

QUANTITATIVE RESULTS FROM THE FLUSHING OF FOUR REDUCING AND ALKALINITY-PRODUCING SYSTEMS¹

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ABSTRACT

Two reducing and alkalinity producing systems (RAPS) at the De Sale II site in Butler County, Pennsylvania and two RAPS at the Oven Run B site in Somerset County, Pennsylvania were flushed. At the De Sale II site, the right RAPS (two RAPS are configured in parallel) was flushed nine months after construction. Eight flush pipes were flushed sequentially for nine minutes each. A total of 18,400 gallons were removed during the flush, which amounted to 5 % of the total volume of water within the RAPS. Only 3.1 lbs. of iron and 2.0 lbs. of aluminum were removed during the flush. This amounted to 0.2 % and 0.3 % of the iron and aluminum that had been retained within the RAPS, respectively. The left RAPS at the De Sale II site was flushed 14 months after construction. Four pipes draining the upper part of the RAPS were flushed simultaneously for 11 hours. The remaining four pipes that drained the lower part of the system were then opened and allowed to flush for four hours, completely draining the system of 378,000 gallons of water. A total of 22.1 lbs. of iron and 14.4 lbs. of aluminum were removed during the flush. This amounted to 1.1 % and 1.3 % of the iron and aluminum that had been retained within the RAPS, respectively. At the Oven Run B site, RAPS 1 (two RAPS are configured in series) was flushed four months after construction. Three flush pipes were flushed 20 minutes each. A total of 131,000 gallons were removed during the flush, which amounted to about 6 % of the total volume of water within the RAPS. A total of 432 lbs. of iron and 167 lbs. of aluminum were removed during the flush. This amounted to 3.0 % and 2.2 % of the iron and aluminum that had been retained within the RAPS, respectively. Two additional similar flushes were documented at the Oven Run B site. While none of these flushes removed a significant percentage of the metals retained within the system, only a small percentage of the void volume was calculated to be filled with precipitates (0.25 % - 5 %) at the time of the flushes.

INTRODUCTION

Numerous passive treatment systems have been constructed to treat mine drainage over the past two decades. The effectiveness of these systems has varied widely. Many systems receiving net alkaline mine drainage or net acidic drainage that contains very low ferric iron and aluminum concentrations have been very effective. Ponds and aerobic wetlands are used to treat net alkaline drainage to oxidize, precipitate and settle iron. Iron removal rates are typically 10-20 grams per day per square meter of surface area (Hedin et al. 1994). Net acidic drainage with very low ferric iron and aluminum concentrations is directed through anoxic limestone drains which add bicarbonate alkalinity (100 –300 ppm as CaCO₃) and in many cases results in net alkaline water (Watzlaf et al. 2000a). Mine drainage containing ferric iron and/or aluminum has been more problematic. Ferric iron is thought to armor limestone, significantly lowering its rate of dissolution. Aluminum, which will precipitate at the higher pH within ALDs, can quickly clog the pore spaces between the limestone rocks and cause the system to fail (Watzlaf et al. 2000a). Compost wetlands have been used to treat this type of water with limited success. These surficial-flow wetlands contain a compost and limestone layer. The required size for effective treatment using compost wetlands can be extremely large. Compost wetlands remove acidity at a rate of 3.5 – 7 grams per day per square meter of surface area (Hedin et al. 1994). Therefore, to treat a modest 25 gal/min flow of pH 3.0 water containing 100 ppm Fe (50 ppm ferric and 50 ppm ferrous) and 20 ppm Al, a wetland of 2 to 4 acres would be required. To reduce the size requirement of compost wetlands, systems were constructed to force the water to flow down through the compost and limestone layers (Kepler and McCleary 1994). These systems are called successive alkalinity producing systems (SAPS) and vertical flow systems.

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To be more descriptive, these have been termed reducing and alkalinity producing systems or RAPS (Watzlaf et al. 2000b). RAPS are commonly constructed with 2 – 3 feet of limestone. A network of perforated pipes is placed in the bottom of this limestone layer. On top of the limestone, a 0.5 – 2 feet layer of organic matter is placed. Typically the organic material is spent mushroom compost, which consists of horse manure, hay, straw, chicken manure and gypsum. Mine water flows down through the system, encountering the reducing environment of the compost before contacting the limestone. The compost layer is intended to remove the dissolved oxygen and convert any ferric iron to the ferrous state to avoid armoring of the limestone. It is thought that RAPS may be less prone to plugging with aluminum than ALDs because of their larger cross-sectional areas (perpendicular to flow paths) and higher available head pressures. The systems are generally constructed to allow for at least 6 feet of head to be utilized, if needed, to overcome losses in permeability. Alkalinity generation rates for these systems range from 40 to 60 grams per day per square meter of surface area for the first RAPS and from 15 to 20 grams per day per square meter of surface area for a second RAPS when two RAPS are used in series (Watzlaf et al. 2000b). Both iron and aluminum are removed within these systems. To extend the life of these systems, most are periodically flushed. No guidelines have been developed to guide the frequency, duration, or intensity of the flushes nor has any quantification of the effectiveness of the flushes been reported. In general, the flush valves are opened until the water “runs clear.” The cloudy water can persist for a few minutes to a few hours. This study quantified both the metals retained prior to and the metals removed during flushing.

