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Chemistry Effects on Flow-Accelerated Corrosion

Boiling Water Reactors: Dissolved Oxygen Investigation

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Technical Report

Chemistry Effects on Flow-Accelerated Corrosion

Boiling Water Reactors: Dissolved Oxygen Investigation

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Final Report, November 2005

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REPORT SUMMARY

This report describes an investigation into the accuracy of the oxygen factor used in the CHECWORKS™ Steam/Feedwater Application (SFA). Oxygen is a major element of the model used to predict the rate of flow-accelerated corrosion (FAC) in nuclear power plant piping.

Background

CHECWORKS SFA and predecessor programs have been used by the nuclear industry to manage damage caused by FAC. An essential element of this program is the correlation used to predict the rate of FAC as a function of plant operating parameters. This correlation has been revised over the years to provide the best possible agreement with plant and laboratory data. Recently, there have been reports that the correlation does not perform well under conditions found in boiling water reactors (BWRs). In particular, the reports have indicated that there is poor agreement between predicted and measured rates of FAC at high values of dissolved oxygen.

Objectives

- To use plant and available laboratory data to examine the performance of the oxygen factor in the CHECWORKS correlation.
- To recommend a revised correlation, if necessary.

Approach

The research team assembled available laboratory and inspection data from four operating BWR units. Comparisons were made of predicted-to-measured wear. When plotted against the dissolved oxygen concentration, it was apparent that the correlation was underpredicting the rate of FAC at high oxygen concentrations. With this result, other sources of data were reviewed and confirmed the same trend.

A number of correlations were developed and tested against the available plant and laboratory data. Each correlation was checked against the available data. Development continued until the research team obtained a satisfactory fit to the plant and laboratory data.

Results

A revised oxygen correlation was developed. This correlation displays superior performance to the current one at high levels of oxygen concentration with identical performance at lower oxygen concentrations.

EPRI Perspective

CHECWORKS SFA is an important element in utility programs to protect piping systems from damage caused by FAC. This work will result in improved predictions of FAC rate for BWRs. The work is especially important for lines with high oxygen content such as reheater drain lines.

Keywords

Flow-accelerated corrosion
Boiling water reactors
Water chemistry
Dissolved oxygen

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- Aaron Kelley, LaSalle Nuclear Generating Station, Exelon
- Doug Ramey, Columbia Generating Service, Energy Northwest

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1 INTRODUCTION

Flow-accelerated corrosion (FAC) is a degradation mechanism that affects carbon steel piping and equipment in power plant environments. FAC is a well-known phenomenon that has been extensively documented [1]. FAC normally occurs in piping and equipment of the extraction steam, heater drains, and feedwater systems. In fact, FAC is the predominant degradation mechanism in these systems.

Historically, most research into FAC has concentrated on conditions found in pressurized water reactors (PWRs). However, FAC also occurs in other reactor types including boiling water reactors (BWRs). Laboratory work on FAC under conditions found in BWRs is very limited, and computer models used to predict the rate of FAC under BWR conditions have relied primarily on extrapolations from PWR conditions.

1.1 CHECWORKS™

CHECWORKS™ Steam Feedwater Application (SFA) Version 2.1 is the latest in a series of EPRI products designed to assist utility engineers to deal with FAC in nuclear power plants [2]. This program is a multipurpose tool to:

- Organize, store, retrieve & manage plant data.
- Evaluate plant water treatments – Water Chemistry Analysis.
- Evaluate local flow conditions – Network Flow Analysis.
- Determine FAC wear rates of modeled locations – Wear Rate Analysis.
- Facilitate outage planning & management – FACTRAK.
- Evaluate UT data obtained during inspections – UT Analysis.
- Facilitate structural acceptance evaluations by means of external applications.
- Visualize piping geometries with an isometric viewer.

An essential part of CHECWORKS™ SFA is the correlation that is used to predict the rate of FAC. This correlation was initially developed in the late 1980s and is periodically reviewed and updated when more data become available. The basis of the correlation is the large amount of both laboratory and plant data that have been assembled for benchmarking the correlation. Further information about the correlation is found in references [1 and 2].

Over time, the correlation has been changed to reflect additional data or plant circumstances. However, it should be noted that the correlation for the effect of dissolved oxygen on rate of FAC has been unchanged for more than 15 years.

Because of the uncertainties in the plant operating conditions, CHECWORKS™ uses what is called a line correction factor (LCF) to adjust the predictions to the measured data on a line-by-line basis. Details of this process are provided in reference [11]. This factor also serves as a figure of merit for goodness of the modeling process. An LCF of unity is ideal, and an LCF between 0.5 and 2.5 is regarded as acceptable. LCFs outside this range are considered to be cause for further evaluation.

Recently, there have been reports of very high LCFs in BWRs under conditions of high dissolved oxygen. These reports have prompted this work.

1.2 Report Organization

This report is organized as follows:

Section 2 presents the objectives of this work.

Section 3 presents the evaluation process used.

Section 4 presents the correlating approach.

Section 5 presents recommendations and conclusions.

Several appendices furnish additional information.

2
OBJECTIVES

The objectives of this work are:

- To review the CHECWORKS™ oxygen factor against laboratory and BWR plant data.
- From this review, determine if there are unacceptably high line correction factors.
- If necessary, recommend a modification to the BWR oxygen factor correlation to provide a better fit of the available data.

3 EVALUATION

This section presents the methodology used to evaluate the oxygen factor currently used in CHECWORKS™ SFA. In order to describe the methodology, a short description of the role of oxygen in establishing the rates of FAC is presented in Section 3.1.

3.1 BWR Water Chemistry

Years of experience have demonstrated that oxygen is a key variable in establishing the rate of FAC. This is particularly true in BWRs where the dissolved oxygen varies from essentially zero in low-pressure extraction lines to more than 1,000 ppb in reheater drains and high-pressure extraction lines.

In distinction, the range of dissolved oxygen in PWRs is much smaller. Typically, the maximum amount of dissolved oxygen in PWRs is found in the condensate and is ~5 ppb. The concentration of dissolved oxygen in most other parts of the steam-feedwater system is essentially zero.

Most of the oxygen in a BWR is generated by radiolysis in the reactor core. This results in a high concentration of oxygen in the main steam line. In fact, the main steam line oxygen concentration is about 10,000 ppb depending on the water chemistry used. Because of this high oxygen concentration in the main steam, it is necessary to vent the feedwater heaters and reheaters to ensure adequate thermal performance. This venting also has the effect of increasing the downstream rates of FAC caused by the lower oxygen concentration. Figure 3-1 presents the results of a sample venting calculation. As shown by this figure, the vent rate has a large influence on the downstream (i.e., drain) oxygen concentration. Note that two typical venting rates, 0.5% and 1.5% are indicated on this figure. Reference [4] presents more information about feedwater heater venting in BWRs.

