Aluminum Solubility in Boron Containing Solutions as a Function of pH and Temperature

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Based on the solubility data summarized in Figure 1, bounding estimates of aluminum solubility in alkaline environments containing boron were obtained. In Figure 1, '$p[Al]_T$' means the negative log to the base 10 of the total aluminum content as dissolved or precipitated in units of mol/kg. The Al solubility was estimated with and without inclusion of data from the Al corrosion loop tests. The bounding curves were drawn based on engineering judgment.

Because we are only interested in alkaline solutions, the chemical form of the dissolved Al is $Al(OH)_4^-$, and $p[Al]_T$ can be replaced by $-\log[Al(OH)_4^-]$, where $\log[Al(OH)_4^-]$ is the log to the base 10 of the molal concentration of $Al(OH)_4^-$. One mole of $Al(OH)_4^-$ has one mole of Al, which is equivalent to 26.98 g.

The upper line in Figure 1 bounds all data except for the two data from the Al corrosion loop tests and one other data point from another loop test based on chemical additions and is given by

$$\begin{aligned} \log\left[Al(OH)_4^-\right] &= pH - 14.1 + 0.0243T \qquad (T \le 162\ ^\circ F) \\ \log\left[Al(OH)_4^-\right] &= pH - 10.41 + 0.00148T \qquad (T > 162\ ^\circ F) \end{aligned}, \tag{1}$$

where T is the temperature in degrees Fahrenheit. Therefore, the solubility of Al in units of ppm can be expressed as:

$$\begin{aligned} [Al(ppm)] &= 26980 \times 10^{pH - 14.1 + 0.0243T} \qquad (T \le 162^\circ F) \\ [Al(ppm)] &= 26980 \times 10^{pH - 10.41 + 0.00148T} \qquad (T > 162^\circ F) \end{aligned}. \tag{2}$$

Shifting the solubility estimate upward to bound the two data points from Al corrosion loop tests gives

$$\begin{aligned} \log\left[Al(OH)_4^-\right] &= pH - 14.4 + 0.0243T \qquad (T \le 175\ ^\circ F) \\ \log\left[Al(OH)_4^-\right] &= pH - 10.41 + 0.00148T \qquad (T > 175\ ^\circ F) \end{aligned}. \tag{3}$$

The corresponding solubility of Al in units of ppm can be expressed as:

$$\begin{aligned} [Al(ppm)] &= 26980 \times 10^{pH - 14.4 + 0.0243T} \qquad (T \le 175^\circ F) \\ [Al(ppm)] &= 26980 \times 10^{pH - 10.41 + 0.00148T} \qquad (T > 175^\circ F) \end{aligned}. \tag{4}$$

Estimates of Al solubility as a function of pH and solution temperature based on Eq. (2) are shown in Figure 2. Eq. (4) gives the more conservative Al solubility curves, i.e., it predicts a lower value for the amount of Al that can present before precipitation occurs, shown in Figure 3. The Al solubility predicted by Eq. (4) is about a factor of 2 lower than that predicted by Eq. (2). The Al solubility predicted by Eq. (2) gives a lower bound on the available solubility data in alkaline solutions containing boron, except for the Al corrosion loop tests. Eq. (4) gives a lower bound on all the available solubility data in alkaline solutions.

Most of the available high temperature (> 140°F) data come from long-term Al solubility tests at ANL[2]. The test solution was alkaline or near neutral and composed of boric acid and sodium hydroxide. Aluminum was added as sodium aluminate. Figure 4 shows typical solution temperature history for the long-term Al solubility tests. The temperature history was to be representative of the temperature of the reactor coolant as it passes through the core, a heat exchanger, and the sump after a LOCA. The test durations at higher temperatures (> 140°F) are short, no more than one day at each temperature. The relatively short test times and the presence of boric acid in the test solution should be kept in mind when applying the proposed Al solubility curves at relatively high temperatures (> 140°F) or in boron-free environments. In a boron-free environment the Al solubility may decrease significantly.