SITE DESCRIPTIONS

De Sale II

The De Sale II site, is located in Butler County, Pennsylvania, within the headwaters of Seaton Creek, a heavily impacted tributary in the Slippery Rock Creek Watershed. The system consists of an equalization pond, two RAPS, an oxidation pond, wetlands, and a horizontal limestone bed. Each RAPS is approximately 325 ft. long and 52 ft. wide and consists of (from the bottom up) 0.5 ft. of limestone for pipe bedding (AASHTO #57), the lower discharge/flush pipes, 2 ft. of limestone (AASHTO #1 (approx. 4 in., 90% calcium carbonate), the upper discharge/flush pipes, 2 ft. of limestone (AASHTO #1), 0.5 ft. of spent mushroom compost, and 2.5 – 3 ft. of water (figure 1a). Networks of piping drain four quadrants at two different vertical levels (upper and lower) within the system. This more extensive underdrain system was developed in an attempt to optimize both the distribution of flow during normal operation and the flushing of accumulated iron and aluminum solids. The underdrain was constructed of 4 in. diameter Schedule 40 PVC pipe. Perforated laterals were placed on 4.5 ft. centers and connected to an un-perforated header with a sanitary-type tee. Perforations were hand-drilled with two, 0.5 in. perforations which were offset approximately 30° from the top of pipe. The perforation spacing was equal to the lateral spacing (4.5 ft.). Four separate header pipes were used for each underdrain level thus dividing the surface area into approximately equal quadrants. The upper and lower underdrain levels effectively divides each RAPS into eight separate “cells”, four upper and four lower (figure 1b).

Since its completion on September of 2000 the RAPS have been functioning effectively, increasing pH from 3.1 to 6.9, adding 370 ppm of alkalinity, and decreasing iron and aluminum concentrations from 27 to 5 ppm, and 11 to 0.3 ppm, respectively.

Oven Run Site B

The Oven Run Site B is located in Somerset County, Pennsylvania, in the Stonycreek River Watershed. The system treats water emanating from three underground mine entries and consists of an equalization pond, a RAPS (RAPS 1), a sedimentation pond, a second RAPS (RAPS 2), and a final sedimentation pond, all in series. Each RAPS consists of (from the bottom up), a geotextile liner, 3 ft. of limestone, 1 ft. of spent mushroom compost, and 2 ft. of standing water. Positioned at the bottom of the limestone layer is 6 in. diameter perforated pipe.

RAPS 1 is 950 ft. long and 100 ft. wide. Three perforated pipes are laid out in parallel running the entire length of the system and spaced 20 ft. apart. At 135 ft., 405 ft., and 675 ft. from the influent to RAPS 1, each of the three parallel perforated pipe are connected to an un-perforated, 10 in. diameter pipe that is used for flushing. In effect, this divides the RAPS into three equal areas for flushing. The ends of these flush pipes are approximately 25 ft. below the elevation of the water in RAPS 1.

RAPS 2 is 552 ft. long and 160 ft. wide. Five perforated pipes are laid out in parallel running the entire length of the system and spaced 25 ft. apart. At 130 ft. and 390 ft. from the influent to RAPS 2, each of the five parallel perforated pipe are connected to an un-perforated, 10 in. diameter pipe that is used for flushing. In effect, this divides the RAPS

into two equal areas for flushing. The ends of these flush pipes are approximately 8 ft. below the elevation of the water in RAPS 2.

Since its completion in October 1999, the total system has increased pH from 2.96 to 6.45, added 534 ppm of alkalinity, and lower iron and aluminum concentrations from 68 to 5 ppm and 41 to 4 ppm, respectively.

METHODS

Flushing at De Sale II

The right RAPS was flushed on June 20, 2001, nine months after the RAPS began treating water. Each of the eight pipes was flushed sequentially at full volume (175 – 360 gal./min. per pipe) for nine minutes. A total of 18,400 gallons of water was removed (~ 4 % of the total volume of water in the RAPS). Samples were collected at 15, 30, 45 seconds, 1, 1.5, 2, 2.5, 3, 3.5, 4, 4.5, 5, 6, 7, 8, and 9 minutes. Dissolved oxygen, temperature, and pH were monitored continuously and recorded at each sample interval. Flows were measured periodically (~ every 1-3 minutes) using three different methods: horizontal pipe discharge method, time volumetric method, and water level changes in RAPS. All three flow measurement techniques were in fairly good agreement (within ~ 15%). Samples were not filtered and consisted of an unacidified and acidified sample. Samples were analyzed in the laboratory for concentrations of standard and trace mine drainage metals and sulfate.

The left system was flushed December 12-13, 2001, after 14 months of treatment. Based on the results of the first flush, it was decided to flush the left system much more aggressively and to drain the system completely. The pipes draining the four upper quadrants were opened at the same time. After these pipes had drained for 11 hours, at which time the flow had diminished to a trickle. After closing the valves to the upper pipes, the lower flush pipes were opened and drained for an additional 4.5 hours (fig 3). Flows were measured periodically (every 10-20 minutes) using the horizontal pipe discharge method which had compared favorably to the timed volumetric method and water level changes method during the previous flush. A total of 378,000 gallons of water were removed from the system. Unfiltered samples were collected from each pipe at 10-minute intervals. Temperature, pH and flow measurements were taken between sample collection.

Samples were acid digested in the analytical laboratory and analyzed for standard and trace metals using standard methods. For unacidified samples, acidity was determined by adding H_2O_2 to the sample, heating, and titrating the solution to pH 8.2 with NaOH (American Public Health Association 1998). If the sample was net alkaline, it was heated with H_2O_2 , and then the solution was titrated with H_2SO_4 to a pH of 4.5. Net alkalinity was reported as a negative net acidity. Metal concentrations in the acidified samples were determined using inductively coupled argon plasma - atomic emission spectroscopy (ICP-AES). Sulfate concentrations were determined by ICP-AES (as total sulfur) on water samples that had been acidified and boiled to remove any hydrogen sulfide.