In consideration of the importance of vent rates, several BWRs have measured the oxygen concentration in various portions of the steam-feedwater system to establish the vent rates. This was viewed as preferable to relying on the design values. The design values of venting may be compromised by a number of factors. For example, wear in the orifice plate would result in a larger than designed vent flow rate.

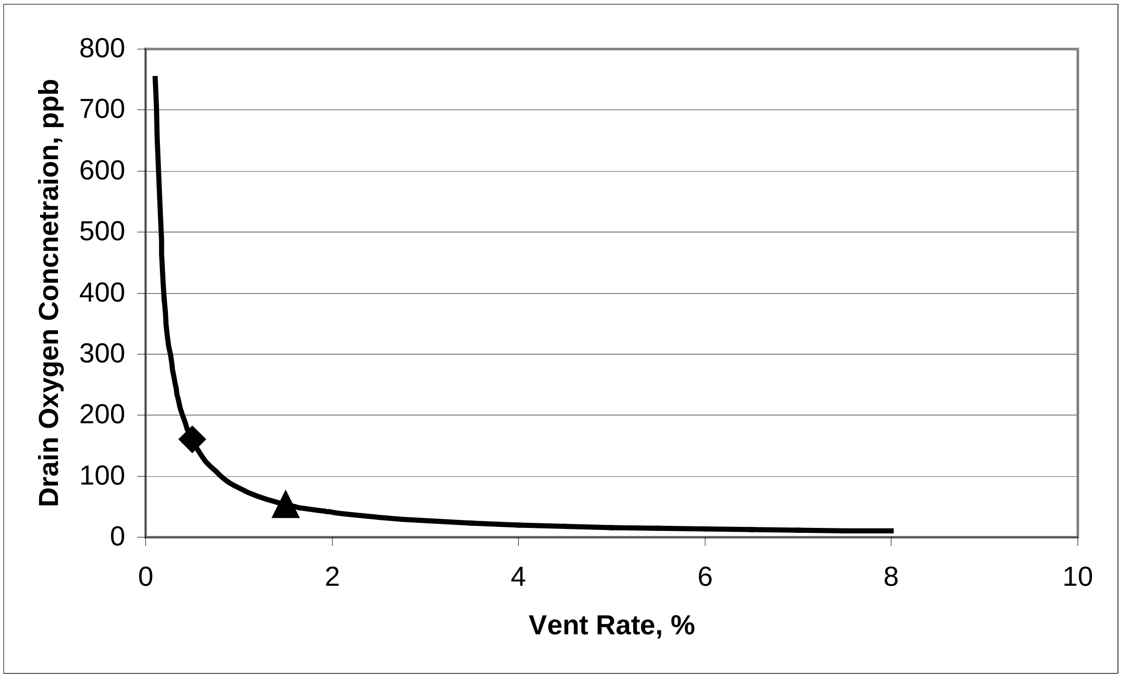

Figure 3-1
Sample Venting Results for a Feedwater Heater at 300°F with a Main Steam Concentration of 10 ppm - Data Points Indicate Two Typical Vent Rates

3.2 Selection of Units

It was decided early in this work to extensively utilize plant data to evaluate the goodness of the correlation. This was done recognizing the fact that plant data have some definite disadvantages, including:

- Variable operating conditions over time.
- Uncertainties associated with interpreting inspection data, particularly at low levels of wear.
- Variation of LCFs for different lines with the same oxygen history.

A brief survey of U.S. BWR units was made to identify units that had used measured oxygen values to tune their venting rates. Four units were found, namely:

- Hatch Unit 2
- LaSalle Units 1 and 2
- Perry

Upon further examination, the Hatch databases had been converted to the latest version of CHECWORKS™ (i.e., SFA Version 2.1), both LaSalle databases were converted to Version 2.1 for the purposes of this study, while Perry was still using an older version of the software (i.e., Version 1.0G). Additionally, since Hatch Unit 1 was also modeled using Version 2.1, it was decided to use its data in the evaluations. Recognizing the convenience of using one program to analyze all of the data, it was decided to use both Hatch and both LaSalle units in this work.

3.3 Initial Plant Results

To evaluate the adequacy of the current correlation, the LCFs for each analysis line for each of the four units were determined. For convenience, these values were plotted against the oxygen level for the last chemistry period. While it is recognized that the oxygen levels of each unit varied with time (see charts in Appendix A), it was decided that it would be more convenient and just as accurate to use the latest oxygen value rather than attempting to come up with some representative average value.

Figure 3-2 presents the results of these calculations. Remembering that an LCF of unity indicates the ideal situation, it can be easily seen that the correlation appears to work well under about 100 ppb. Above 100 ppb there appears to be a definite problem with the LCFs increasing tremendously. This result confirms the anecdotal reports of excessively high LCFs at high levels of dissolved oxygen.

