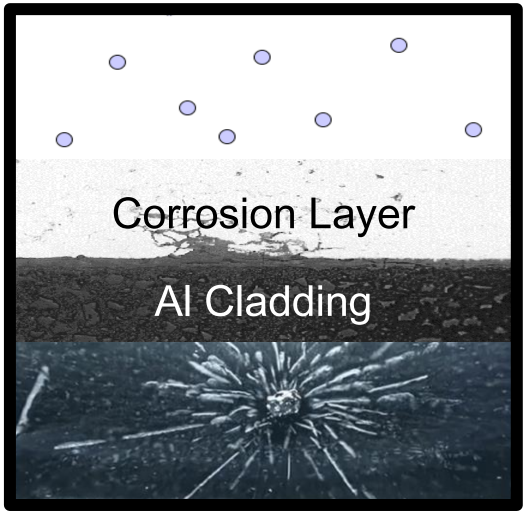
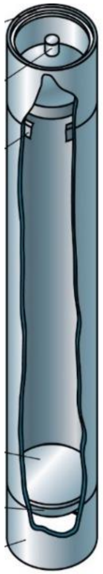
Radiolytic Gas Generation due to ASNF Corrosion Layers

- Thermal and chemical corrosion of *Aluminum-clad Spent Nuclear Fuel* (ASNF) is well understood.
- Radiation-induced **H_2** gas generation from the attendant Al corrosion layer(s) is less understood for ASNF.
- Radiolytic generation of **H_2** from solid and gaseous sources presents potential challenges for the long-term storage of ASNF (>50 years) in the form of:
  - **over pressurization**
  - **cladding embrittlement**
  - **formation of flammable gas mixtures**









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Radiation-Induced H_2 Production Pathways

Water Radiolysis

$H_2O \rightsquigarrow e_{aq}^-, H^\bullet, {}^\bullet OH, H_2, H_2O_2, H_{aq}^+$

Surface Processes

$Al_{(s)} \rightsquigarrow h^+ + e^-$

Water Processes

$H_2O^* \rightarrow H_2 + O$

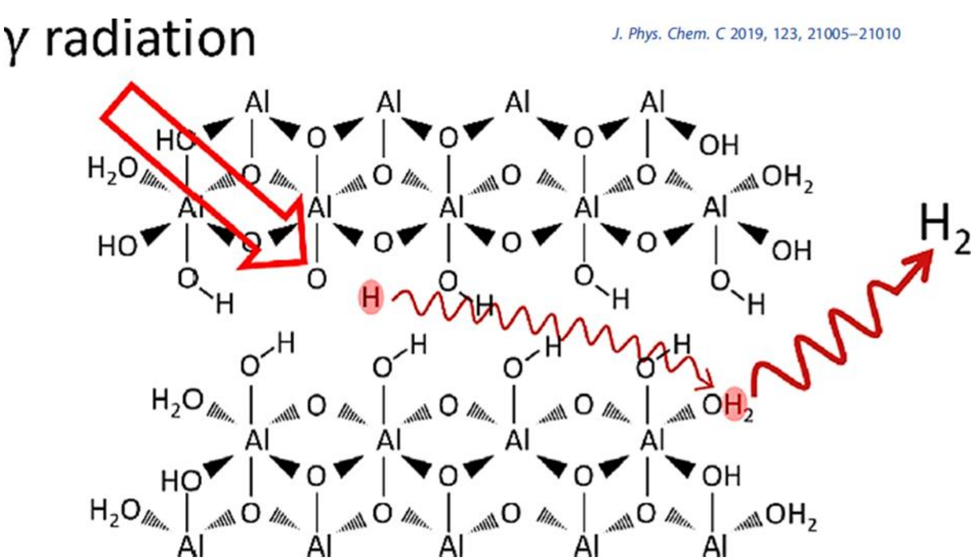
$e_{aq}^- + e_{aq}^- + 2H_2O \rightarrow H_2 + 2OH^-$

$e_{aq}^- + H^\bullet + H_2O \rightarrow H_2 + OH^-$

$e_{aq}^- + H_{aq}^+ \rightarrow H^\bullet$

$H^\bullet + H_2O \rightarrow H_2 + {}^\bullet OH$

$H^\bullet + H^\bullet \rightarrow H_2$



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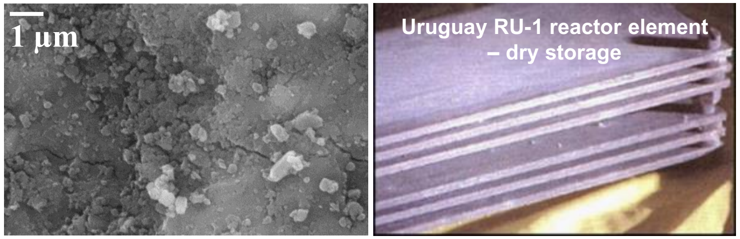
Task 2 Research Goal

Aim

- Provide quantitative experimental data and insight into the rate of H_2 generation from the attendant corrosion layer on aluminum alloy coupons to inform complementary modelling efforts.