Flushing at Oven Run Site B

The RAPS have been flushed 13 times (about every 2 – 4 months) since their construction in October 1999. This paper reports on the flush of RAPS 1 on February 24, 2000 and February 1, 2001 and the flush of RAPS 2 on February 1, 2001. The February 24, 2000 flush occurred after 4 months of treatment. The February 1, 2001 flush occurred 1.5 months after a prior flush.

In February 2000, RAPS 1 was flushed during two separate days. Pipe 1 was flushed on February 3 and pipes 2 and 3 were flushed on the February 24. During the flush of pipe 1, the valve was opened fully and samples were collected at 2, 12, and 20 minutes after which the valve was closed. For the flush of pipes 2 and 3, both valves were opened and samples were collected at 2, 10, and 20 minutes. For both of the RAPS 1 and RAPS 2 flushes in February 2001, all flush pipes were opened with samples being collected at 6, 20, and 30 minutes. A raw and an acidified sample were collected. None of the samples were filtered.

No flow measurements were taken during the reported flush, however, flows were estimated by measuring the depression in the water level in the RAPS during a subsequent flush. Flow averaged 6535 gal/min for all three flush pipes in RAPS 1 and 3048 gal/min for the two flush pipes in RAPS 2. All samples were analyzed by the Pennsylvania Department of Environmental Resources using standard methods.

RESULTS AND DISCUSSION

Flushing at De Sale II

The two RAPS at the De Sale II site are essentially equivalent. They were constructed in parallel, have the same dimensions, contain the same type and amount of media (limestone, compost, etc.) and receive water from a common source. However, the effluent water quality produced by the two systems has differed somewhat, most notably in the iron concentration. While both the right and left RAPS have been retaining iron, the effluent from the right RAPS has been higher in iron than that from the left RAPS. Effluent aluminum levels have been equivalent and low (<1 ppm) for both systems. In this study, the right RAPS was flushed first and the left was flushed 5 months later. Based on the laboratory analyses of the water samples obtained during the right RAPS flush, a more thorough flushing of the left RAPS was attempted and the system was completely drained.

Right System Flush

The right RAPS was flushed nine months after it began treating water. From available monitoring data, including flow measurements and water quality analyses, it was calculated that the RAPS had accumulated 1710 lbs. of iron and 688 lbs. of aluminum during these first nine months of operation. The basic criterion used during this flush was that the water should be allowed to flow until it ran clear. In practice, the flush was continued for some additional time. During the flush, a total of 18,400 gallons of water was removed. Figure 2 shows the average Fe and Al concentrations from the upper and lower flush pipes. The maximum metal concentrations shown in the first few minutes corresponded to visibly discolored water. Both the visual observations and the lab analyses indicate that the initial slug of material is quickly removed from the system. The iron and aluminum concentrations after seven minutes of flushing were the same as the dissolved metal concentration indicating that no solid material was eluting.

Numerical integration of the loads corresponding to the concentrations shown in Figure 2 provided the total amount of iron and aluminum removed during the flush. This amounted to only 3.1 lbs. of iron (0.2 % of the iron retained since construction) and 2.0 lbs. of aluminum (0.3 % of the aluminum retained since construction). If one assumes that the water flowed into the pipe uniformly from every direction, the range of influence of this flush can be estimated from the pipe dimensions, the gallons flushed, and by assuming a limestone porosity of about 50% (Hedin and Watzlaf 1994). It is estimated that the last water through each pipe had been, on average, only 4 inches from the pipe before the flush began. Thus, it is doubtful that much, if any of the metal oxyhydroxide laden water actually entered the pipes during this limited flush. Our conclusion is that "flushing until the water runs clear" is probably not a sufficient criterion for effective flushing.

Left System Flush

The left RAPS was flushed 14 months after it began treating water. From available monitoring data, including flow measurements and water quality analyses, it was calculated that the RAPS had accumulated 2090 lbs. of iron and 1100 lbs. of aluminum during these first 14 months of operation. Because of the low amount of metals removed during the flushing of the right RAPS, the criterion used during this flush was that the water should be allowed to flow as long as possible, i.e., until the system was drained. In practice, the four pipes draining the upper quadrants were flushed until the flow slowed to a trickle, then the pipes draining the lower four quadrants were opened and allowed to flow until the system was totally drained. During the flush, a total of 378,000 gallons of water was removed. Figure 3 shows the flows measured from the eight pipes. To a first approximation, the flows in both the upper and lower sections decrease going from quadrant 4 to quadrant 1. Qualitatively, this is consistent with the pressure drop expected due to the increasing length of 4 in. diameter pipe draining the quadrants. However, it would also be consistent with a clogging mechanism in which the settling of suspended material, such as clays, predominated in the quadrants closest to the RAPS inlet. The flows dropped slowly at first and then more rapidly after the first 7 to 8 hours. At about 11 hours the upper quadrants had drained and the valves to the lower quadrants were opened. Flows were higher and longer for the upper quadrants than for the lower quadrants because these pipes drained the standing water, the compost water, and the top limestone layer (total of 5 ft. of head), whereas the lower quadrant pipes drained only the bottom limestone layer (2 ft. of head) (see Figure 1).

The temperature and pH were monitored throughout the flush and these data are shown in Figure 4. The trends for both parameters are the same; both decrease as the cooler, more acidic surface water penetrates the lower strata faster than

the chemical and thermal equilibration can occur. At about 7 hours the values began to climb toward their earlier levels. This is at the same point at which the flow was seen to sharply decrease in Figure 3 (and residence time increase) indicating that the thermal and chemical equilibration rates were now becoming competitive with the flow rate. At a little over 8 hours (where the breaks in the upper quadrant trend lines occur) it was necessary to shut off the flow due to darkness. The next morning the temperature and pH continued to increase further to near their initial values. The pH actually attained somewhat higher values, perhaps because of the overnight stop-flow during which extended contact with the limestone occurred.