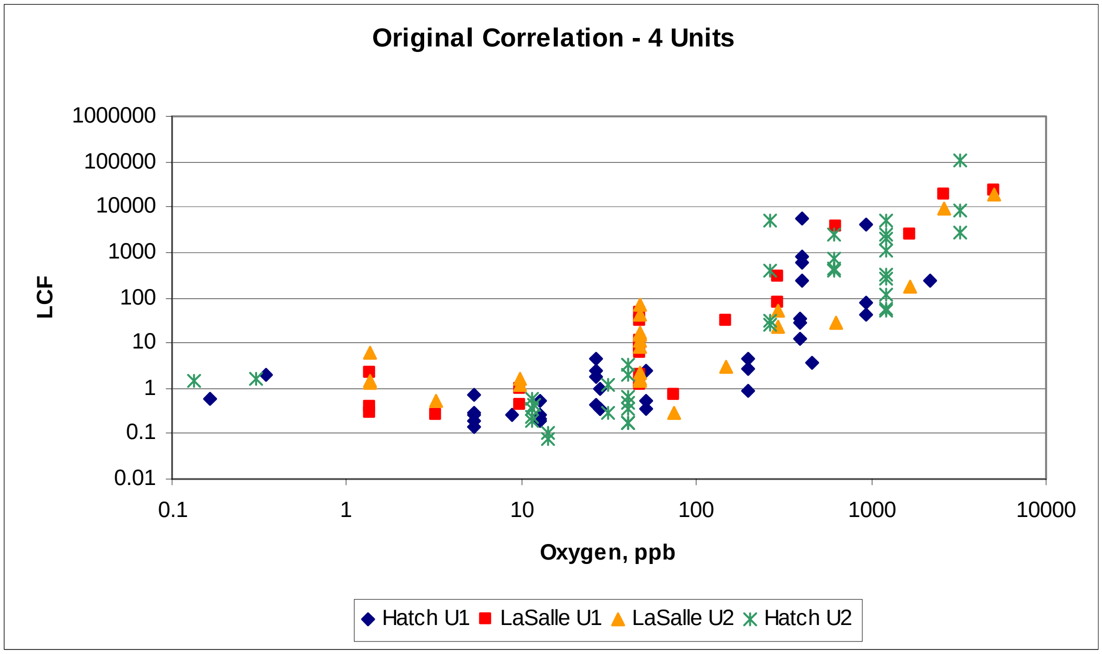

Figure 3-2
Line Correction Factors for Original Correlation

3.4 Laboratory Results

In order to understand the situation with the high LCFs, the laboratory data used initially to develop the correlation were reexamined [5-9]. Concurrently, a brief literature search was conducted. Unfortunately, this search did not turn up any new, relevant references.

Although the original papers were not available, a summary of the data sets is presented in Table 3-1. Figure 3-3 compares the prediction of the original correlation with three of the sets of the laboratory data. Note that the Brush and Pearl data set were not included in the comparisons, as it only contained useable data at low oxygen concentrations. Further note that the KWU data were consistently below the other data sets. This may be caused by measurement difficulties as the steel used in these tests contained significant amounts of alloying elements which would serve to reduce all of the rates of FAC.

Table 3-1
Summary of Oxygen Laboratory Data

Investigator	Reference	Geometry	Steel	Velocity	Temperature
Brush & Pearl	5	Coupon	"carbon steel"	1.8 m/s	38 – 204°C
Izumiya	6	Pipe	SS4	-	100°C
Kastner	7	Plate	15Mo3 (SA204 Grade A) 13CrMo44 (SA182,F11,F12)	35	120°C
Resch	8, 9	Pipe	St35.8(A106)	1.6	75°C

[Note all tests were conducted with neutral water (i.e., pH= 7.0)]

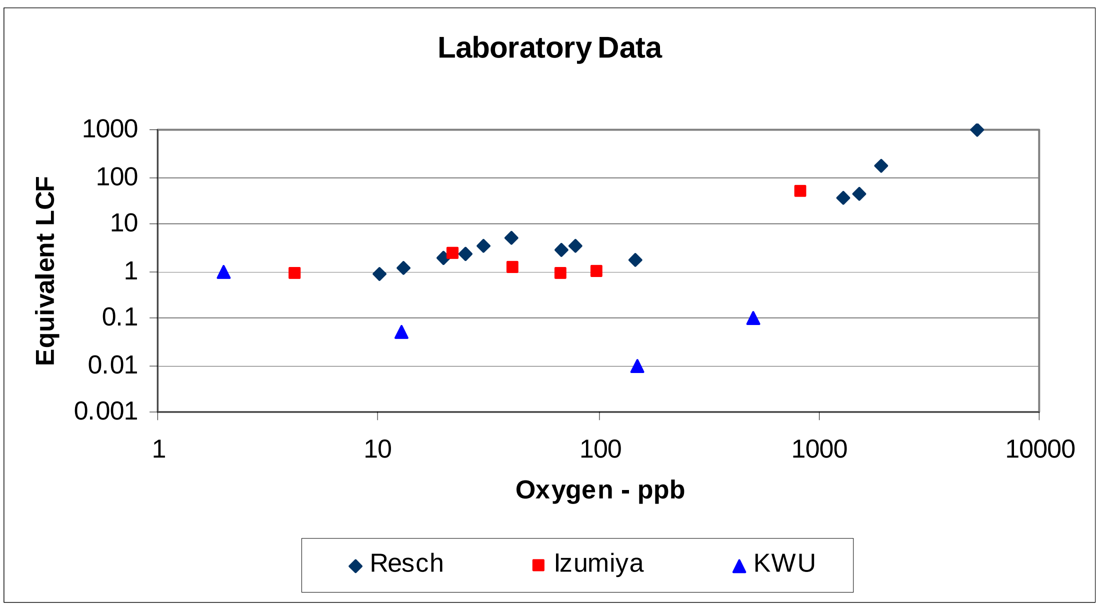

Figure 3-3
Equivalent Line Correction Factors for Laboratory Data Using the Original Correlation

To facilitate comparisons, Figure 3-3 is plotted in a similar manner as Figure 3-2, that is, as an equivalent LCF. Once again, the correlation seemed to behave properly up to about 100 ppb, and then seriously underpredicted the data at higher amounts of oxygen.

3.5 Data from the BWRVIP

Recently, the BWRVIP has published a chart showing some FAC data versus dissolved oxygen [10]. This chart is reproduced with a curve of the CHECWORKS™ prediction superimposed upon it. See Figure 3-4. As can be seen there is very good agreement between the measurements and the CHECWORKS™ prediction. As these data are only up to an oxygen value of about 100 ppb, they were not used in developing the revised correlations.

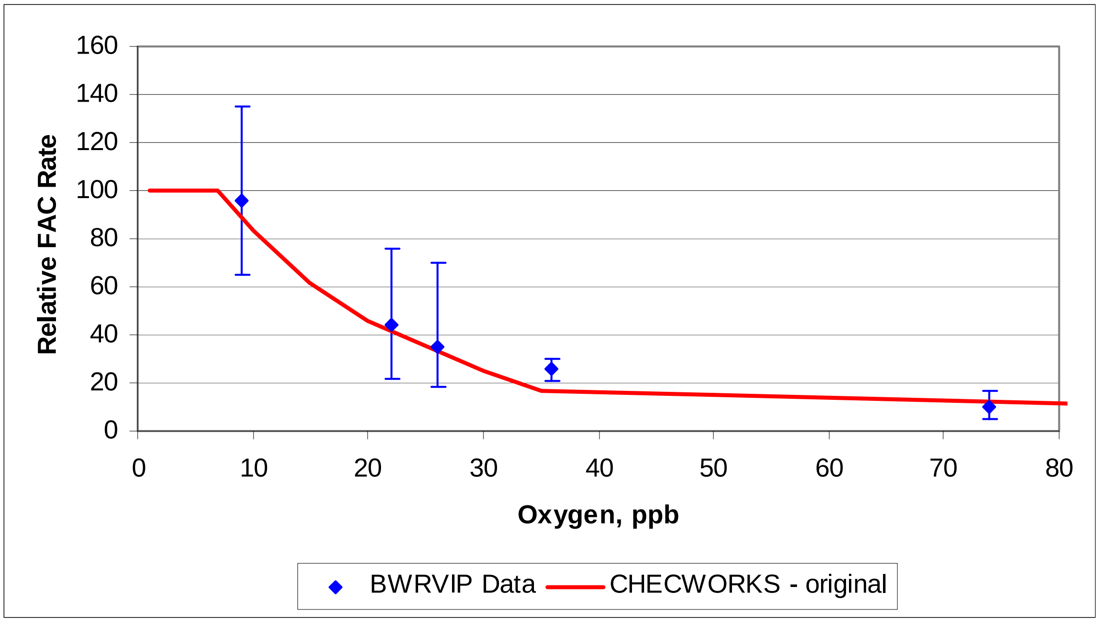

Figure 3-4
BWRVIP "Recent Data" Compared to CHECWORKS

3.6 Preliminary Conclusions

Based on the examination of the original correlation, the following conclusions can be drawn:

