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Dissolution of Used Nuclear Fuel using Recycled Nitric Acid

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Key Words

UNF

H-Canyon

Dissolver

Running Title

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Dissolution of Used Nuclear Fuel using Recycled Nitric Acid

Abstract: SRNL evaluated the feasibility of using HB-Line anion exchange column waste streams from AFS-2 processing for the dissolver solution for Used Nuclear Fuel (UNF) processing. The targeted UNF for dissolution using recycled solution are fuels similar to the University of Missouri Research Reactor (MURR) fuel. The objectives of this experimental program were to validate the feasibility of using impure dissolver solutions with the MURR dissolution flowsheet to verify they would not significantly affect dissolution of the UNF in a detrimental manner.

Initial dissolution experiments were unsuccessful in dissolving Al alloy sufficiently using 0.002 M Hg in solutions containing impurities in the concentration ranges expected to originate from AFS-2 processing. These impurities included F, Fe, Cr, Ni, Mn, Al, Cl, B, and Gd. Solutions with these impurities dramatically slowed or stopped the dissolution. Through this work, it was discovered that increasing the concentration of the Hg catalyst could overcome the deleterious effects of these impurities together. Experiments were subsequently performed with individual impurities to identify those that are problematic and to determine the amount of Hg required to overcome their effects. Iron was identified as the impurity that most significantly impacted the dissolution rates. The Hg catalyst concentration was increased from 0.002 M to 0.012 M to dissolve Al in the presence of all the impurities at their maximum concentrations (including Fe at 10 g/L).

INTRODUCTION

An evaluation was performed on the feasibility of using HB-Line (HBL) anion exchange column waste streams from AFS-2 processing for the dissolver solution for Used Nuclear Fuel (UNF) processing (1,2). The targeted UNF for dissolution using recycled solution are fuels similar to the University of Missouri Research Reactor (MURR) fuel (4-6). MURR fuel consists of Al clad, U-Al alloy fuel plates (4).

Bundles of UNF containing MURR-like fuel assemblies are conventionally dissolved by a Hg-catalyzed, HNO_3 flowsheet containing pure reagents (6). The Hg catalyst is added gradually after the dissolver has reached temperature to achieve a maximum catalyst concentration (conventional processing used 0.002 M Hg) (6). The proposed initial HNO_3 concentration is dependent on the amount of Al and U to be dissolved, targeting a final HNO_3 concentration of 0.5–1.0 M after completion of the dissolution of the last charge. Boric acid or $\text{Gd}(\text{NO}_3)_3$ may be used as a nuclear safety poison. Concentrations of up to 2 g/L of B or Gd in surrogate dissolver solutions have been observed to be stable from precipitation (4).

The AFS-2 column waste will consist of 7 to 7.5 M HNO_3 solutions from column reconditioning, raffinate, column wash, and head and tail cuts. AFS-2 column waste impurities and ranges have been evaluated for UNF dissolutions of fuels which are validated as similar to MURR. An estimate of the elements and respective concentrations that may be present in the column waste solution is provided and includes K, F, Fe, Cr, Ni, Mn, Al, Cl, B, Am, and Pu (2-3, 7).

The corrosion products (Fe, Cr, Ni, and Mn) originate from the 304L stainless steel of the 6.1D dissolver used for AFS-2 Pu metal dissolutions (7). Some Fe is solubilized from dissolution of the carbon-steel cans containing the Pu that are charged to the dissolver and the bundle end caps which secure the cans in the bundle. The AFS-2 solution may contain B from the purification of Pu to meet the Aqueous Polishing (AP) Interface Control Document (ICD) Specification. However, if the solution is from the purification of Pu to meet the MOX Process (MP) ICD Specification, no B will be present (3). After Pu dissolution, but prior to transfer from H-Canyon to HBL, ferrous sulfamate (FS) may be added as needed to the AFS-2 feed to reduce any Pu(VI) and Cr(VI) (3-6, 7). The amount added may result in the presence of sulfate, and/or ammonium ions (from sulfamate) at corresponding concentrations.

EXPERIMENTAL

Simulated HBL column waste streams containing contaminants expected from AFS-2 processing were prepared and evaluated by SRNL for their feasibility for use as the dissolver solution for UNF processing. The recycle waste streams will be received by H-Canyon in Tank 11.1, transferred to the 6.4D dissolver, and adjusted, as needed (e.g. to the appropriate acidity). The AFS-2 column waste is projected to consist of the column reconditioning, the column raffinate, the column wash, and the elution head and tails cuts (2). While the reconditioning, head cut, and tails cut would be relatively pure HNO_3 solutions, the raffinate and wash would carry the impurities from the AFS-2 feed stream. The combined column waste stream is projected to have a HNO_3 concentration in the 7.0–7.5 M range with the following major components and concentrations listed in Table 1 (7). Additionally $\text{Gd}(\text{NO}_3)_3$ may be used as a nuclear safety poison during fuel dissolution.

Reagents used to prepare simulants used for dissolution experiments are also provided in Table 1. The impurity concentrations were selected at either the maximum or minimum of the range with the exception of KF and Al. In an effort to produce bounding or maximum gas generation rates, 0.1 M KF and either 0 M or 0.075 M Al were used.