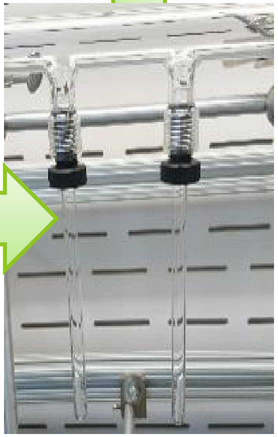
Objectives

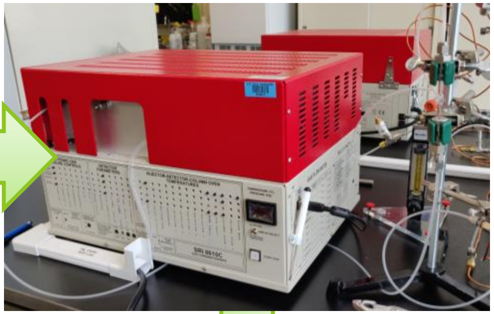
- Evaluate radiation-induced H_2 generation as a function of:
  - **absorbed gamma dose**
  - **corrosion layer composition**
  - **gaseous environment**
  - **relative humidity**
  - **temperature**

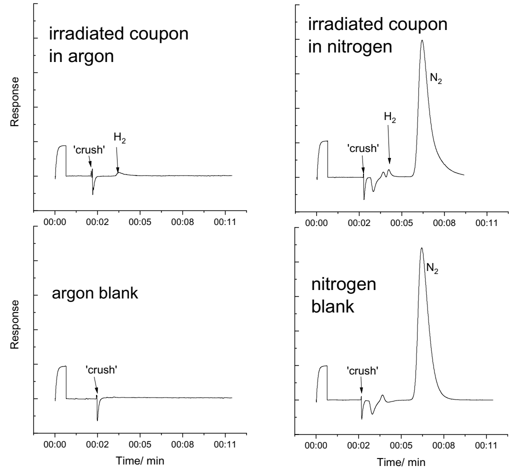


RU-1 (**Al-1100**): 8 years in-reactor at ~70°C; ~30 years dry storage; 0.2-25 µm thick corrosion layer of gibbsite (P) and possibly boehmite (S).

Experimental Methodology







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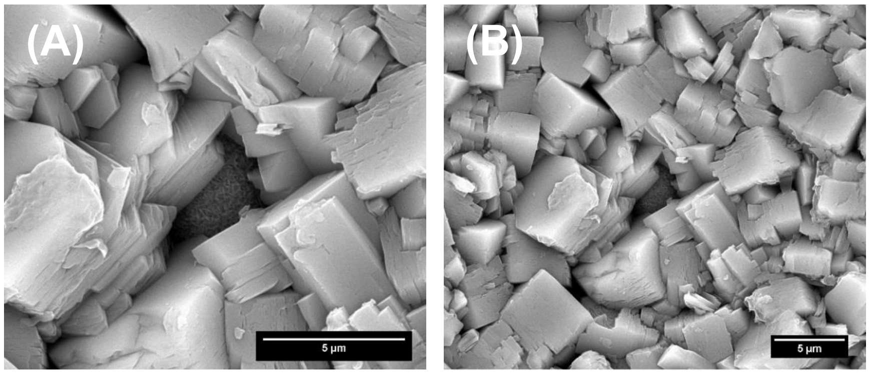
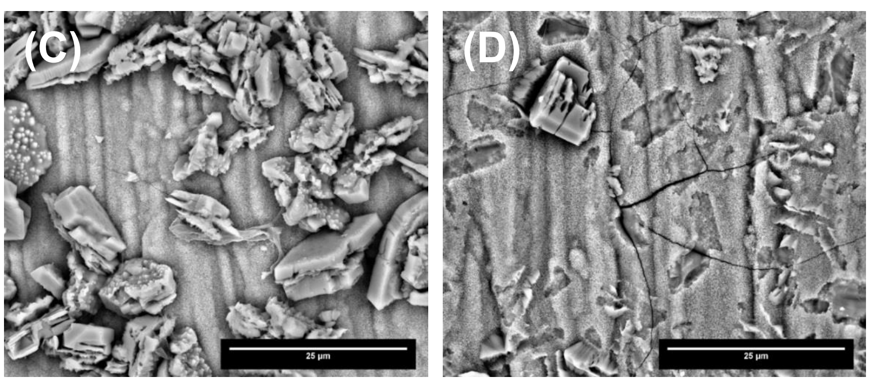
- J.A. LaVerne and P.L. Huestis, *J. Phys. Chem. C*, 2019, **123 (34)**, 21005.
- T.E. Lister, Vapor Phase Corrosion Testing of Pretreated Al1100, INL/EXT-18-52249, 2018.
- C. Vargel, Chapter B.1 - Introduction to The Corrosion of Aluminium in Vargel, C. (Eds.), Corrosion of Aluminium, Elsevier, 2004.