- Both the laboratory data and the plant data are consistent. There is good agreement up to about 100 ppb of dissolved oxygen. Above this value, both the laboratory and plant data are consistently underpredicted by the correlation. That is, the correlation predicts a lower corrosion rate than is actually experienced.
- There does not seem to be a dramatic difference between the Hatch 1 and Hatch 2 results (Hatch 2 used oxygen measurements to tune the CHECWORKS™ model, whereas Hatch 1 did not).

4
DEVELOPMENT OF A REVISED CORRELATION

This section describes the evaluations made to obtain a more accurate correlation of oxygen factor versus dissolved oxygen. A more detailed description of these evaluations is provided in Appendix B.

4.1 Approach

An iterative approach was used to develop the improved correlation. Ultimately, five different correlations were examined. The LCFs for each iteration and for each analysis line of the four units were determined. These were plotted against the dissolved oxygen output by the program. The individual and combined plots were examined, particularly at high levels of dissolved oxygen. Also developed were plots of the revised correlations against laboratory data. Figures 4-1 and 4-2 display the results of the original and final correlations against plant and laboratory data respectively.

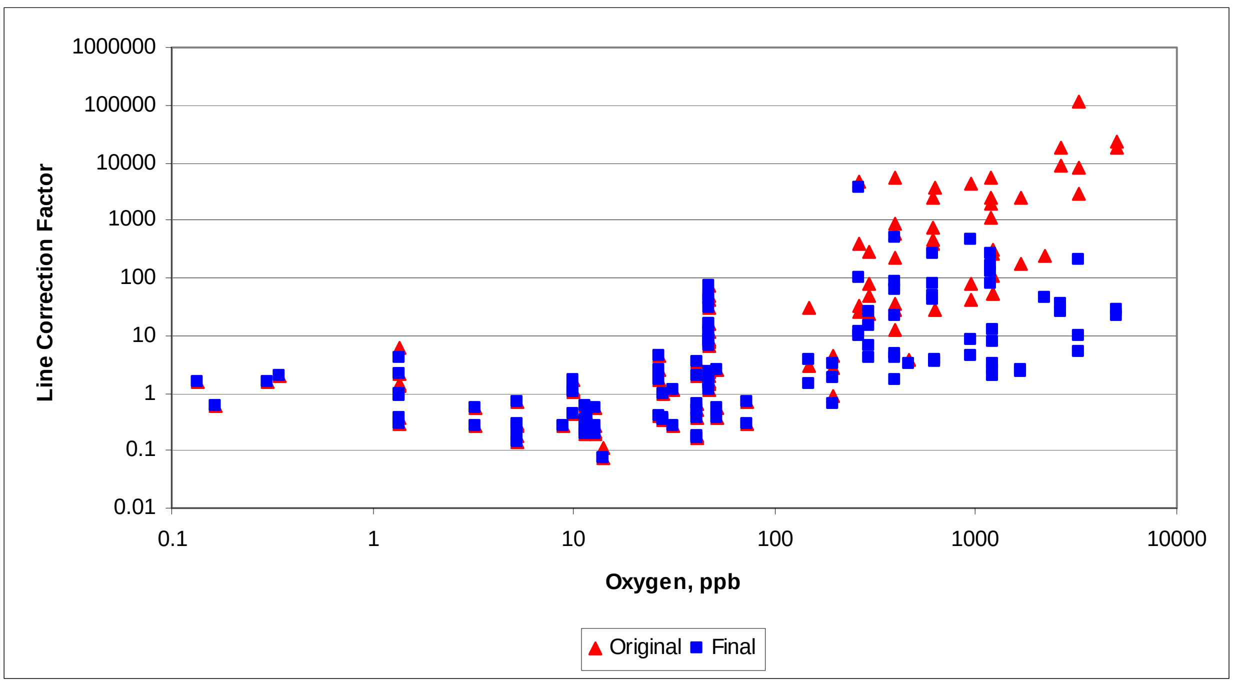

Figure 4-1
Original and Final Correlation Against Plant Data

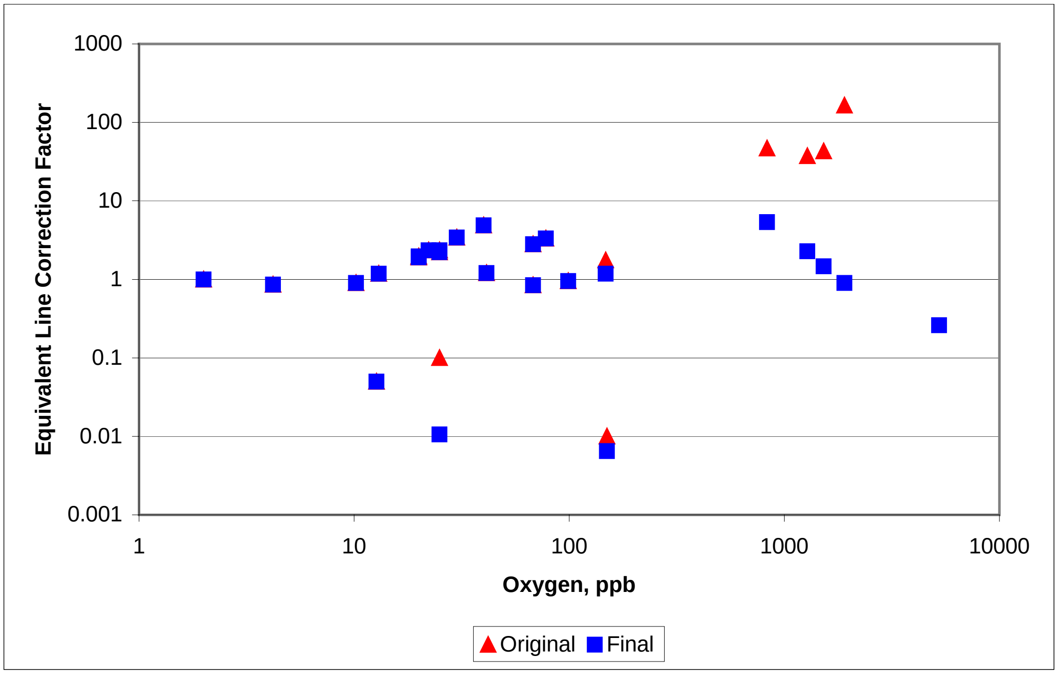

Figure 4-2
Original and Final Correlation Against Laboratory Data

For each iteration, summary statistics were developed showing the performance of the correlation against the original correlation, and other correlations. Table 4-1 presents summary statistics for the four units examined. Tables 4-2 through 4-5 present these statistics by unit for each of the correlations developed.