Description of Dissolution and Gas Collection Apparatus

The gas generation rates and H₂ concentrations were determined using a dissolver apparatus shown in Fig. 1 that contains a boiling flask with multiple ports, a condenser, an in-line sample bulb, and a water-submerged gas collection Tedlar™ bag. The apparatus was assembled in a chemical hood. A second apparatus was placed in a radiological hood for conducting experiments with U-Al alloys. The dissolution vessel and off-gas system use removable glass bulbs to sample and measure the H₂ concentration of the gas by gas chromatography (GC) (6-7). The bulbs are coupled to a gas collection system that fills a Tedlar™ bag which allows measurement of the gas generation rate through water displacement in a graduated column. A second gas collection apparatus was also fabricated to accommodate larger gas generation volumes, when needed.

Al-1100 alloy coupons were used for a portion of the dissolution experiments. Four coupons were cut to approximate dimensions of 19 x 11 x 3 mm and each had a 1/16 inch hole drilled for fastening the coupon to glass rods used to lower them into the dissolving solution. The coupons were lightly sanded, washed with soap and water, and then weighed and measured. The coupons were sanded to maximize reactivity as well as to generate consistent results. The coupons weighed about 1.7 g each with a surface area of approximately 6 cm². Each coupon was tied by

Teflon™ string through the 1/16 inch hole to a glass rod labeled with the coupon position number (for coupon identification). The glass rods penetrated the lid of the boiling flask and were sealed by compressed O-ring fittings. This setup allowed for dissolution of all 4 coupons without breaking the gas-sealed system by lowering each glass rod sequentially over the duration of the experiment. A 150-mL aliquot of 7 M HNO₃ solution was used unless otherwise noted. The experiments targeted a nominal 1.7 M final dissolved Al concentration.

The first series of experiments were performed as described previously by Almond et al. (6), where the Hg was initially present in solution and the solution was heated to 100 °C before lowering the first coupon. In a second series of experiments described below, the Hg was slowly added while the initial coupon was present in the boiling dissolving solution. For these experiments, nominally 140 mL of solution was weighed and added to the flask containing a Teflon™ stir bar and then the flask was sealed. The dissolution vessel and off-gas collection system (including 8 gas sample bulbs) were leak checked by filling the system with Ar to inflate the Tedlar™ bag and observing a constant water column height over several minutes. The stir bar rotation was set at 325 rpm. A stopwatch was started as the first coupon was lowered into the solution at room temperature. The solution was then heated to 100 °C. The off-gas system was vented to relieve pressure (to zero the off-gas collection system). A syringe pump was subsequently started to meter the Hg into the solution. The Hg addition was completed during the first coupon dissolution. Time versus water displacement was manually recorded until the coupon was visually observed to have completely dissolved. For each coupon dissolution, a gas sample was taken generally at 450 mL of off-gas volume (about half the total gas produced for each coupon) and a second sample was taken after the coupon had completely dissolved. The

collected gas was then vented at the gas bulb connection from the Tedlar™ bag, leaving residual gas in the remainder of the void space of the apparatus. Coupon 2 was subsequently lowered into the hot HNO_3 and dissolved. Coupons 3 and 4 were then added in the same manner producing a total of 4 off-gas generation rate data sets (1 per coupon), and 8 gas samples (2 per coupon) for each experiment that spanned the range of Al concentrations in solution.

Coupons prepared from a 30 wt % U-Al alloy were used in a series of experiments as described above. The 30 wt % U-Al coupons were cut to a nominal size of 20 x 12 x 3 mm giving a mass of 1.6–2.1 g. Four coupons were used for each dissolution resulting in 8 gas samples (2 per coupon) giving a final Al concentration of 1.3–1.5 M.

Control of experimental parameters such as Hg addition (versus having the Hg initially present) was implemented to take credit for the reduced off-gas rates that result from the slow addition of Hg as performed in H-Canyon. The first experiments were performed with the Hg initially present in solution and resulted in larger initial off-gas rates than would be expected during an H-Canyon dissolution where the Hg is added slowly (15). Implementation of Hg metering reduced the off-gas rates during the dissolution of the initial coupon which more closely matches the operations in the H-Canyon dissolver.

Simulant Compositions

Simulated column recycle solutions were used for analysis of gas generation rates and gas composition. Al-1100 alloy was dissolved during Experiments 20, 22, 23, 24, 31, 49, and 50 and used minimum and maximum contaminant concentrations both with and without B (Table 2 and

3). In Experiment 31, the Hg was increased to 0.016 M to investigate the impact of excess Hg on off-gas rate and composition.

Experiments 53 and 54 were performed with 30 wt % U-Al alloy and solutions containing minimum and maximum contaminants, respectively. Experiments 55 and 56 were performed with 30 wt % U-Al alloy using Fe as a controlling impurity. The compositions of the simulants for these experiments are provided in Table 3.

RESULTS AND DISCUSSION

Initial dissolution experiments with 0.002 M Hg representative of the prior MURR flowsheet (4-6) were unsuccessful in dissolving Al alloy sufficiently with the impurities and concentration ranges expected from AFS-2 column waste streams (3). The impurities included K, F, Fe, Cr, Ni, Mn, Al, Cl, B, and Gd. Single-impurity scoping experiments initially performed with Al-1100 (7). During these scoping experiments, it was also discovered that increasing the concentration of the Hg catalyst could be used to overcome the deleterious effect of the impurities. Experiments were subsequently performed with individual impurities to identify the ones that are problematic for metal dissolution and to determine the amount of Hg required to overcome this effect. Iron was postulated to be the main impurity controlling Al dissolution and off-gas rates for Al and U-Al alloys based on these experiments (7). An experimental plan was developed to measure off-gas rates and H₂ concentrations for impurities at the minimum and maximum expected impurity concentrations. In addition, experiments with Fe impurity only were performed based on the results of the scoping experiments.