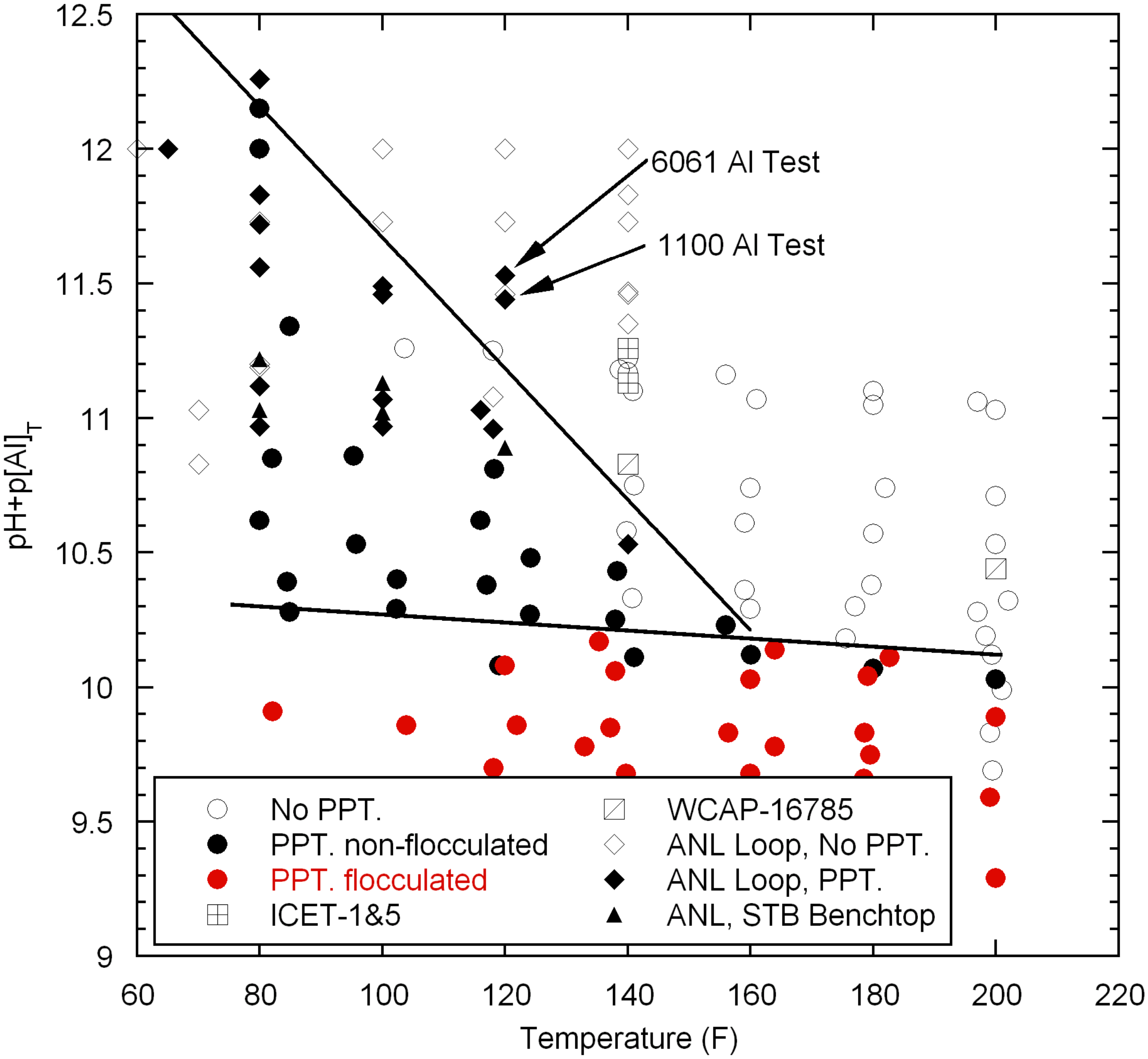

Figure 1. Al stability map in the 'pH+p[Al]$_T$' vs. temperature domain for solutions containing boron; filled and open symbols mean the occurrence of Al hydroxide precipitation and no precipitation, respectively; 'pH' and 'p[Al]$_T$' mean the solution pH at temperature and the negative log to the base 10 of the total aluminum content as dissolved or precipitated in units of mol/kg (reproduced from Ref. [1]).