Table 4-1
Composite Statistics

	Original	Trial 1	Trial 2	Trial 3	Trial 4	Final
Number of LCFs	125	125	125	125	125	125
Maximum LCF	110,980	30,685	3,558	3,569	3,569	3,569
Median LCF	2.638	2.482	2.281	2.281	2.281	2.221
Mean LCF	1861	846	129	71	63	53
Binned Values						
>10,000	4	3	0	0	0	0
10,000 > # > 5,000	4	1	0	0	0	0
5,000 > # > 1,000	9	10	4	1	1	1
1,000 > # > 500	3	1	5	2	2	1
500 > # > 100	10	12	9	12	10	7
100 > # > 50	5	5	4	4	6	5
50 > # > 2.5	29	30	39	42	42	43
2.5 > # > 0.5	32	34	35	35	35	39
0.5 > # > 0.0	29	29	29	29	29	29

Table 4-2
Statistics for Hatch Unit 1

	Original	Trial 1	Trial 2	Trial 3	Trial 4	Final
Number of LCFs	40	40	40	40	40	40
Maximum LCF	5,501	2,359	671	529	524	515
Median LCF	1.0	1.0	1.0	1.0	1.0	1.0
Mean LCF	264	123	39	30	29	28
Binned Values						
>10,000	0	0	0	0	0	0
10,000 > # > 5,000	1	0	0	0	0	0
5,000 > # > 1,000	1	2	0	0	0	0
1,000 > # > 500	2	0	2	1	1	1
500 > # > 100	2	3	2	2	1	1
100 > # > 50	1	1	1	2	3	2
50 > # > 2.5	9	9	9	9	9	10
2.5 > # > 0.5	11	12	13	13	13	13
0.5 > # > 0.0	13	13	13	13	13	13

Table 4-3
Statistics for Hatch Unit 2

	Original	Trial 1	Trial 2	Trial 3	Trial 4	Final
Number LCFs	39	39	39	39	39	39
Maximum LCF	110,980	30,685	3,558	3,569	3,569	3,569
Median LCF	26.0	18.2	6.2	3.4	3.4	2.5
Mean LCF	2510	873	156	108	100	88
Binned Values						
>10,000	1	1	0	0	0	0
10,000 > # > 5,000	2	0	0	0	0	0
5,000 > # > 1,000	6	7	2	1	1	1
1,000 > # > 500	1	1	1	1	1	0
500 > # > 100	6	6	7	6	5	6
100 > # > 50	2	1	2	1	2	2
50 > # > 2.5	3	5	9	12	12	10
2.5 > # > 0.5	7	7	7	7	7	9
0.5 > # > 0.0	11	11	11	11	11	11

Table 4-4
Statistics for LaSalle Unit 1

	Original	Trial 1	Trial 2	Trial 3	Trial 4	Final
Number of LCFs	23	23	23	23	23	23
Maximum LCF	23,787	23,787	2,303	354	189	47
Median LCF	7.5	7.5	6.3	6.3	6.3	3.4
Mean LCF	2141	1513	137	31	20	9
Binned Values						
>10,000	2	1	0	0	0	0
10,000 > # > 5,000	0	1	0	0	0	0
5,000 > # > 1,000	2	0	1	0	0	0
1,000 > # > 500	0	0	1	0	0	0
500 > # > 100	1	3	0	2	2	0
100 > # > 50	1	1	0	0	0	0
50 > # > 2.5	7	7	11	11	11	12
2.5 > # > 0.5	6	6	6	6	6	7
0.5 > # > 0.0	4	4	4	4	4	4

Table 4-5
Statistics for LaSalle Unit 2

	Original	Trial 1	Trial 2	Trial 3	Trial 4	Final
Number of LCFs	23	23	23	23	23	23
Maximum LCF	18,936	12,551	1,649	353	199	73
Median LCF	8.1	8.1	5.6	4.2	4.2	3.8
Mean LCF	1237	683	105	33	23	12
Binned Values						
>10,000	1	1	0	0	0	0
10,000 > # > 5,000	1	0	0	0	0	0
5,000 > # > 1,000	0	1	1	0	0	0
1,000 > # > 500	0	0	1	0	0	0
500 > # > 100	1	0	0	2	2	0
100 > # > 50	1	2	1	1	1	1
50 > # > 2.5	10	9	10	10	10	11
2.5 > # > 0.5	8	9	9	9	9	10
0.5 > # > 0.0	1	1	1	1	1	1

4.2 Blind Test

In order to validate the revised correlation, a blind test was performed using the databases from the Columbia Generating Station and the Fermi 2 Nuclear Generating Station. The LCFs for the original and final correlations are plotted in Figures 4-3 and 4-4 with the statistics for these correlations presented in Tables 4-6 and 4-7.

The blind test results demonstrate similar improvement in the LCFs as previously seen in the Hatch and LaSalle units.