Figure 4 also shows total iron and aluminum concentrations at selected times in the upper and lower pipes within the first quadrant, during the flush. The maximum metal concentrations shown in the first few minutes corresponded to visibly discolored water similar to what was seen for the right RAPS flush. The graphs from the three other quadrants were similar except that the spike in the Fe and Al concentrations seen at about nine hours in Figure 4 did not occur in the other quadrants. That Al and Fe occurred in the same spike was curious but analysis of the Fe to Al ratio showed that it changed as the spike eluted and thus the spike was probably not due to a single iron-aluminum compound. However, in total, little additional material was removed from the system even after prolonged flushing. Of the retained 2090 lbs. of iron and 1100 lbs. of aluminum, the flush removed 22.1 lbs. of iron (1.1 % of the iron retained since construction) and 14.4 lbs. of aluminum (1.3 % of the aluminum retained since construction).

Prior to the flush, no decrease in the permeability of the RAPS had been observed. There was less than a 0.05 ft. difference in the elevation between the RAPS water level and the level of the discharge pipe, indicating that very little head was necessary to push the water through the RAPS. The system was probably maintaining permeability because very little void volume had been lost up to that time. The 2090 lbs. of retained iron corresponds to 4000 lbs. of $\text{Fe}(\text{OH})_3$. Previous measurements have indicated that a cubic centimeter of iron sludge contains 0.17 grams iron (Watzlaf et al., in press). Using this value, approximately 197 cubic feet of iron sludge was retained in the RAPS. Making similar assumptions for the aluminum sludge results in 103 cubic feet of aluminum sludge, for a total sludge volume of 300 cubic feet. Assuming a 25 % void in the compost and a 50 % void in the limestone, the RAPS contains about 21,000 cubic feet of void space, with the precipitated sludge occupying only about 1.4 % of this void. Thus, it may be argued that too little material had accumulated to be flushed effectively. Larger masses of material would present a larger cross sectional area to the rapidly flowing water and would be more likely to be transported down-flow.

Flushing at Oven Run Site B

The RAPS at the Oven Run site, which are somewhat older than those at De Sale II, have been flushed 13 times since their construction. This paper reports on two of those flushes (February 2000 and February 2001). The criterion used during these flushes was that the water should be allowed to flow until it ran clear, similar to what was used during the flush of the right RAPS at the De Sale II site.

The first flush of RAPS 1 occurred four months after it began treating water. From the available monitoring data, including flow measurements and water quality analyses, it was calculated that the RAPS had accumulated 6522 kg of iron and 3440 kg of aluminum during these first four months of operation. During the flush, a total of 131,000 gallons of water was removed.

The second flush of RAPS 1 considered here occurred about a year later (16 months after construction) but it had been treating water for only about 7 weeks since the prior flush. A number of flushes had occurred between the first and second flush for which we have data. From the routine monitoring data, it was calculated that the RAPS had accumulated 2410 lbs. of iron and 1200 lbs. of aluminum during the 7 weeks since its last flush. During the flush, a total of 196,000 gallons of water was removed.

Figure 5a and 5b show the Fe and Al concentrations from the 3 flush pipes. The high metal concentrations seen in the first few minutes corresponded to visibly discolored water. Both the visual observations and the lab analyses indicate that the initial slug of material is quickly removed from the system, as was seen at De Sale II.

The amount of metals removed during the first flush of RAPS I amounted to 432 lbs. of iron (3.0 % of the iron retained since construction) and 167 lbs. of aluminum (2.2 % of the aluminum retained since construction). The amount of metals removed during the second flush of RAPS I amounted to 166 lbs. of iron (6.9 % of the iron retained since the previous flush, 7 weeks before) and 88.2 lbs. of aluminum (7.2 % of the aluminum retained since the previous flush, 7 weeks before). Thus, on a percentage basis, the efficiency of the flushing in RAPS I appears to increase over time,

however, the actual amount of metals held within the substrates may be considerably greater than the value that had accumulated in the 7 weeks since its last flush.

The flush of RAPS 2 considered here occurred after it had been receiving water for about 16 months. However, it had been treating water for only about 7 weeks since the prior flush. From the routine monitoring data, it was calculated that the RAPS had accumulated 2810 lbs. of iron and 2200 lbs. of aluminum during the 7 weeks since its last flush. During the flush, a total of 91,000 gallons of water was removed. Figure 5c shows the Fe and Al concentrations from the 2 flush pipes of RAPS 2. Of the 2810 lbs. of retained iron and 2200 lbs. of retained aluminum, 12.7 lbs. of iron (0.5 %) and 28.7 lbs. (1.3 %) of aluminum were removed during the flush. Unlike RAPS 1 where higher incremental metal removals were found (~ 7 %), RAPS 2 flushed poorly.

The percentage of void volume that the retained metals had occupied can be calculated for the Oven Run RAPS as well. Using the fact that a cubic centimeter of iron sludge contains 0.17 grams iron (Watzlaf et al., in press) and assuming a 25 % void in the compost and a 50 % void in the limestone, RAPS 1 and RAPS 2 can be estimated to contain approximately 135,000 cubic feet of void each. For RAPS 1, the 14,400 lbs. of iron and 7580 lbs. of aluminum retained prior to the February 2000 flush would result in 2070 cubic ft. of sludge which amounts to 1.52 % of the void volume available. Similarly, for the February 2001 flush, the 2410 lbs. of iron and 1200 lbs. of aluminum would result in 340 cubic ft. of sludge which amounts to an incremental loss of 0.25 % of the void volume available. For the flush in February of 2001 of RAPS 2, the 2810 lbs. of iron and 2200 lbs. of aluminum would result in 472 cubic ft. of sludge which amounts to an incremental loss of 0.35 % of the void volume available. Even if you consider that all of the material retained since construction (assuming no removal in previous flushes) the void volumes of RAPS 1 and 2 were still < 5 % filled with precipitates at the time of the February 2001 flush. Thus, it may be argued that too little material had accumulated to be flushed effectively.