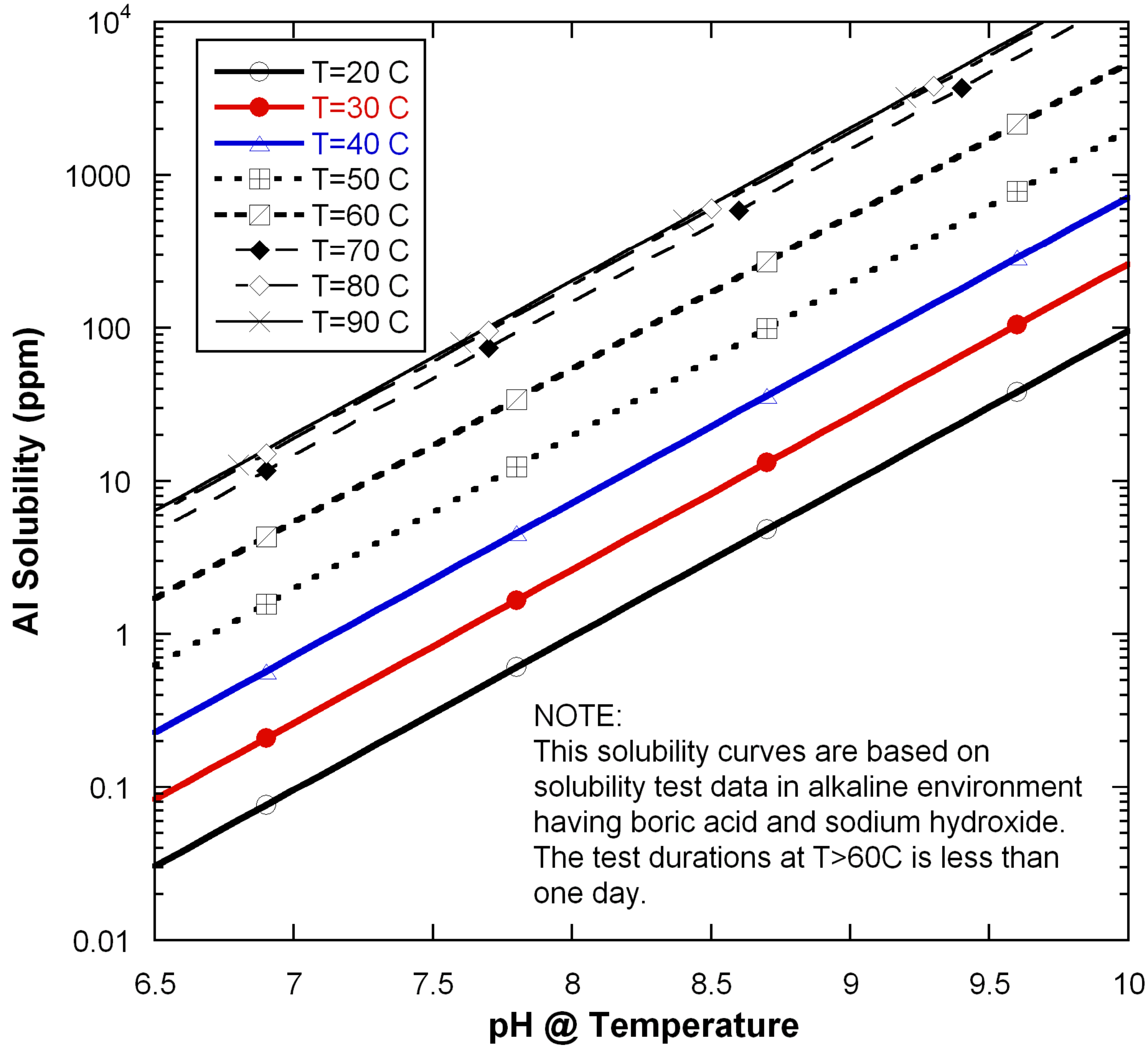

Figure 2. Al solubility curves as functions of pH and temperature without considering test data from Al corrosion loop tests.