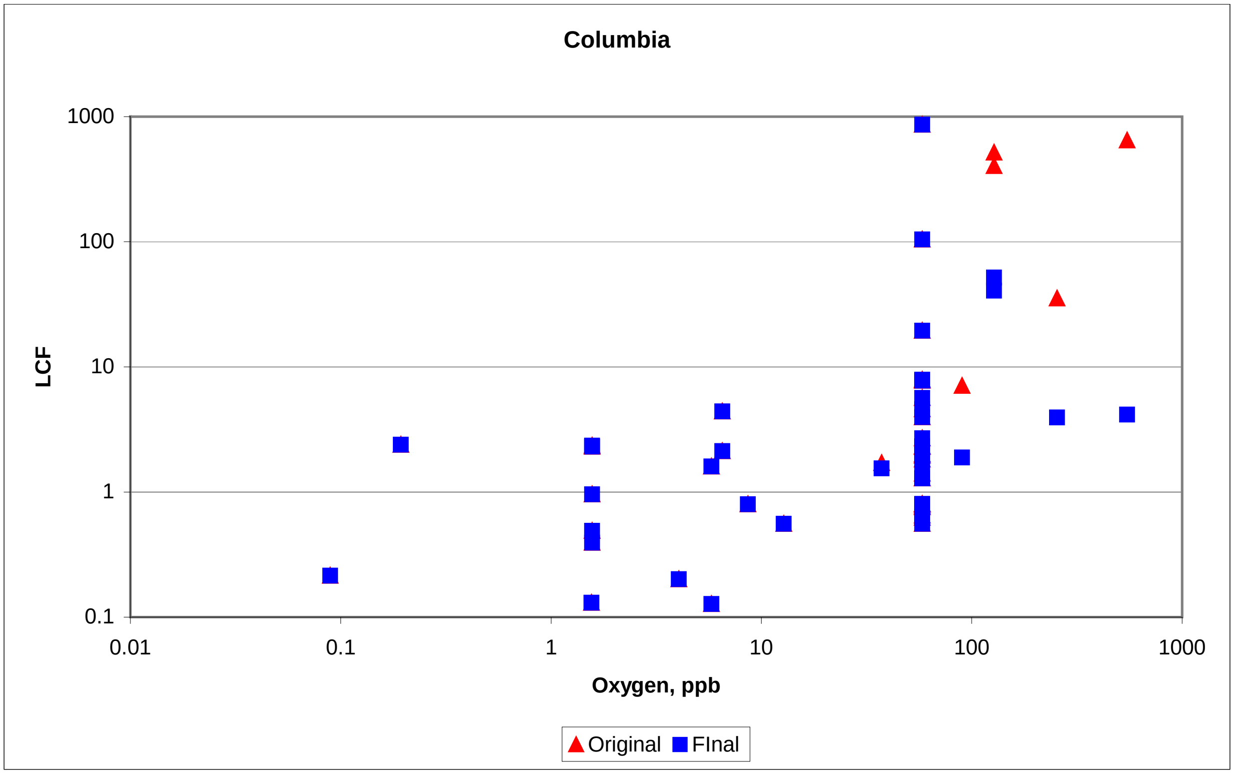

Figure 4-3
Results of Blind Test on Columbia

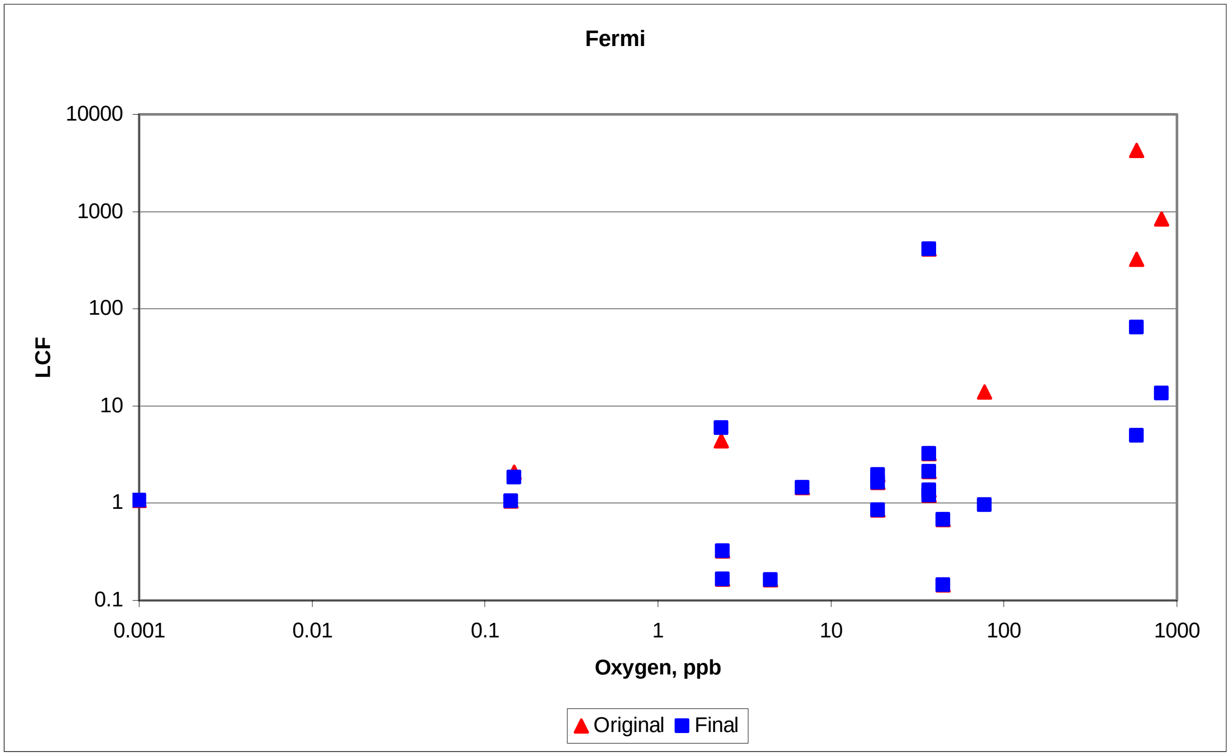

Figure 4-4
Results of Blind Test on Fermi 2

Table 4-6
Statistics for Columbia

	Original	Final
Number of LCFs	46	46
Maximum LCF	866	866
Median LCF	1.89	1.85
Mean LCF	58	25
Binned Values		
>10,000	0	0
10,000 > # > 5,000	0	0
5,000 > # > 1,000	0	0
1,000 > # > 500	3	1
500 > # > 100	2	1
100 > # > 50	0	1
50 > # > 2.5	10	11
2.5 > # > 0.5	25	26
0.5 > # > 0.0	6	6

Table 4-7
Statistics for Fermi 2

	Original	Final
Number of LCFs	23	23
Maximum LCF	4276	415
Median LCF	1.63	1.44
Mean LCF	256	23
Binned Values		
>10,000	0	0
10,000 > # > 5,000	0	0
5,000 > # > 1,000	1	0
1,000 > # > 500	1	0
500 > # > 100	2	1
100 > # > 50	0	1
50 > # > 2.5	4	5
2.5 > # > 0.5	11	12
0.5 > # > 0.0	4	4

5
RECOMMENDATIONS AND CONCLUSIONS

Based on the results of this work, it is recommended that the revised correlation be implemented into the next major release of CHECWORKS™ SFA. It is further recommended that the users of the program be notified that an improved correlation will be available and that FAC predictions at high oxygen conditions be used with caution.