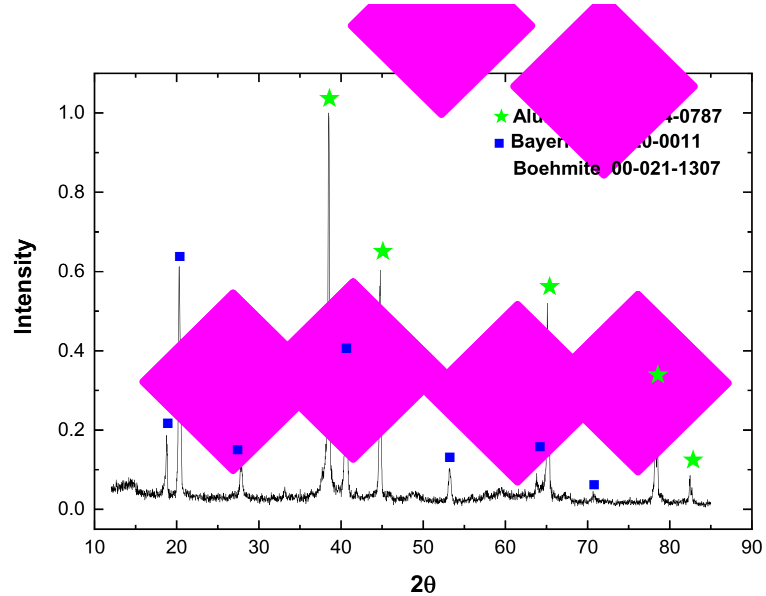
Corrosion Layer Composition

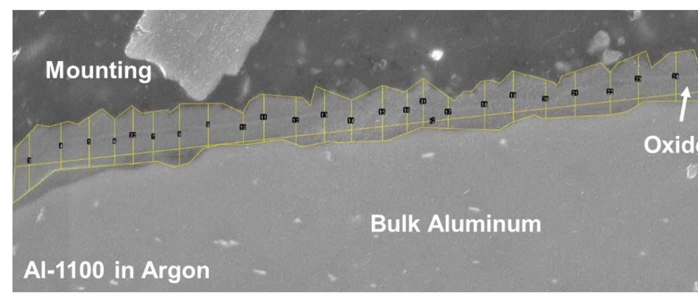
Non-Irradiated



H_3PO_4 Acid Strip







Average corrosion layer thickness of 5.3 ± 0.3 μm.

- Parker-Quaife, E.H.; Verst, C.; Heathman, C.R.; Zalupski, P.Z.; **Horne, G.P.**, *Radiation Physics and Chemistry*, **2020**, *177*, 109117.
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- Schoen, R., Roberson. C.E., 1970. Structures of Aluminum Hydroxide and Geochemical Implications. The American Mineralogist vol. 55.
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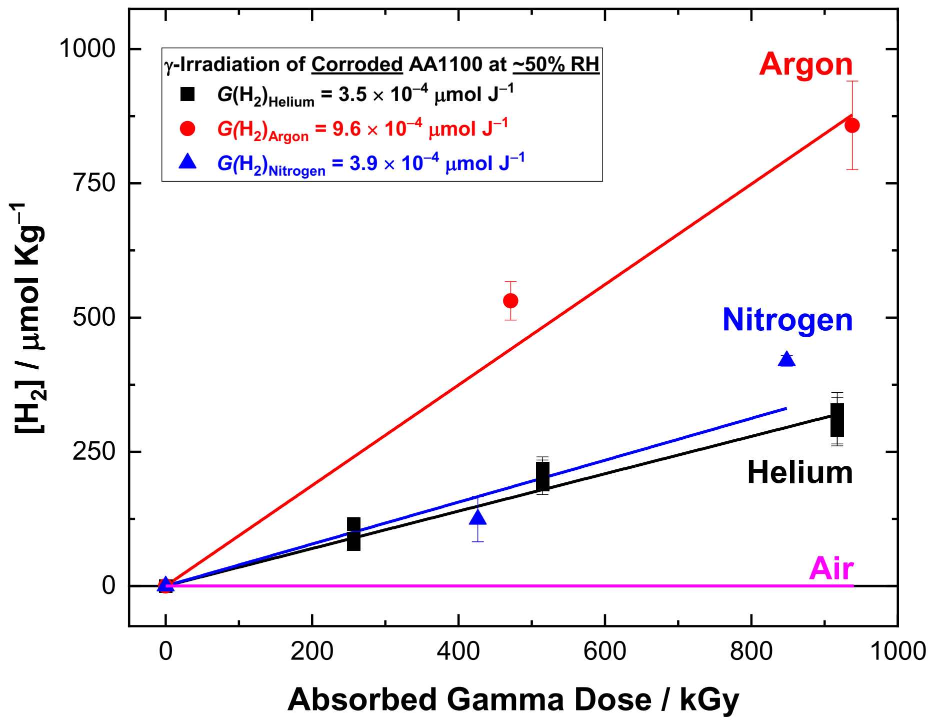
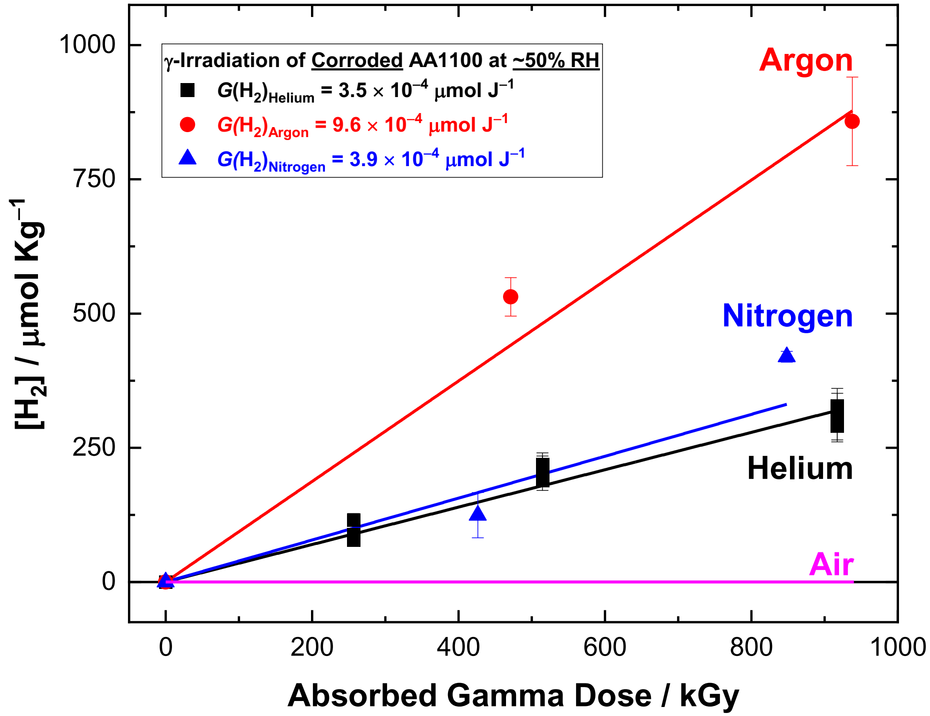
Absorbed Gamma Dose Dependence