Off-gas rates for Al-1100 with Hg Initially Present

Al-1100 alloy dissolutions with Hg initially present were performed with the minimum and maximum impurity solutions described in Table 2 to provide a comparison with dissolutions performed using impurity-free solutions (6). Off-gas rates were measured and the off-gas volume generated per coupon was tracked by recording height changes in the water column of the Tedlar™ bag system used in the experimental setup. The water column heights were used to calculate the volumes of gas generated. The volumes of gas generated were then corrected for the slight pressure created by the rising water column above the Tedlar™ bag collection system as well as the tubing volume that was submerged in the water column.

Experiments 20, 22, 23, 24, and 31 (Table 2) which were performed using solutions containing impurities and 0.012 M Hg produced similar off-gas rates for the initial coupon compared to impurity-free Experiment 25 also performed using a solution containing 0.012 M (Fig. 2) (with the exception of Experiment 20). However, for coupons 2–4, the off-gas rates for the experiments performed with impurities were reduced compared to Experiment 25.

The impact of B with minimum contaminants (Experiment 22, B = 0 g/L, Experiment 24, B = 1.6 g/L) had no apparent effect on the measured off-gas rates. The impact of B with maximum contaminants (Experiment 20, B = 0 g/L, Experiment 23, B = 1.6 g/L) also had no effect on the measured off-gas rates. Experiment 20 had a decreased rate for the initial coupon compared to the other experiments in the group (Table 2); however, the experiment was not repeated to validate the result.

H₂ Gas Concentrations for Al-1100 Dissolution Experiments

Eight off-gas samples were collected sequentially (1-8) during each dissolution experiment (two samples were collected for each of four coupons dissolved). The gas samples were quantitatively analyzed by GC for H₂, O₂, and N₂.

The analyzed concentrations of the off-gas species from the Al metal dissolutions were corrected to account for dilution from gas in the dissolution vessel, condenser, Viton[®] tubing, and sample bulb. To calculate the adjusted concentrations, ideal mixing of the gases in the void space was assumed and the effect of temperature variations in the gas was assumed negligible. For H₂ or any other component of the off-gas, the adjusted concentration is calculated by material balance (6-7).

The H₂ concentration profiles in Fig. 3 show a trend of reduced H₂ concentration as impurities increased. The minimum impurity simulants (Experiments 22, 24, and 31) produced a maximum corrected H₂ concentration of 6.7, 5.6, and 5.9 vol %, respectively. The maximum impurity simulants (Experiments 20 and 23) had H₂ maximums of 3.0 and 2.9 vol %, respectively. The impact of B with minimum contaminants (Experiment 22, B = 0 g/L, Experiment 24, B = 1.6 g/L) had no apparent effect on the H₂ concentrations. The impact of B with maximum contaminants (Experiment 20, B = 0 g/L, Experiment 23, B = 1.6 g/L) also had no apparent effect on the H₂ concentrations.

Off-gas Rates for Dissolution of Al-1100, 30 wt % U-Al Alloy with Metered Hg

The slow addition of Hg to the dissolving solution was implemented to take credit for the reduced off-gas rates that result from the slow addition of Hg like in the H-Canyon dissolver (15). Experiments 49, 50, 53, 54, 55, and 56 included the slow addition of Hg. These experiments were performed with the simulants and corresponding alloys as shown in Table 3. Each experiment consisted of four sequentially dissolved Al coupons. For each experiment, the total Hg addition (to 0.012 M Hg) was completed before the second coupon was lowered into the solution. Therefore, results from the dissolution of coupons 2–4 are analogous to the unmetereed experiments. This technique resulted in four sequential off-gas rate measurements for each coupon in the experiment as the dissolved Al concentration increased.

Experiments 53-56 were performed with 30 wt % U-Al alloy to study the effects of all contaminants and with Fe-only at minimum and maximum ranges. A total of four coupons were sequentially dissolved for each experiment giving final dissolved Al concentrations of 1.3 to 1.5 M. In Fig. 4, dissolutions using solutions containing Fe at minimum (Experiment 55) and maximum (Experiment 56) concentrations (2.5 and 10 g/L, respectively) were shown to provide similar off-gas rates when compared to dissolutions using simulants containing all impurities at either minimum or maximum ranges. The off-gas rates generally were highest for minimum Fe, followed by maximum Fe, then minimum contaminants, and maximum contaminants. The data demonstrates that the simulant containing Fe at 2.5 g/L is bounding (i.e. the maximum rate) for off-gas rates with 30 wt % U-Al alloy regardless of additional impurities present up to the maximum impurity ranges studied.

Experiment 49 was performed with Al-1100 and minimum contaminants. Experiment 50 was performed with Al-1100 and 2.5 g/L Fe. The off-gas rate profiles for Experiment 49 and

Experiment 50 with Al-1100 were similar to Experiment 55 ($\text{Fe} = 2.5 \text{ g/L}$) that used 30 wt % U-Al alloy (Fig. 4 and 5).