It is important to note that it is unlikely that the precipitates are distributed uniformly throughout the available void volume. It is more likely that precipitation is occurring in a band (Watzlaf 1997). The width and position of the band would be determined by the pH gradient and rates of precipitation and agglomeration. Therefore, the permeability of the RAPS could be significantly reduced long before 100 % of the void volume was occupied.

It is interesting to note that, although the clogging of RAPS is thought to be due to Al precipitation, Fe is being retained as well. The amounts of iron and aluminum being retained in these systems are shown in Table 1. In addition to the RAPS studied here, the Jennings ALD, which eventually failed, is included for comparison. In 4 of the 6 cases studied here, the molar ratio of Fe to Al is close to 1, in the other 2 the ratio is close to ½. This raises the question of whether a stoichiometric iron aluminate may be forming under the conditions prevalent in these systems. The predominate aqueous-phase Al species present at the pH values seen in these effluents (6.4-6.9) is expected to be $\text{Al}(\text{OH})_4^-$ (Cravotta 2001). But, to our knowledge, insoluble ferrous or ferric aluminates such as $\text{Fe}(\text{Al}(\text{OH})_4)\text{OH}$ (molar ratio of 1) or $\text{Fe}(\text{Al}(\text{OH})_4)_2\text{OH}$ (molar ratio of ½), have not been reported. At least 2 RAPS systems that have exhibited major decreases in permeability, one at Jennings and one in the Tangascootack watershed, will undergo autopsies in the near future. Perhaps data from those will assist in the interpretation of this data.

Table 1. Amounts of retained iron and aluminum prior to flushes.

Flush or Failure	Accumulation Type	Fe Retained (lbs.)	Al Retained (lbs.)	Fe/Al Molar Ratio
De Sale II Left RAPS	Total	1710	708	1.17
De Sale II Right RAPS	Total	2090	1100	0.92
Oven Run B, RAPS 1, Feb 2000	Total	14,400	7580	0.92
Oven Run B, RAPS 1, Feb 2001	Incremental	2410	1200	0.97
Oven Run B, RAPS 2, Feb 2001	Incremental	2810	2200	0.62
Jennings (Watzlaf et al. 2000b)	Total	1260	1280	0.48

CONCLUSIONS

Of the flushes documented here, none removed very much of the retained iron or aluminum. The most efficient achieved only 7 % removal of the incremental amount of metals accumulated since the previous flush (Table 2). None of the systems were experiencing any loss of permeability prior to the flushes. In fact, only a very small percentage (0.25 % – 5 %) of the void volumes were calculated to be filled with iron and aluminum precipitates. Lack of efficiency

has not yet led to failures of these systems and, in one case, efficiency may be improving with time. However, the long-term prospects for these systems appear questionable at best, if the current levels of metal removal via flushing continue.

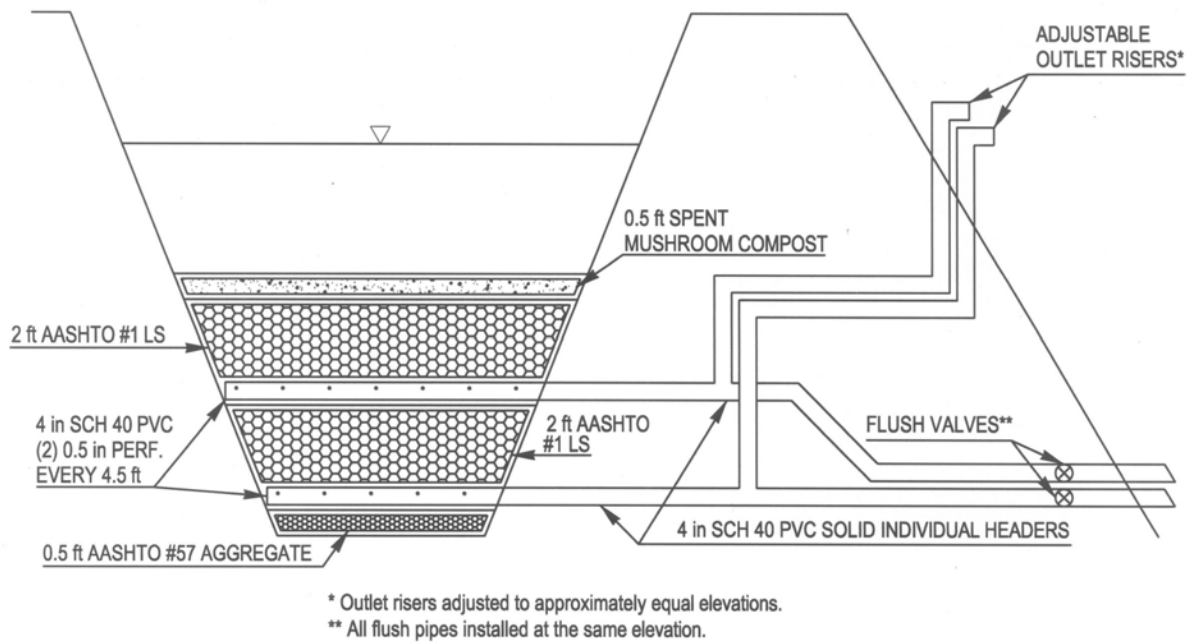
Table 2. Amount of water, iron, and aluminum flushed for the five flush events reported in this paper.