The two principal conclusions of this work are:

- The original oxygen factor correlation has been improved upon. The final correlation displays better agreement with both the plant and the laboratory data.
- The Hatch 1 data agree better with the revised correlation than Hatch 2. This may be true since the Hatch 2 database, the one tuned with oxygen measurements, had higher levels of oxygen leading to higher line correction factors. It may also be possible that the "tuned model" reflected only the current conditions, and that past conditions were considerably different.

6 REFERENCES

1. Chexal, B., et al., *Flow-Accelerated Corrosion in Power Plants*. EPRI, Palo Alto, CA: 1998, EPRI Report TR-106611-R1.
2. *CHECWORKS™ Steam/Feedwater Application, Version 2.1*. EPRI, Palo Alto, CA: 2004. 1009600.
3. Chexal, V.K., & Horowitz, J.S., *Flow Assisted Corrosion in Carbon Steel Piping – Parameters and Influences.* Proceedings of the Fourth Symposium on Environmental Degradation of Materials in Nuclear Power Systems – Water Reactors, Jekyll Island, Georgia, 1989.
4. Miller, A. D., *Brunswick-2 Water Chemistry*. EPRI NP-1795, April 1981.
5. Bush, E.G., and Pearl, W.L., "Corrosion and Corrosion Product Release in Neutral Water," *Corrosion* 28 (1972) 4, pp.129 -136.
6. Izumiya, M., et al., "Corrosion and/or Erosion in BWR Plants and Their Countermeasures," presented at the International Symposium on Water Chemistry and Corrosion Problems of Nuclear Reactor Systems and Components, Vienna, Austria, November 1982, sponsored by the IAEA, paper 4.
7. Kastner, W., Hofmann, P., Nopper, H., "Erosion Corrosion in Power Plants – Decision-making Tools for Counteracting Material Degradation," *VGB Kraftwerkstechnik 70 (1990), Number 11, pp. 806-845.*
8. Resch, G., Einfluß der Sauerstoffkonzentration auf die Beständigkeit von Stahl in Wässrigen Lösungen, *VGB-Speisewassertagung* 1969, S. 17 – 22.
9. Resch, G., Neue Richtwerte für Kesselspeise- und Kesselwasser Ein Beitarag zur Neuerfasung, 1972, *VGB Kraftwerkstechnik, Mitteilingen der VGB,* Heft 5, Okt. 1972, S. 385-390.
10. *BWR Water Chemistry Guidelines – 2004 Revisio*n. EPRI, Palo Alto, CA: 2004. TR-1008129.
11. *CHECWORKS™ Steam/Feedwater Application: Guidelines for Plant Modeling and Evaluation of Component Inspection Data*. EPRI, Palo Alto, CA: 2004. 1009599.

A
PLANT DATABASES USED

This appendix presents a brief description of the four databases used to develop the revised correlation. Two additional databases were used to perform a blind comparison of the performance of the revised correlation. In all cases, CHECWORKS™ SFA Version 2.1 was used to perform the comparisons.

A.1 Hatch Unit 1

Hatch Unit 1, in distinction to Hatch Unit 2, did not have the vent rates adjusted to match the plant predictions of oxygen to measured concentrations. Rather, design values of vent rates were used. Figure A-1 presents a chart of the average feedwater oxygen versus operating time for this unit. Figure A-2 presents a plot of the average steam line oxygen versus operating time for this unit.