- The volume of H_2 increased with absorbed gamma dose.
- No H_2 was detected in the absence of a AA1100 coupon at any investigated humidity (0%, 50%, and 100%).

- Parker-Quaife, E.H.; Verst, C.; Heathman, C.R.; Zalupski, P.Z.; **Horne, G.P.**, *Radiation Physics and Chemistry*, **2020**, *177*, 109117.

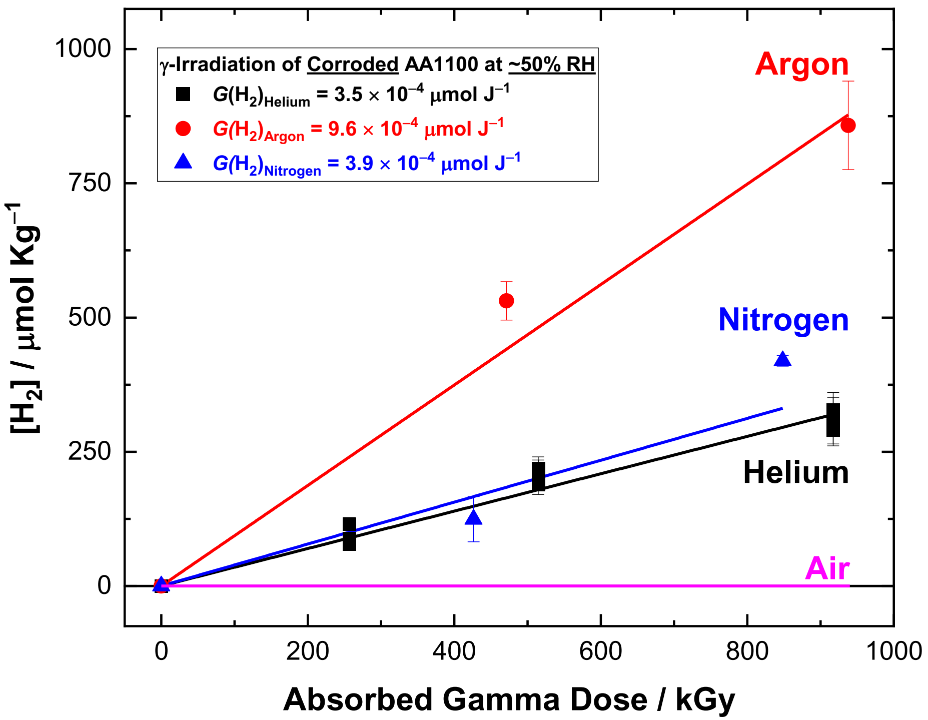
Gaseous Environment Dependence



- No H_2 was quantified in the presence of **Air**, O_2 scavenges radicals (e.g., e_{aq}^- and **H•**).
- **Nitrogen** and **Helium** play a minor role in H_2 inhibition, attributed to gas phase radical processes.