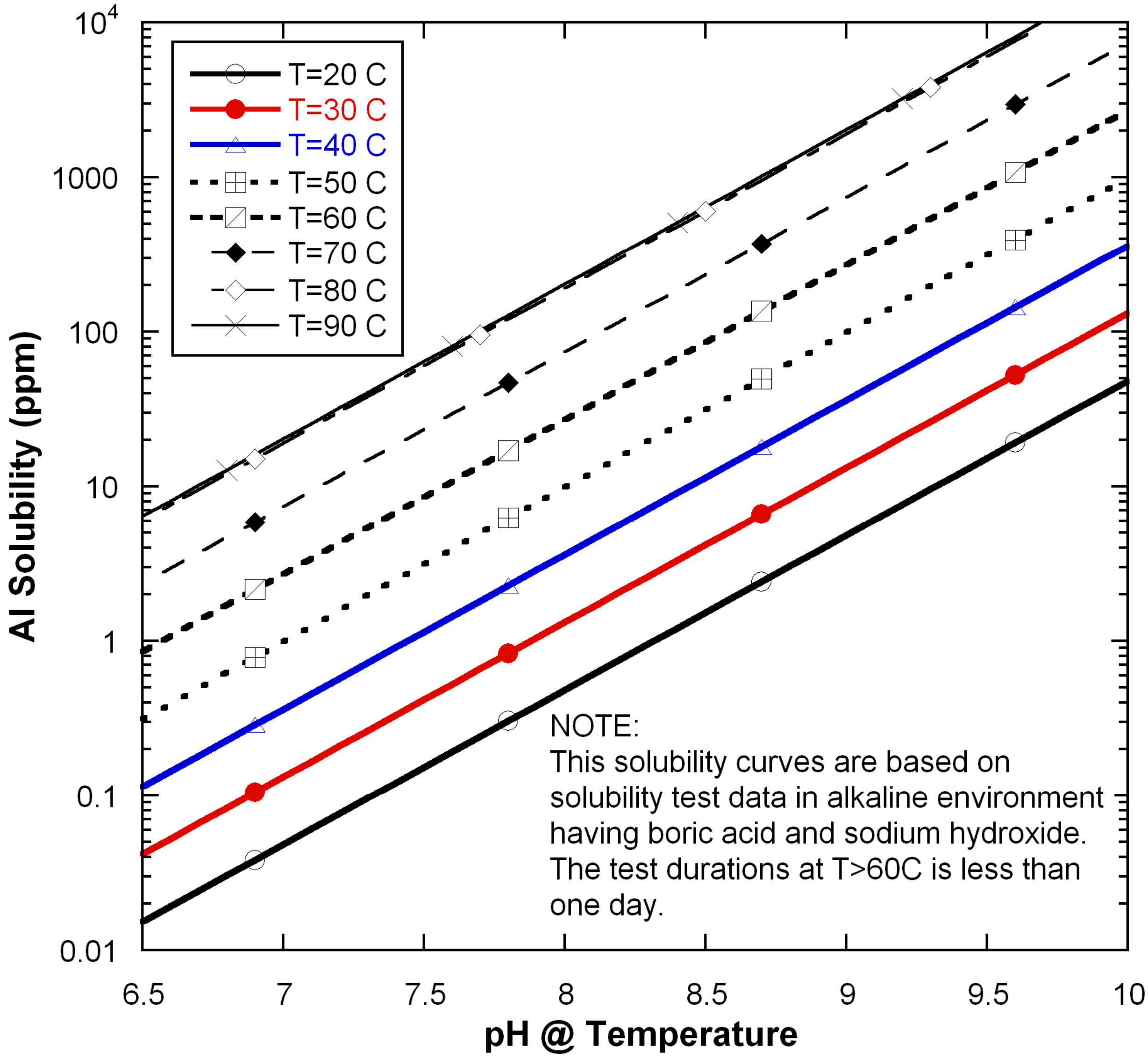

Figure 3. Al solubility curves as a function of pH and temperature with considering test data from Al corrosion loop tests.

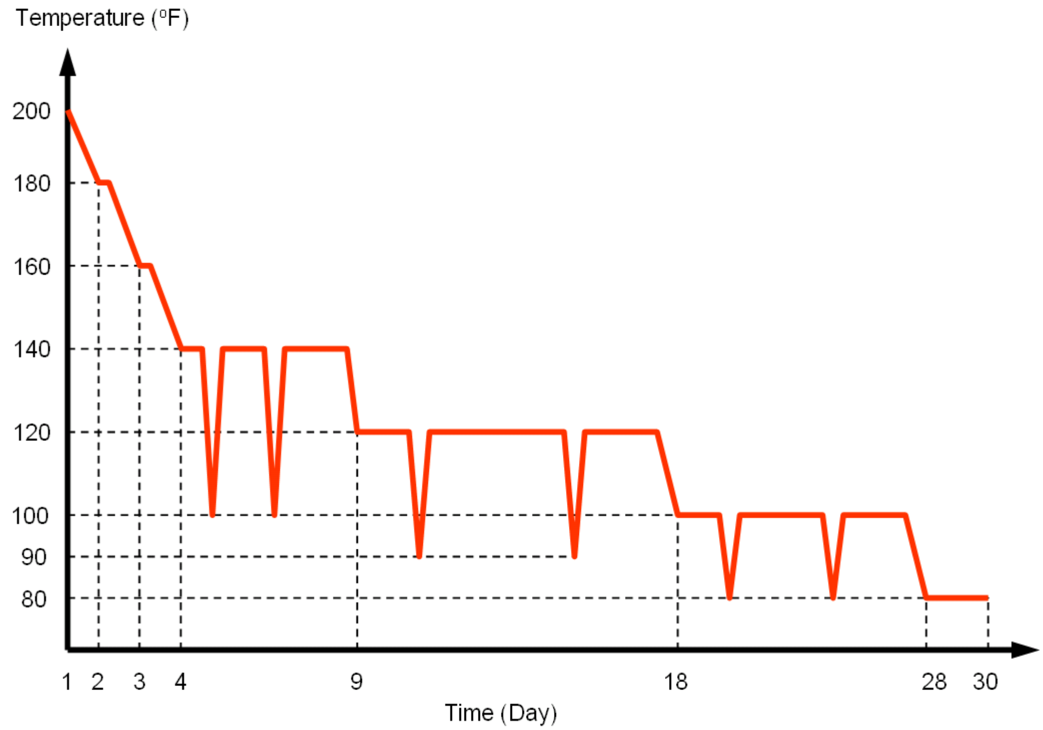

Figure 4. Typical solution temperature history for the long-term 30-day Al solubility tests (reproduced from Ref. [2]).

References

1. C. B. Bahn, K. E. Kasza, W. J. Shack, and K. Natesan, *Technical Letter Report on Evaluation of Head Loss by Products of Aluminum Alloy Corrosion,* ADAMS Accession No. ML082330153, U.S. Nuclear Regulatory Commission, Washington, D.C., August 2008.

2. C. B. Bahn, K. E. Kasza, W. J. Shack, and K. Natesan, *Technical Letter Report on Evaluation of Long-term Aluminum Solubility in Borated Water Following a LOCA,* ADAMS Accession No. ML081550043, U.S. Nuclear Regulatory Commission, Washington D.C., February 2008.