H₂ Gas Compositions for Al-1100, 30 wt % U-Al Alloys Dissolved with Impure Simulants with Metered Hg

Eight off-gas samples were collected sequentially (1-8) during each Al-1100 dissolution experiment (two samples were collected for each of four coupons dissolved). The gas samples were quantitatively analyzed by GC for H₂, O₂, and N₂. For Experiments 49, 50, 53, 54, 55 and 56 the corrected H₂ concentrations by GC are provided in Fig. 3 and 6. The raw H₂ concentration measurements are provided in (7).

The H₂ profiles for experiments using Al-1100 and 30 wt % U-Al alloys are plotted in Fig. 3 and Fig. 6, respectively, for comparison. In Fig. 3, Experiment 49 and 50 produced a high H₂ value for the last gas bulb sample, which may be explained by low free acid in the dissolving solution. The free acid concentration following completion of Experiments 49 and 50 were 0.217 M and 0.426 M, respectively. The increased H₂ at low acidity is consistent with previous observations when approaching acid deficient conditions (17). The free acid concentrations measured following Experiments 23 and 34 were 0.454 and 0.402 M, respectively, yet the experiments did not produce an increased H₂ in the final bulb (Fig. 3). However, the dissolving solutions contained maximum contaminants, which were shown in this work to suppress H₂ generation. Therefore, the threshold acidity that promotes increased H₂ generation for the systems studied is estimated at $\leq 0.4 \text{ M}$. Final free acid measurements following completion of all other experiments (unless otherwise mentioned) were greater than 0.6 M and did not exhibit an increased H₂ concentration in the final bulb relative to the previous bulbs.

The H₂ concentrations were generally reduced as the impurity concentrations in the solutions were increased during the dissolution of both alloys, with U-Al alloy producing greater H₂ concentrations initially at low dissolved Al concentrations. By comparison of experiments performed with solutions containing impurities to experiments performed with solutions containing Fe as the only impurity, Fe appears to be the major contributor to decreasing H₂ concentrations in the off-gas. The H₂ concentrations for Experiment 55 with Fe at 2.5 g/L are very similar to Experiment 53 containing all impurities at minimum concentrations (including Fe at 2.5 g/L). Again, Experiment 56 containing Fe at 10 g/L had a similar H₂ concentration profile when compared to Experiment 54 which was performed using a maximum impurity simulant (that included 10 g/L Fe).

FLAMMABILITY CALCULATIONS

The methodology used for the flammability calculations are summarized below and discussed in detail by Almond et al. in a separate report (7). To dissolve the MURR-type fuel assemblies in the H-Canyon dissolver without exceeding the 60% LFL limit on H₂, calculations were performed using the off-gas rate and mass balance corrected H₂ concentration data discussed in prior sections of this manuscript and surface area calculations performed by Daniel et al. (18).

A criterion of 60% of the H₂ LFL value at 200 °C was used for the fuel dissolution calculations using a temperature correction from Dyer's work (20). The H₂ LFL at 200 °C was chosen due to the iodine reactor in the off-gas stream of the H-Canyon dissolver being heated to 200 °C. The

H₂ LFL values come from data reported by Scott et al. (at 28 °C) based on measurements using an air, H₂, N₂O, and NO mixture (21).

The dissolver off-gas calculations for the 30 wt % U-Al alloy fuels in L-Bundles (i.e., MURR-type fuel) were performed using a graded approach where a fit of the off-gas rate data in terms of dissolved Al was performed that was continuous over the dissolved coupon range. The magnitude of the off-gas rate for an L-Bundle containing a fuel assembly is based on the outer surface area of the L-Bundle since it has the greater surface area and is dissolved initially as described by Daniel et al. (18). The H₂ concentration with air dilution is then compared with 60% of the calculated H₂ LFL.

CONCLUSIONS

To achieve complete dissolution of Al and U-Al alloys in the presence of up to the maximum impurities anticipated in the waste solution from the HBL, a modified MURR flowsheet specific for using the anion exchange raffinate was developed. A Hg catalyst concentration of 0.012 M is necessary to dissolve the UNF in the presence of the maximum impurity concentration range anticipated in the AFS-2 raffinate recycle streams. Iron was identified as the most inhibiting impurity to the dissolution. The use of 0.012 M Hg was demonstrated to be successful in dissolving the Al alloys with minimum and maximum contaminant levels present in the dissolving solution including Fe up to 10 g/L with and without the presence of B.

ACKNOWLEDGEMENTS

The work was supported by the US Department of Energy's Office of Environmental Management. The Savannah River National Laboratory is operated by Savannah River Nuclear Solutions under contract number DE-AC09-08SR22470.

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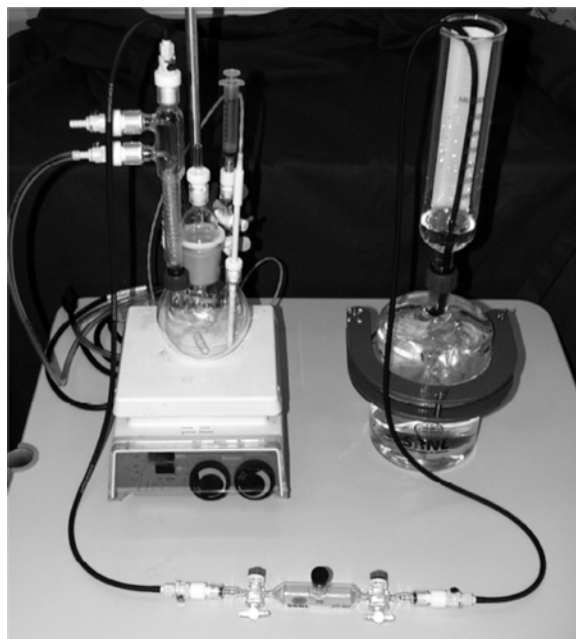


FIG. 1. Dissolution Vessel and Off-gas Collection System.