- Parker-Quaife, E.H.; Verst, C.; Heathman, C.R.; Zalupski, P.Z.; **Horne, G.P.**, *Radiation Physics and Chemistry*, **2020**, *177*, 109117.

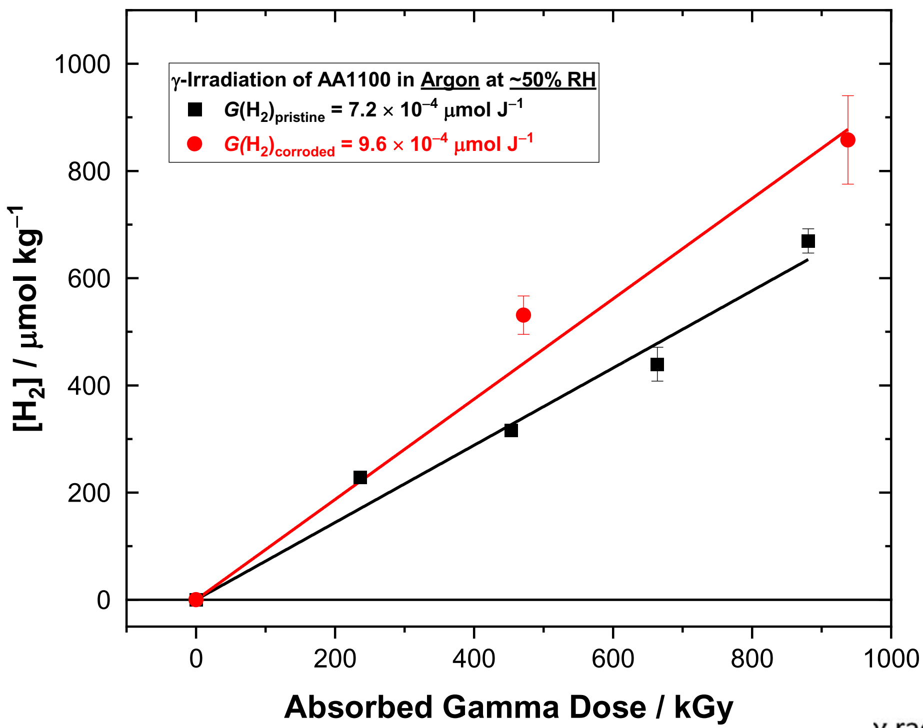
Gaseous Environment Dependence



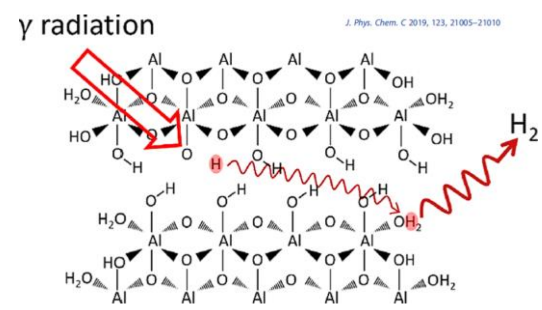
- For example, irradiation of **He** atmospheres promotes ***Penning Ionization***: **He*** + H_2 → **He** + H_2^+ + e^-.
- **Argon** affords the highest yield of H_2 as its ionization potential is "*just right*" (E^o_{Argon} = 15.76 V *vs*. E^o_{H2} = 15.4 V).

- Parker-Quaife, E.H.; Verst, C.; Heathman, C.R.; Zalupski, P.Z.; **Horne, G.P.**, *Radiation Physics and Chemistry*, **2020**, *177*, 109117.