Flush	Water Flushed		Iron Flushed		Aluminum Flushed	
	gallons	% of total	lbs.	% of retained	Kg	% of retained
De Sale II Right RAPS	18,400	5	3.11	0.2 %	2.03	0.3 %
De Sale II Left RAPS	378,000	100	22.1	1.1 %	14.4	1.3 %
Oven Run B, RAPS 1, Feb 2000	131,000	6	432	3.0 %	166	2.2 %
Oven Run B, RAPS 1, Feb 2001	196,000	9	166	6.9 %	88.2	7.2 %
Oven Run B, RAPS 2, Feb 2001	91,000	4	12.7	0.5 %	28.7	1.3 %

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(a)



(b)

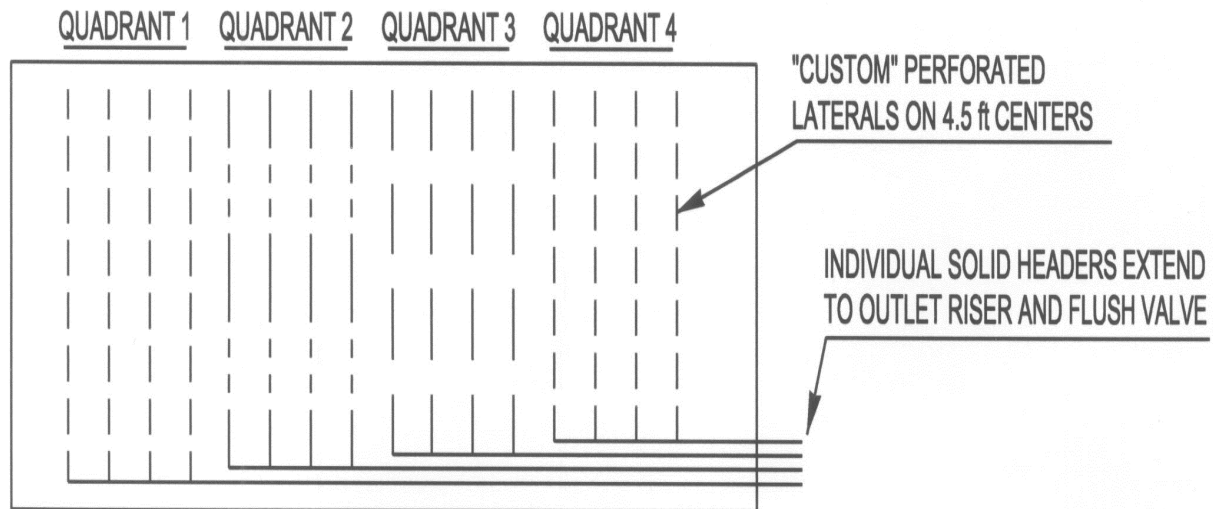


Figure 1. Schematics of the De Sale II RAPS; (a) cross section showing layers of substrate and location of upper and lower flush pipes and (b) plan view showing general layout of flush pipes (in actuality, over 130 laterals were used). Both right and left RAPS are identical.

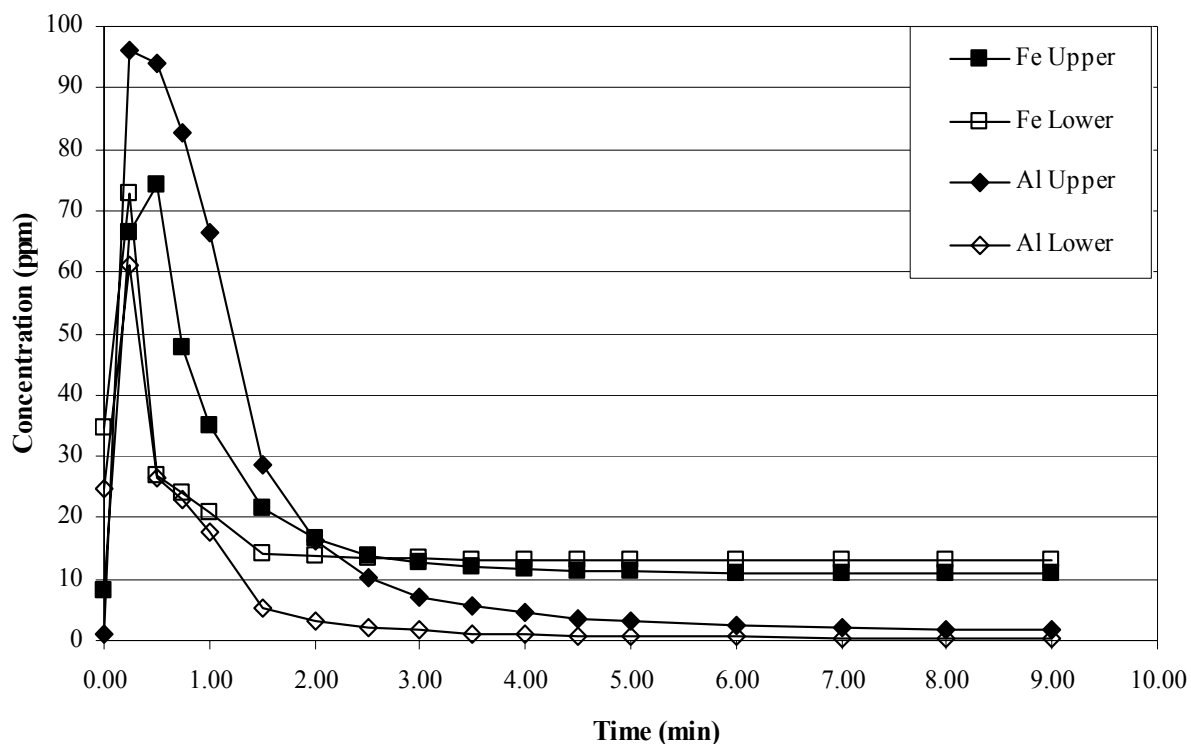


Figure 2. Iron and aluminum concentrations during the flush of the right RAPS at the De Sale II site. Each line represents average concentration from four upper or lower flush pipes.