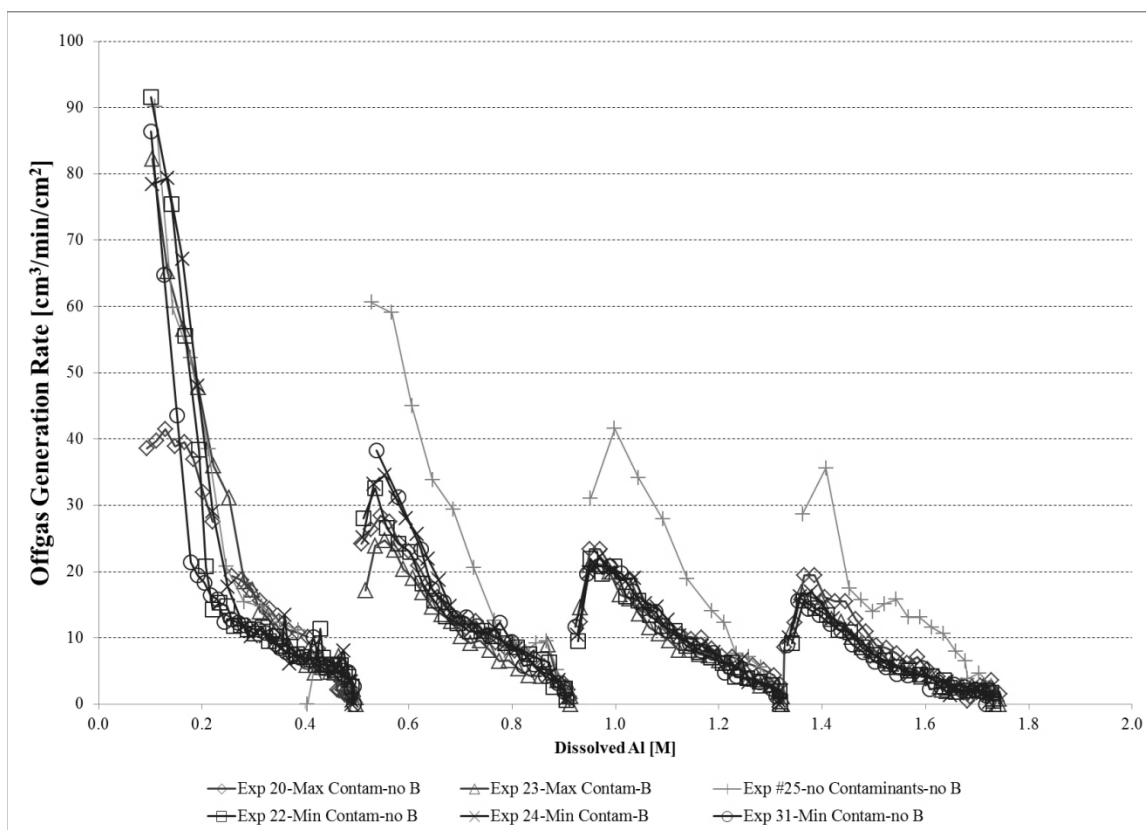


FIG. 2. Off-gas generation rates for dissolution of Al-1100 with Hg initially present.