Oxyhydroxide Corrosion Layer Dependence

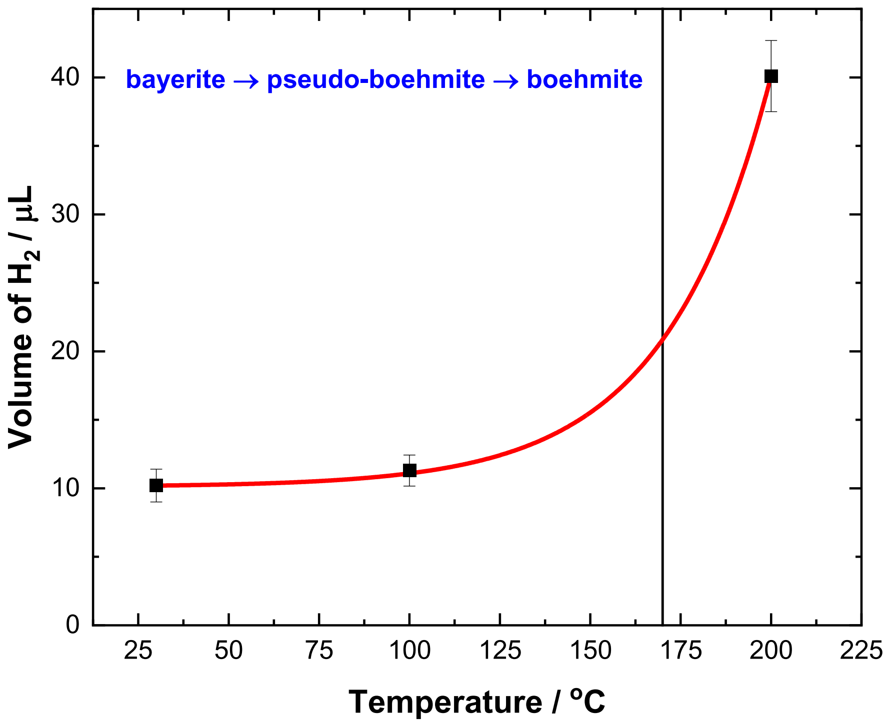


- Corrosion-induced oxyhydroxide layers provide **>OH$_2$/>OH$^-$/>OH** groups for promotion of **H_2** formation.



- Parker-Quaife, E.H.; Verst, C.; Heathman, C.R.; Zalupski, P.Z.; **Horne, G.P.**, *Radiation Physics and Chemistry*, **2020**, *177*, 109117.

Temperature Dependence



- Higher H_2 yields at 200 °C due to: *(i)* phase transformation of corrosion layers starting at ~170 °C; *(ii)* and more efficient release of $H^{\bullet}$ and H_2 from boehmite layers

- L. Lundberg, ERA-NRE-94-096, EG&G, 1994.
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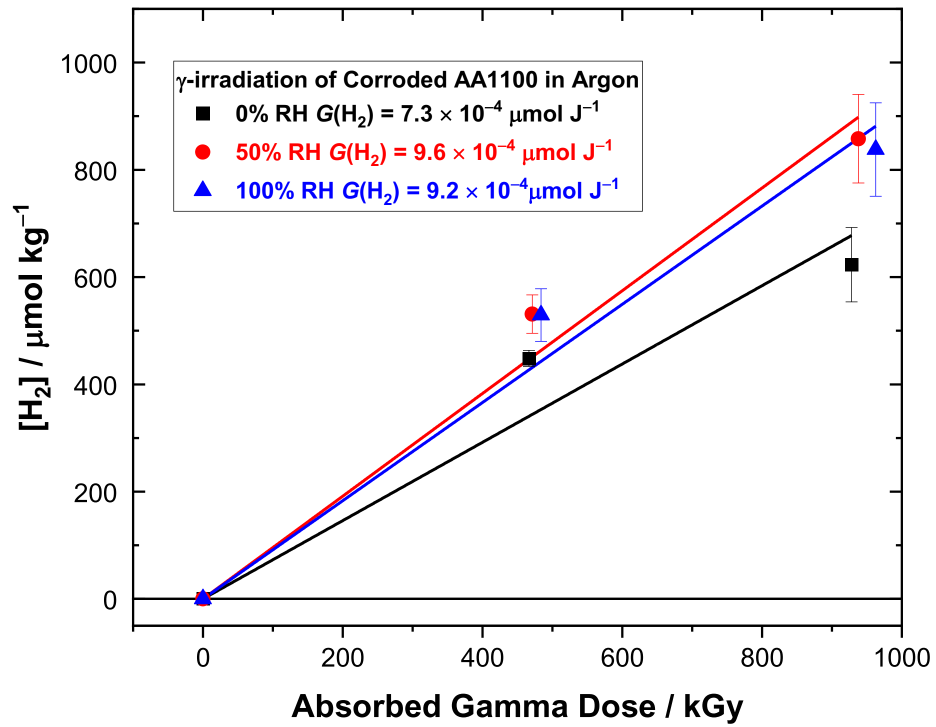
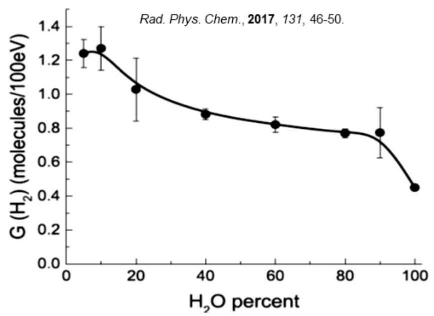
- M.V. Glazoff and T.E. Lister, INL/EXT-18-51694, Idaho National Laboratory, 2018.
- J.A. LaVerne and P.L. Huestis, *J. Phys. Chem. C*, 2019, **123**, 21005.

Humidity Dependence





- Higher H_2 yields with increasing relative humidity.
- Direct water radiolysis and energy migration from the irradiated coupon to surface bound water molecules.