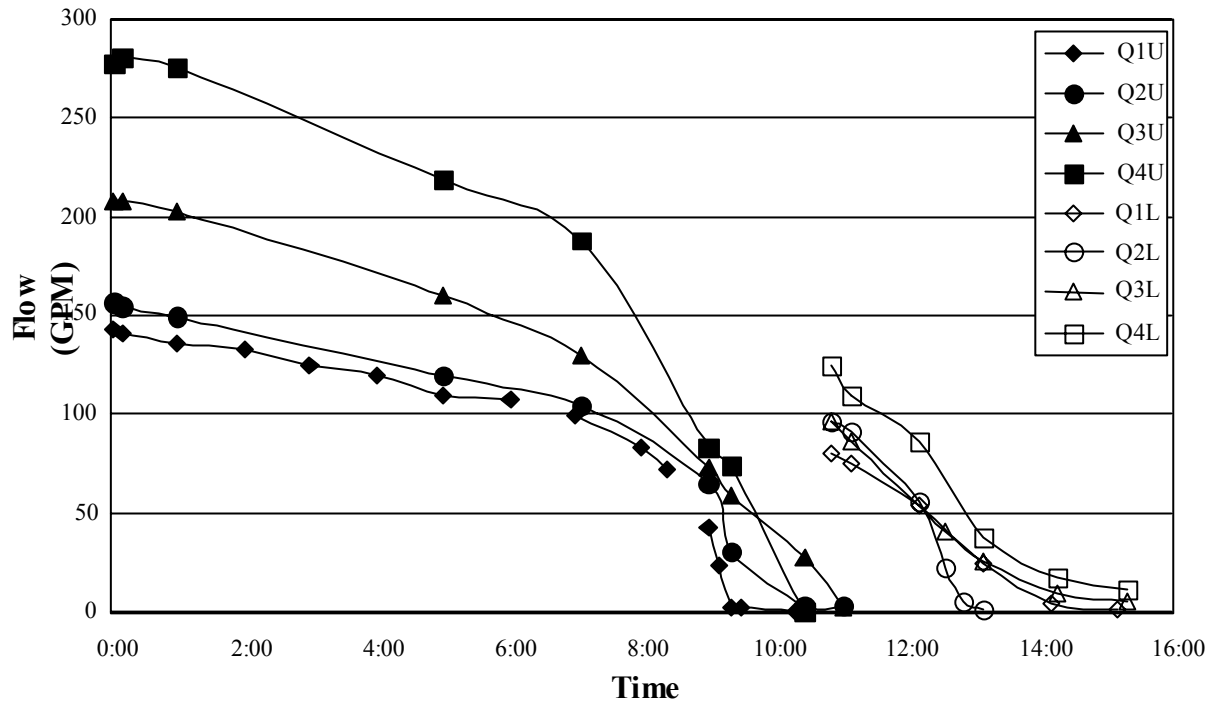


Figure 3. Flow from each flush pipe during the flush of the left RAPS at the De Sale II site. Q = quadrant; U = upper; L = lower.