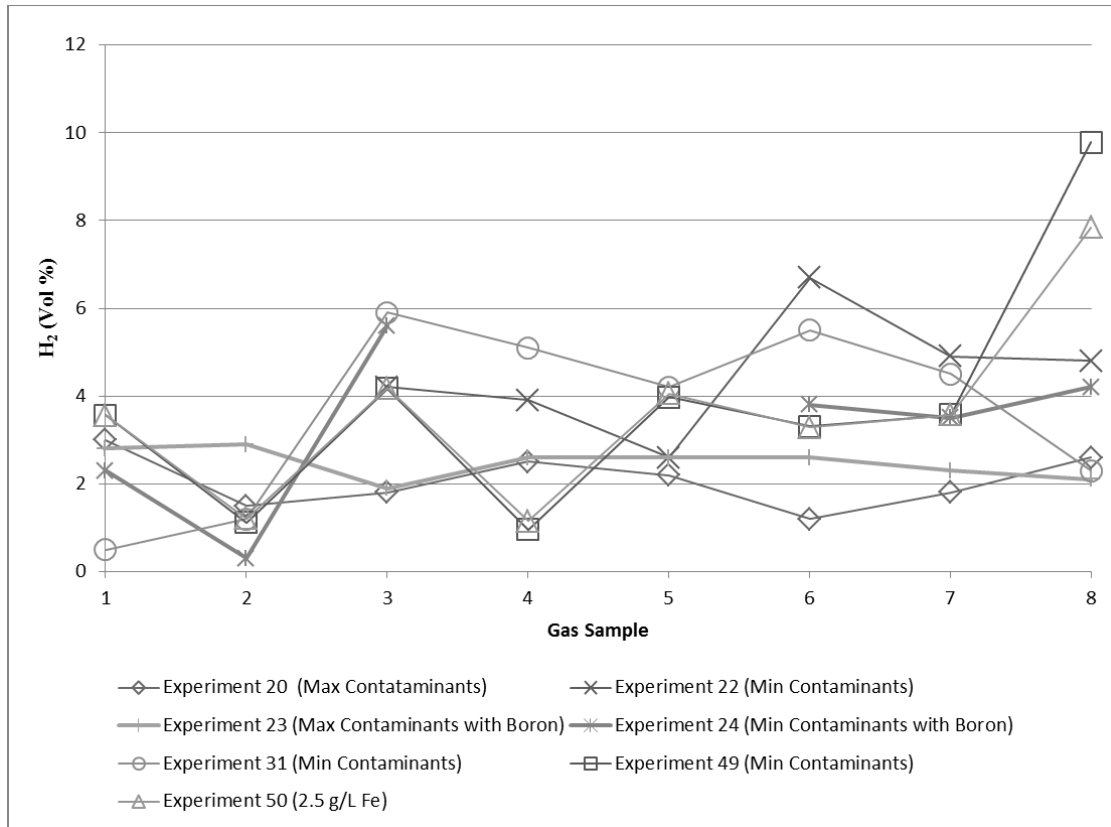


FIG. 3. Hydrogen profiles for Al-1100 alloys dissolved with contaminants.