- L. Lundberg, ERA-NRE-94-096, EG&G, 1994.
- J.A. Kaddissy, S. Esnouf, D. Durand, D. Saffre, E. Foy, and J.-P. Renault, *J. Phys. Chem. C*, 2017, **121**, 6365.
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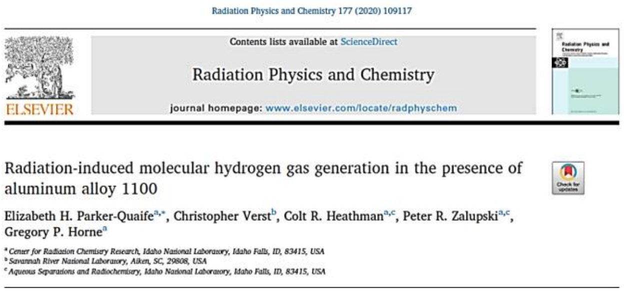
- J.A. LaVerne and P.L. Huestis, *J. Phys. Chem. C*, 2019, **123**, 21005.

Conclusions

1. Radiation promotes H_2 formation from AA1100 coupons.
2. *G*(H_2) is dependent on *gaseous environment*, *temperature*, *humidity*, and *presence of a corrosion layer*.
3. This work has generated a series of G(H_2) values to support predictive model development.

Future Research Questions

1. How does corrosion layer surface composition change with absorbed dose upon reaching steady-state?
2. What effect does alloy composition have on H_2 production?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Radiation-induced molecular hydrogen gas generation in the presence of aluminum alloy 1100

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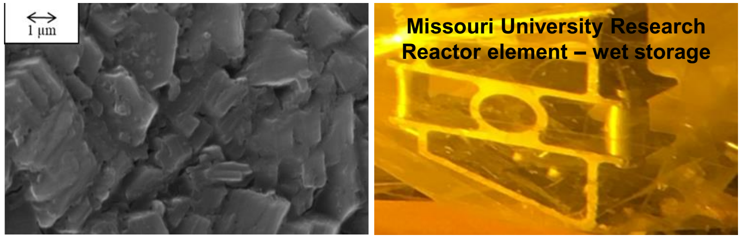
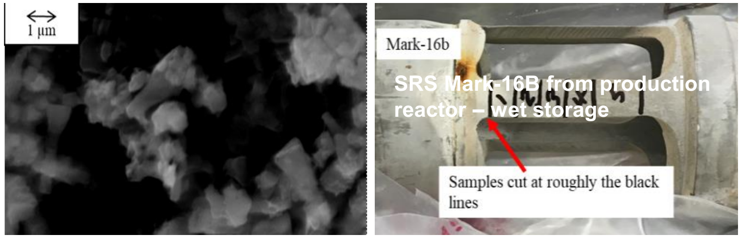


MURR (Al-6061): ~113 days in-reactor at ≥ 60°C; <18 years wet storage at ~22°C; 5-10 µm thick corrosion layer of bayerite (P) and boehmite (S).



Mk-16b (Al-6061 or Al-6063): ~220 days in-reactor at ≥ 34 °C; ~40 years wet storage at ~22°C; 5-15 µm thick corrosion layer of bayerite (P), boehmite (S), and gibbsite (T).

Acknowledgements

U.S. DEPARTMENT OF ENERGY

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Center for Radiation Chemistry Research

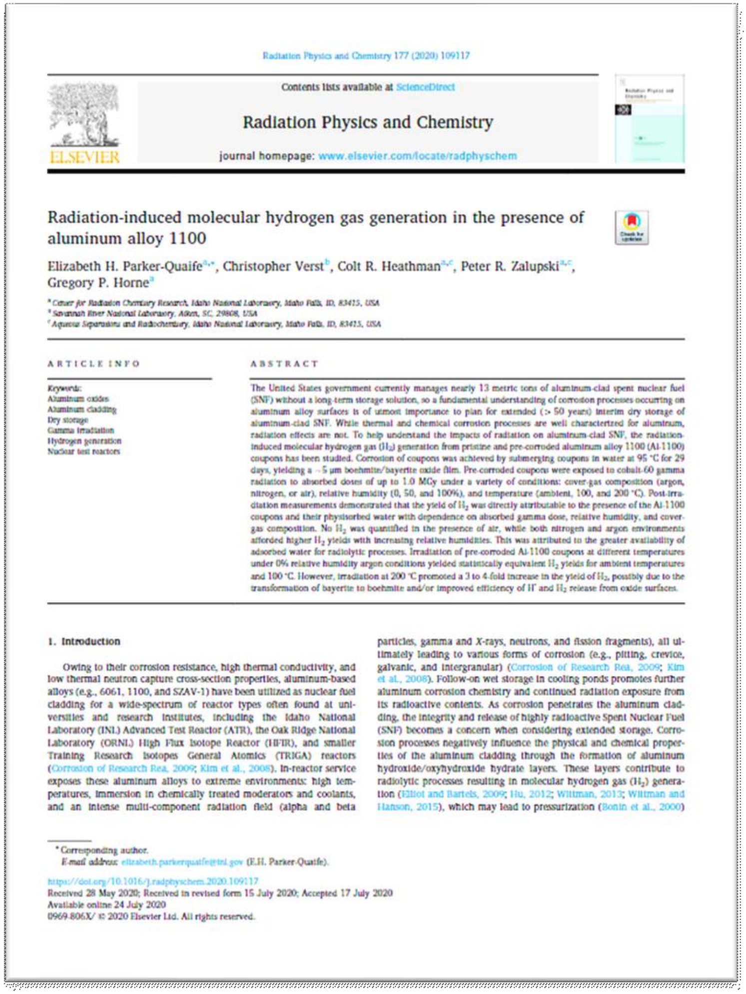
Summary of Project Deliverables (FY19-20)