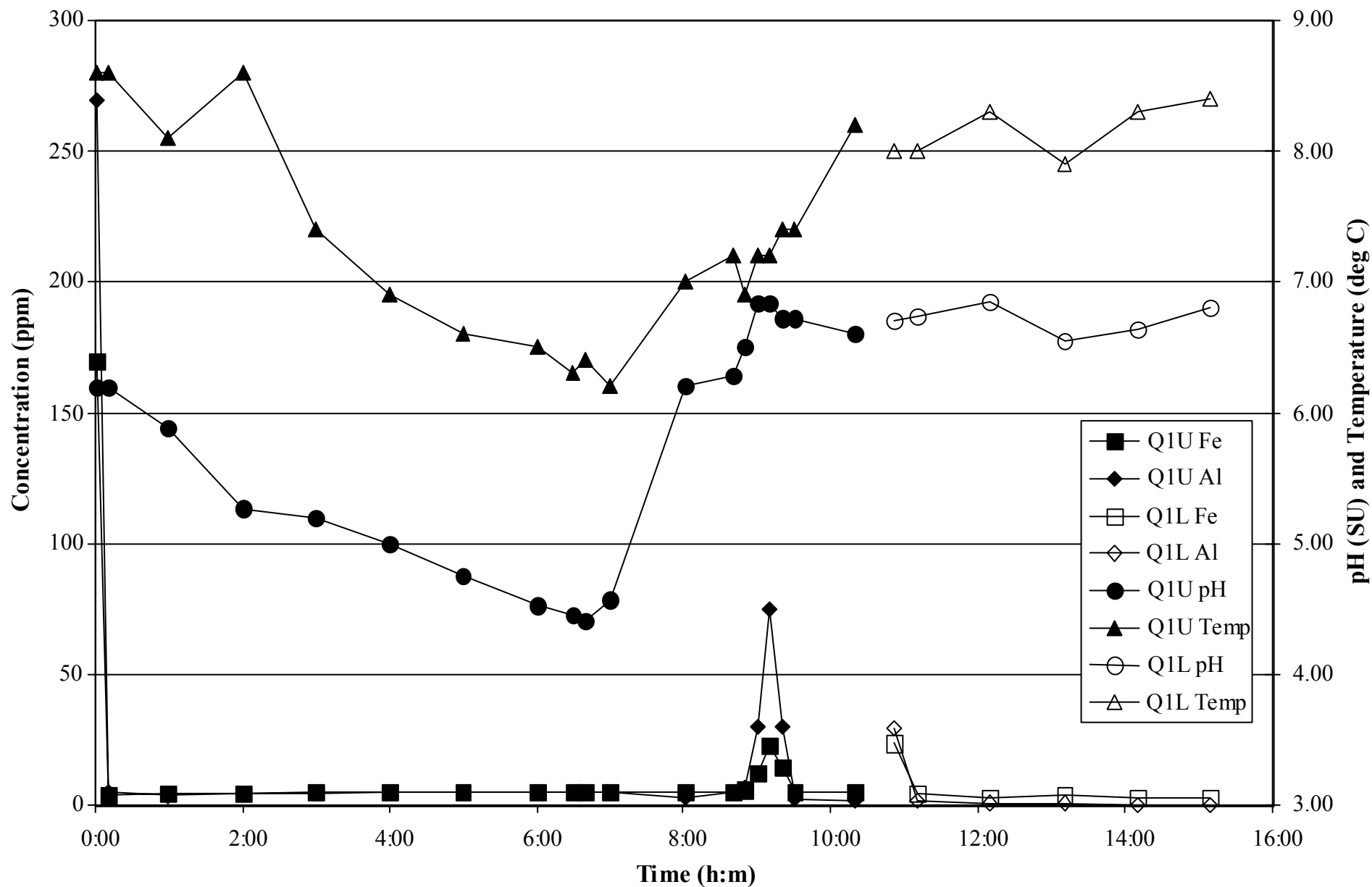


Figure 4. Iron and aluminum concentrations, pH, and temperature from the upper (U) and lower (L) flush pipes in quadrant 1 during the flush of the left RAPS at the De Sale II site.

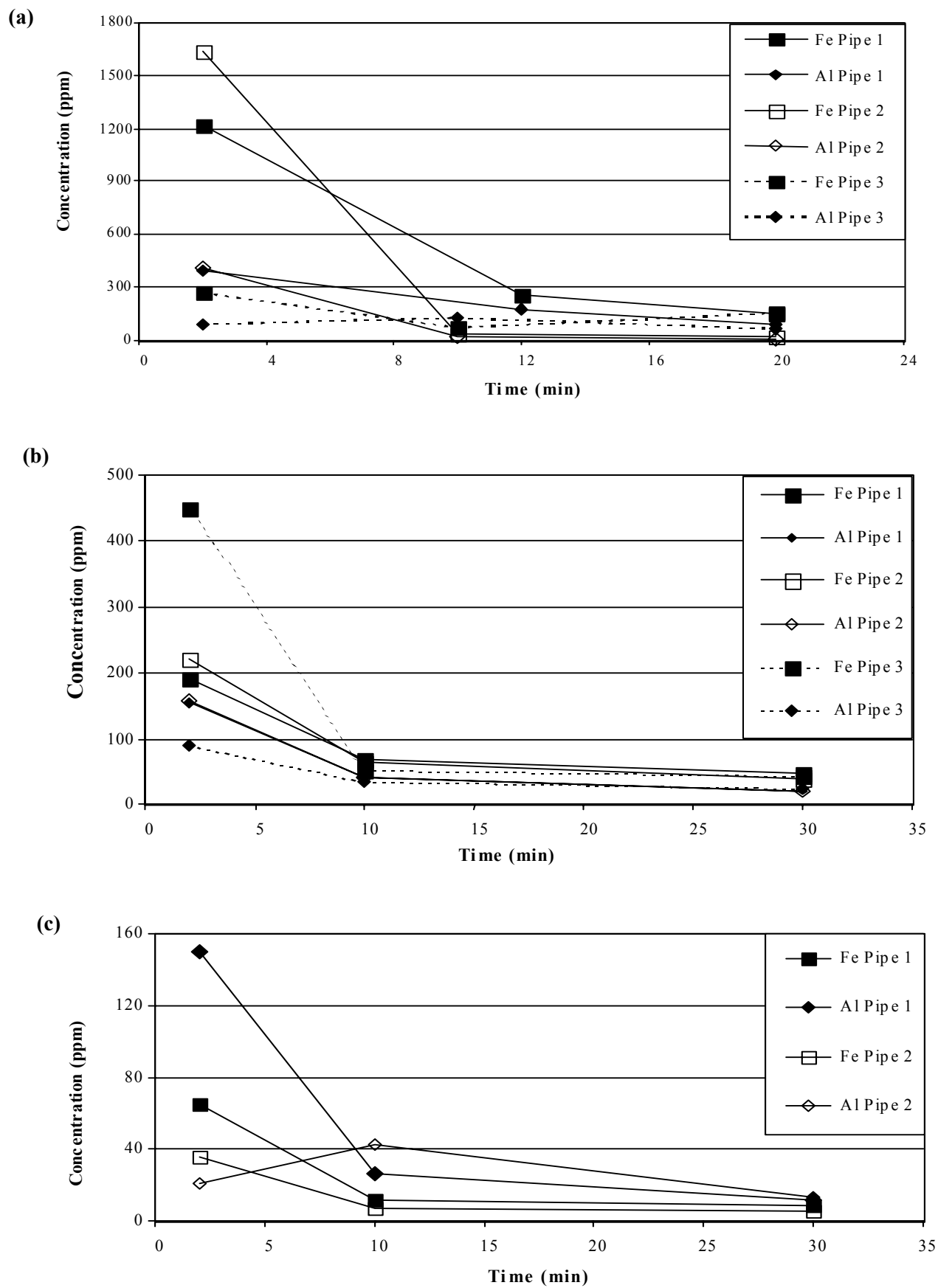


Figure 5. Iron and aluminum concentrations during the Oven Run B flush: (a) RAPS 1, Feb. 2000; (b) RAPS 1, Feb. 2001; (c) RAPS 2, Feb. 2001.