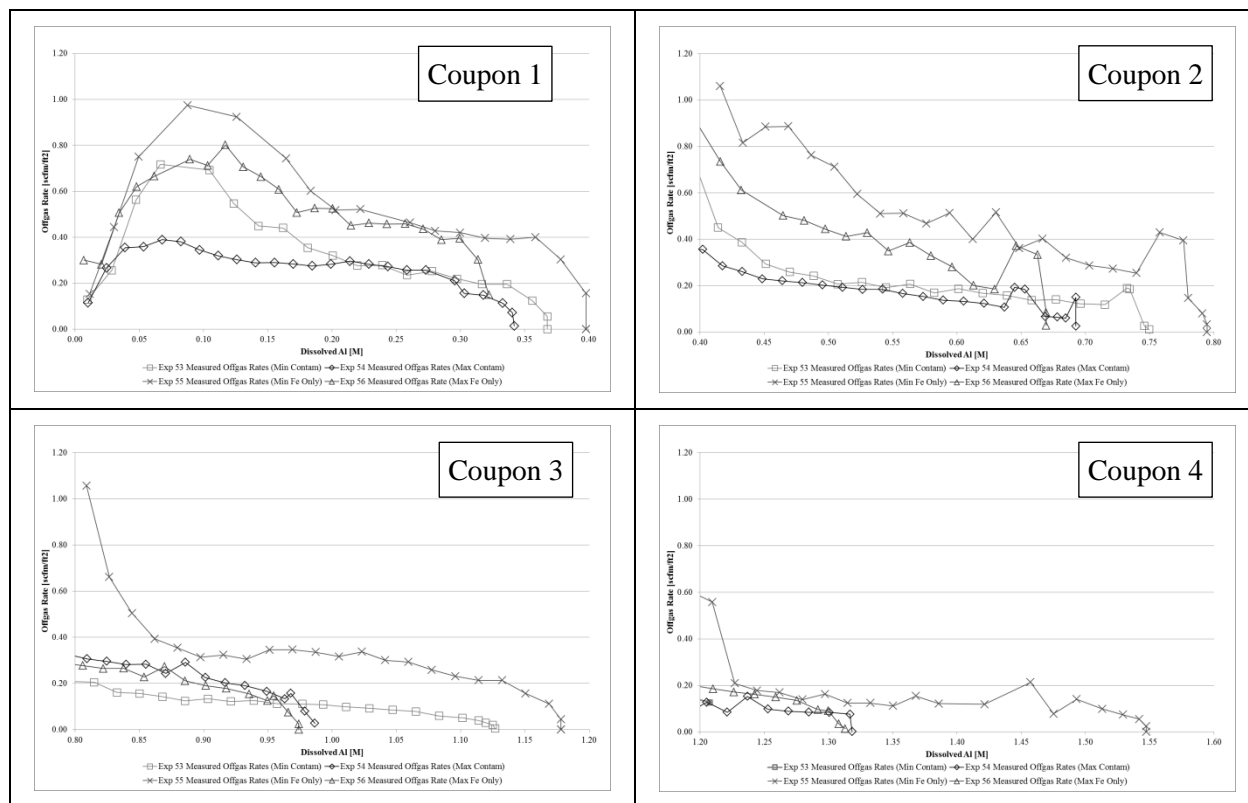


FIG. 4. Comparison of off-gas rates for Experiments 53-56 for 30 wt % U-Al

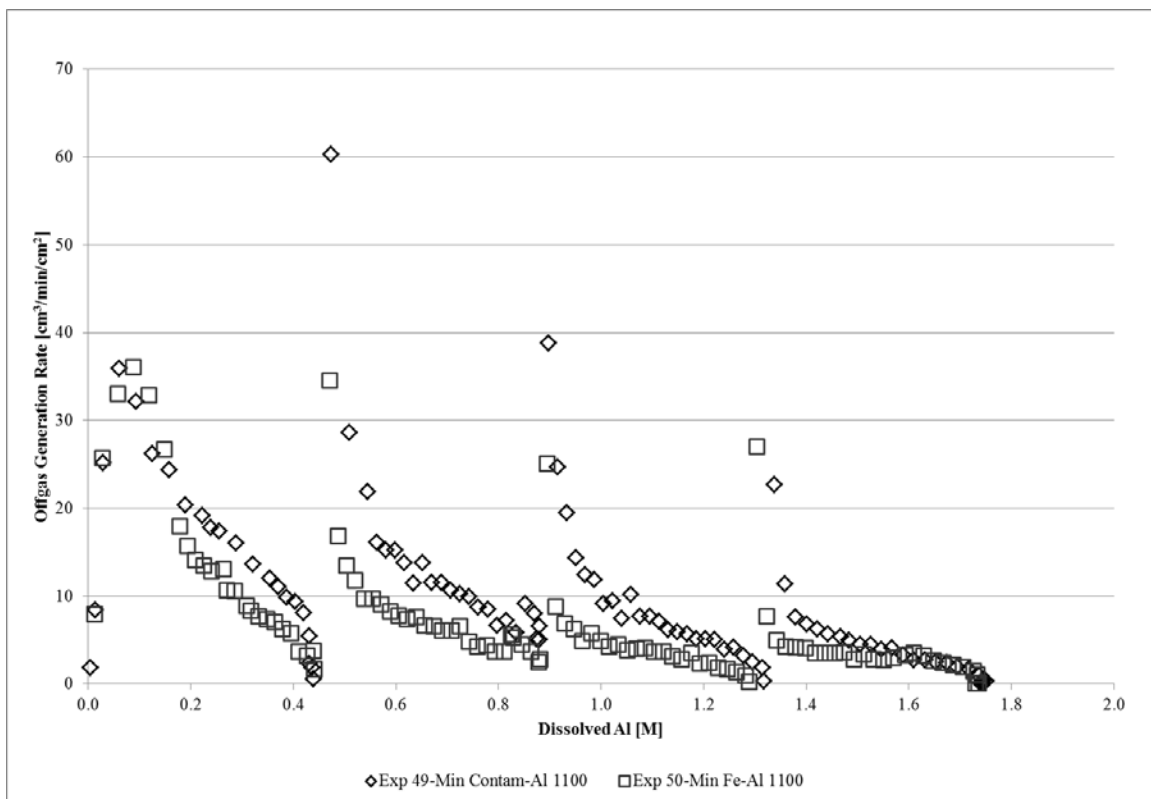


FIG. 5. Comparison of off-gas rates for Experiment 49 (minimum contaminants) and Experiment 50 (Fe 2.5 g/L) for Al-1100 alloy.

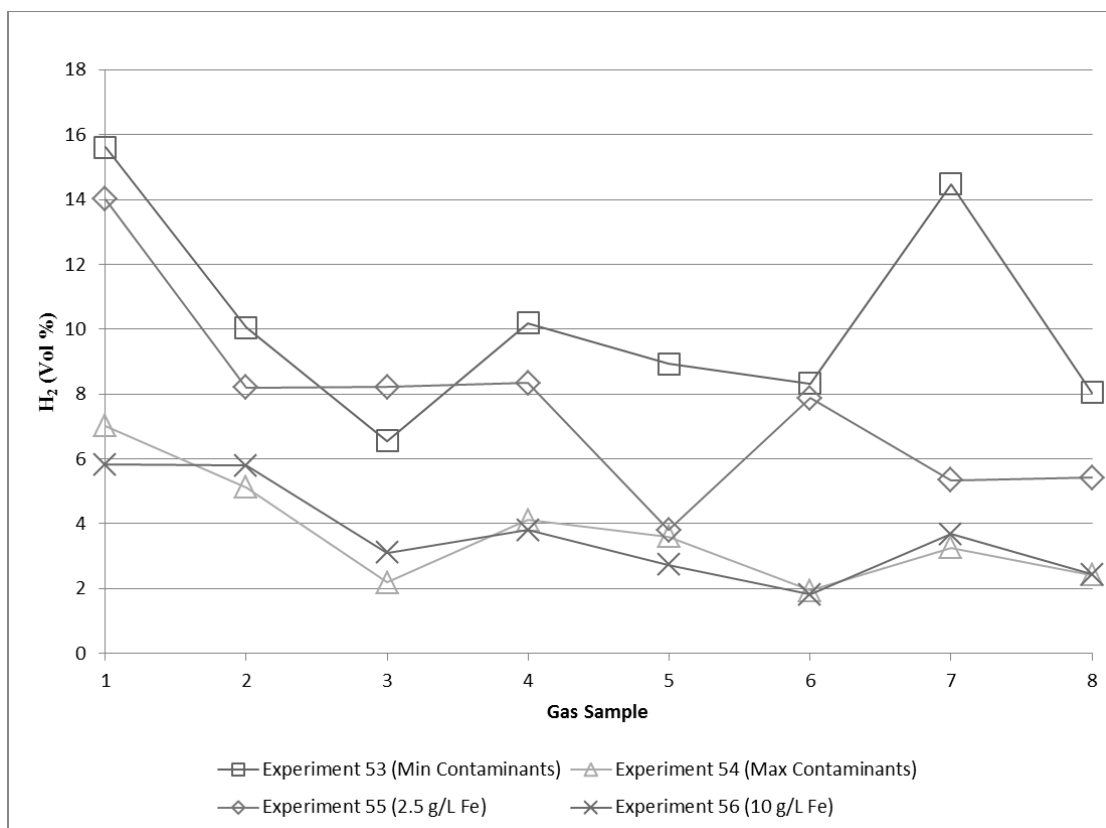


FIG. 6. Hydrogen profiles for 30 wt % U-Al alloys dissolved with contaminants.