1. **Milestone 2.6:** Complete Round-Robin Hydrogen Gas Analysis Capability Comparison. Technical report, DOI: https://doi.org/10.2172/1755761.

2. **Milestone 2.7:** Evaluation of Techniques for the Measurement of Molecular Hydrogen Gas in Helium Matrices. Technical report.

3. **Milestone 2.8:** *Preliminary Radiolytic Gas Generation Measurements from Helium-Backfilled Samples*. Technical report, DOI: https://doi.org/10.2172/1768757.

4. Parker-Quaife *et al.*, *Rad. Phys. Chem.*, **2020**, *177*, 109117, DOI: https://doi.org/10.1016/j.radphysch em.2020.109117.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ABSTRACT

The United States government currently manages nearly 13 metric tons of aluminum-clad spent nuclear fuel (SNF) without a long-term storage solution, so a fundamental understanding of corrosion processes occurring on aluminum alloy surfaces is of utmost importance to plan for extended (> 50 years) interim dry storage of aluminum-clad SNF. While thermal and chemical corrosion processes are well characterized for aluminum, radiation effects are not. To help understand the impacts of radiation on aluminum-clad SNF, the radiation-induced molecular hydrogen gas (H_2) generation from pristine and pre-corroded aluminum alloy 1100 (Al-1100) coupons has been studied. Corrosion of coupons was achieved by submerging coupons in water at 95 °C for 29 days, yielding a ~5 μm boehmite/bayerite oxide film. Pre-corroded coupons were exposed to cobalt-60 gamma radiation to absorbed doses of up to 1.0 MGy under a variety of conditions: cover-gas composition (argon, nitrogen, or air), relative humidity (0, 50, and 100%), and temperature (ambient, 100, and 200 °C). Post-irradiation measurements demonstrated that the yield of H_2 was directly attributable to the presence of the Al-1100 coupons and their physisorbed water with dependence on absorbed gamma dose, relative humidity, and cover-gas composition. No H_2 was quantified in the presence of air, while both nitrogen and argon environments afforded higher H_2 yields with increasing relative humidities. This was attributed to the greater availability of adsorbed water for radiolytic processes. Irradiation of pre-corroded Al-1100 coupons at different temperatures under 0% relative humidity argon conditions yielded statistically equivalent H_2 yields for ambient temperatures and 100 °C. However, irradiation at 200 °C promoted a 3 to 4-fold increase in the yield of H_2, possibly due to the transformation of bayertie to boehmite and/or improved efficiency of $H^{\cdot}$ and H_2 release from oxide surfaces.

1. Introduction

Owing to their corrosion resistance, high thermal conductivity, and low thermal neutron capture cross-section properties, aluminum-based alloys (e.g., 6061, 1100, and SZAV-1) have been utilized as nuclear fuel cladding for a wide-spectrum of reactor types often found at universities and research institutes, including the Idaho National Laboratory (INL) Advanced Test Reactor (ATR), the Oak Ridge National Laboratory (ORNL) High Flux Isotope Reactor (HFIR), and smaller Training Research Isotopes General Atomics (TRIGA) reactors (Corrosion of Research Rea, 2009; Kim et al., 2008). In-reactor service exposes these aluminum alloys to extreme environments: high temperatures, immersion in chemically treated moderators and coolants, and an intense multi-component radiation field (alpha and beta particles, gamma and X-rays, neutrons, and fission fragments), all ultimately leading to various forms of corrosion (e.g., pitting, crevice, galvanic, and intergranular) (Corrosion of Research Rea, 2009; Kim et al., 2008). Follow-on wet storage in cooling ponds promotes further aluminum corrosion chemistry and continued radiation exposure from its radioactive contents. As corrosion penetrates the aluminum cladding, the integrity and release of highly radioactive Spent Nuclear Fuel (SNF) becomes a concern when considering extended storage. Corrosion processes negatively influence the physical and chemical properties of the aluminum cladding through the formation of aluminum hydroxide/oxyhydroxide hydrate layers. These layers contribute to radiolytic processes resulting in molecular hydrogen gas (H_2) generation (Elliot and Bartels, 2009; Hu, 2012; Wittman, 2013; Wittman and Hanson, 2015), which may lead to pressurization (Bonin et al., 2000)

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