TABLE 1

Estimation of Contaminant Ranges from AFS-2 Column Waste and Reagents used for Simulant Preparation

Element/ Species	Concentration	Description	Reagent Name	Chemical Formula
K	0.05–0.1 M	Dissolution Catalyst	Potassium Fluoride	KF
F	0.05–0.1 M	Dissolution Catalyst	Potassium Fluoride	KF
Fe	2.5–10 g/L	Impurity, Corrosion Product Valence Adjustment	Iron(III) nitrate Nonahydrate,	$\text{Fe}(\text{NO}_3)_3 \cdot 9\text{H}_2\text{O}$
			2.14 M Ferrous Sulfamate solution	$\text{Fe}(\text{NH}_2\text{SO}_3)_2$
Cr	0.5–2.0 g/L	Corrosion Product	Chromium(III) Nitrate Nonahydrate	$\text{Cr}(\text{NO}_3)_3 \cdot 9\text{H}_2\text{O}$
Ni	0.2–1.0 g/L	Corrosion Product	Nickel(II) Nitrate Hexahydrate	$\text{Ni}(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O}$
Mn	0.05–0.20 g/L	Corrosion Product	50 wt % Manganous(II) Nitrate solution	$\text{Mn}(\text{NO}_3)_2$
Al	0.075–0.2 M	Fluoride Complexant	Aluminum Nitrate Nonahydrate	$\text{Al}(\text{NO}_3)_3 \cdot 9\text{H}_2\text{O}$
Cl	500 ppm	Impurity	Sodium Chloride	NaCl
B	0–1.6 g/L	Neutron Poison	Boric Acid	H_3BO_3
Gd	0.25–2.0 g/L	Neutron Poison	Gadolinium (III) Nitrate Hexahydrate	$\text{Gd}(\text{NO}_3)_3 \cdot 6\text{H}_2\text{O}$
Am- 241*	5–15 mg/L	Impurity	---	---
Pu*	0–0.1 g/L	Plutonium Losses	---	---

*Omitted in simulants

TABLE 2

Simulants for AFS-2 Column Waste Dissolution Experiments with Hg Initially Present

Contaminants	Experiment 20	Experiment 22	Experiment 23	Experiment 24	Experiment 31
	Al-1100	Al-1100	Al-1100	Al-1100	Al-1100
	Max Contam.	Min Contam.	Max Contam.	Min Contam.	Min Contam.
HNO ₃	7.0 M	7.0 M	7.0 M	7.0 M	7.0 M
Hg [*]	0.012 M	0.012 M	0.012 M	0.012 M	0.016 M
K	0.1 M	0.1 M	0.1 M	0.1 M	0.1 M
F	0.1 M	0.1 M	0.1 M	0.1 M	0.1 M
Fe _{total}	10 g/L	2.5 g/L	10 g/L	2.5 g/L	2.5 g/L
Fe _{FS}	---	2 g/L	6 g/L	2 g/L	2 g/L
Cr	2.0 g/L	0.5 g/L	2.0 g/L	0.5 g/L	0.5 g/L
Ni	1.0 g/L	0.2 g/L	1.0 g/L	0.2 g/L	0.2 g/L
Mn	0.20 g/L	0.05 g/L	0.20 g/L	0.05 g/L	0.05 g/L
Al	0.075 M	0.075 M	0.075 M	0.075 M	0.075 M
Cl	500 ppm	500 ppm	500 ppm	500 ppm	500 ppm
B	---	---	1.6 g/L	1.6 g/L	---
Gd	2.0 g/L	0.25 g/L	2.0 g/L	0.25 g/L	0.25 g/L

*Initial Hg concentration

TABLE 3

Composition of Dissolving Solutions with Metering of Hg

Contaminants	Experiment 49	Experiment 50	Experiment 53	Experiment 54	Experiment 55	Experiment 56
	Min	Fe _{min}	Min	Max	Fe _{min}	Fe _{max}
	Contam.	Al-1100	Contam.	Contam.	30 wt % U- 30 wt % U-	30 wt % U- 30 wt % U-
	Al-1100		Al	Al	Al	Al
HNO ₃	7.0 M	7.0 M	7.0 M	7.0 M	7.0 M	7.0 M
Hg [*]	0.012 M	0.012 M	0.012 M	0.012 M	0.012 M	0.012 M
K	0.1 M	0.1 M	0.1 M	0.1 M	0.1 M	0.1 M
F	0.1 M	0.1 M	0.1 M	0.1 M	0.1 M	0.1 M
Fe _{total}	2.5 g/L	2.5 g/L	2.5 g/L	10.0 g/L	2.5 g/L	10.0 g/L
Fe _{FS}	2.0 g/L	2.0 g/L	2.0 g/L	6.0 g/L	2.0 g/L	6.0 g/L
Cr	0.5 g/L	---	0.5 g/L	2.0 g/L	---	---
Ni	0.2 g/L	---	0.2 g/L	1.0 g/L	---	---
Mn	0.05 g/L	---	0.05 g/L	0.20 g/L	---	---
Al	0.0 M	---	0.0 M	0.0 M	---	---
Cl	500 ppm	---	500 ppm	500 ppm	---	---
B	---	---	---	---	---	---
Gd	0.25 g/L	---	0.25 g/L	2.0 g/L	---	---

*Final Hg concentration after Hg addition during experiment