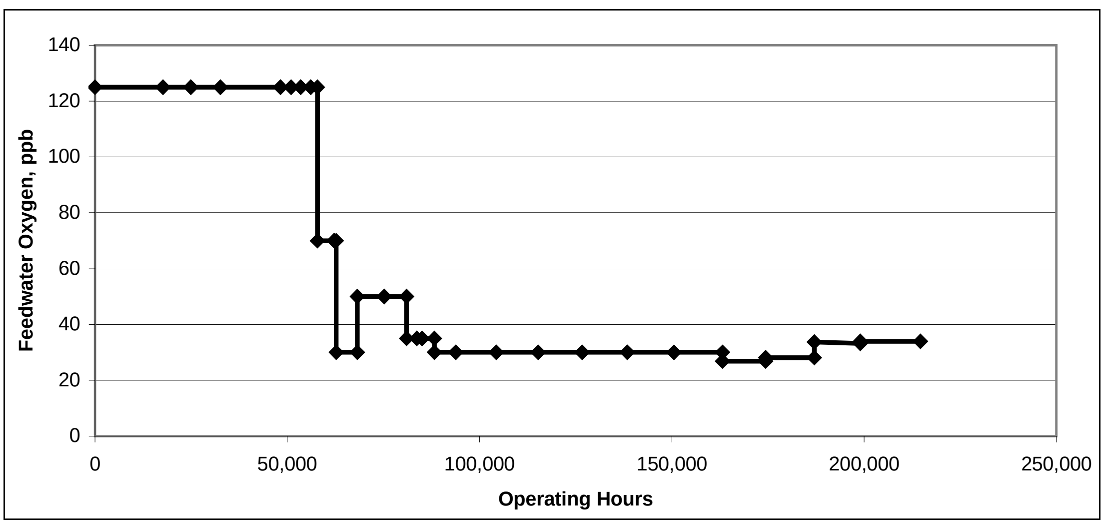

Figure A-1
Hatch Unit 1 Feedwater Oxygen History

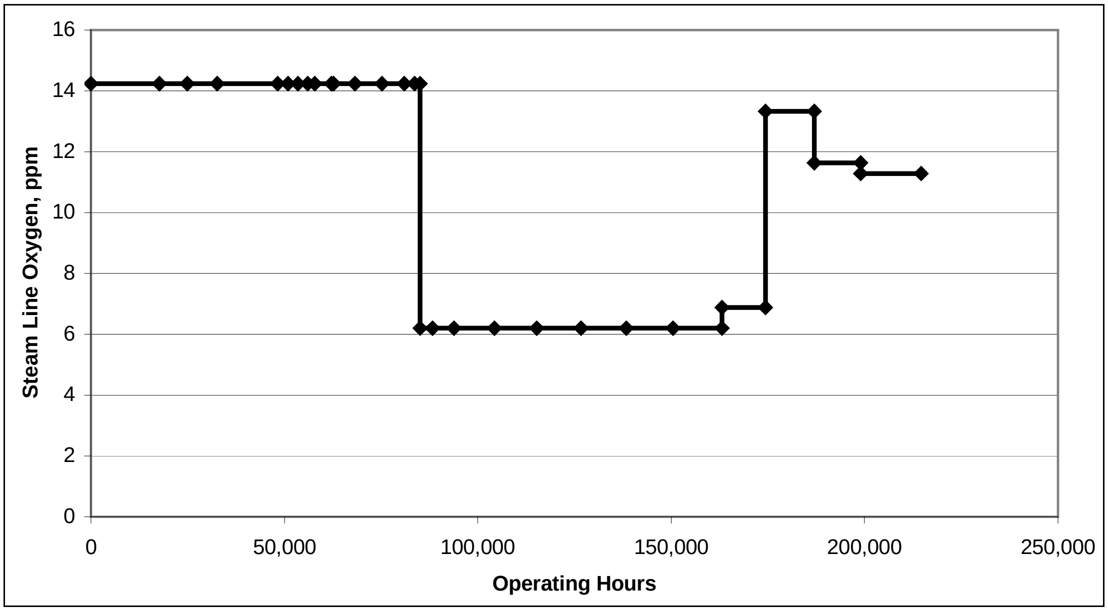

Figure A-2
Hatch Unit 1 Main Steam Line Oxygen History

A.2 Hatch Unit 2

Hatch Unit 2 had the vent rates tuned to match plant measurements of the oxygen concentration. Figure A-3 presents a chart of the average feedwater oxygen versus operating time. Figure A-4 presents a plot of the average steam line oxygen versus operating time.

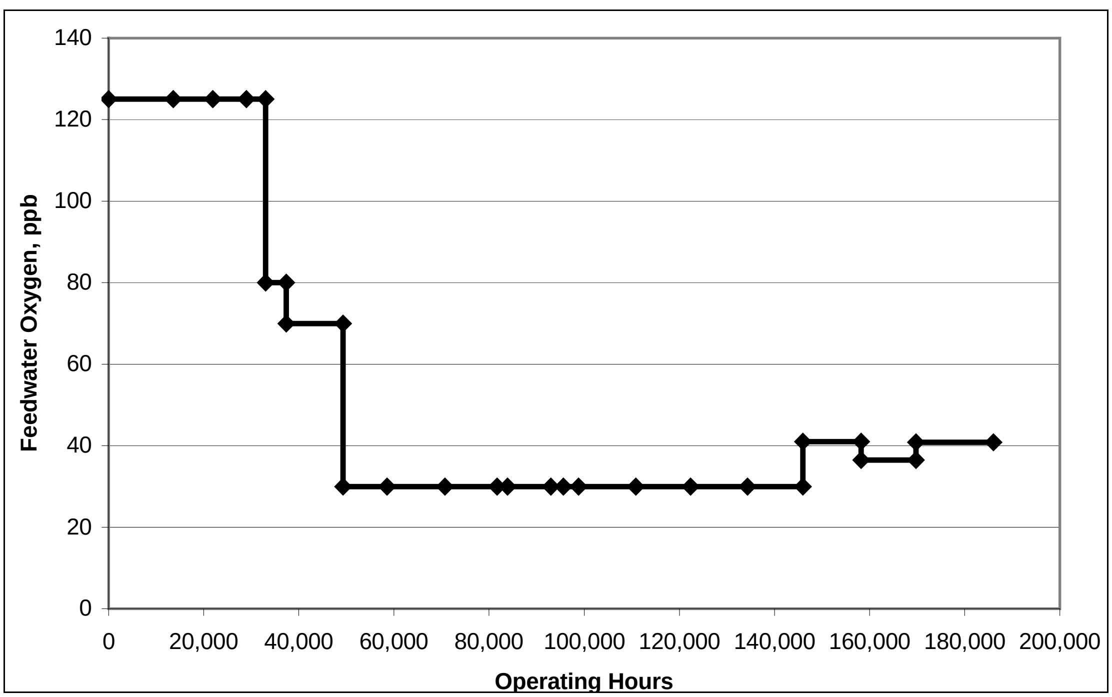

Figure A-3
Hatch Unit 2 Feedwater Oxygen History

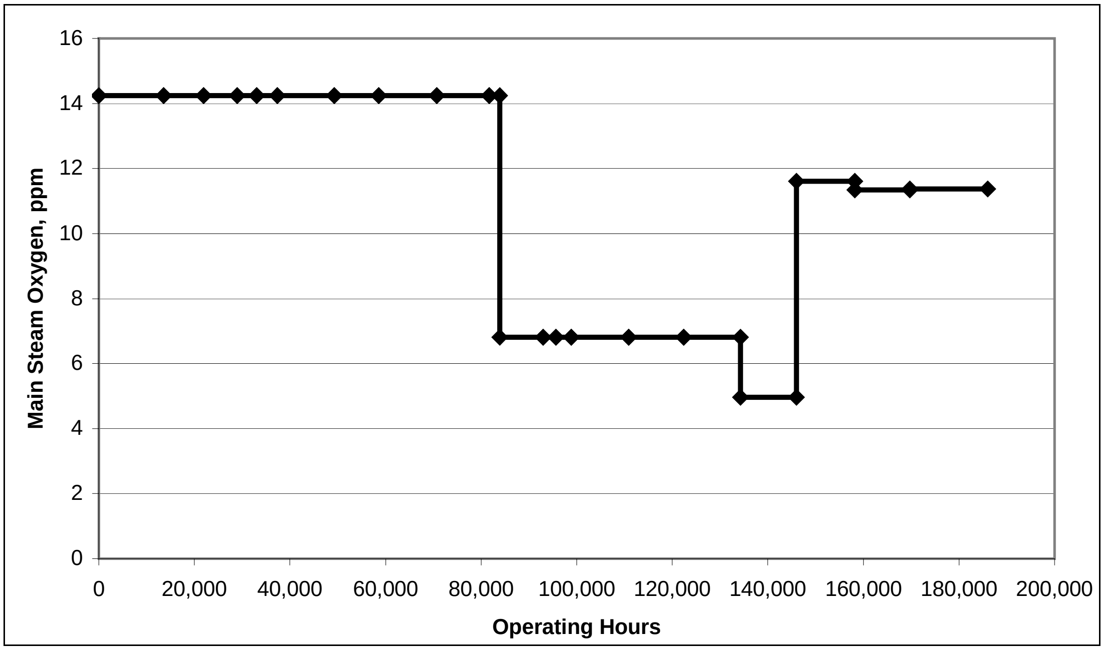

Figure A-4
Hatch Unit 2 Main Steam Line Oxygen History

A.3 LaSalle Units 1 and 2

Both LaSalle units had the vent rates tuned to match plant measurements of the oxygen concentration. Figures A-5 and A-7 present charts of the average feedwater oxygen versus operating time. Figures A-6 and A-8 present plots of the average steam line oxygen versus operating time.

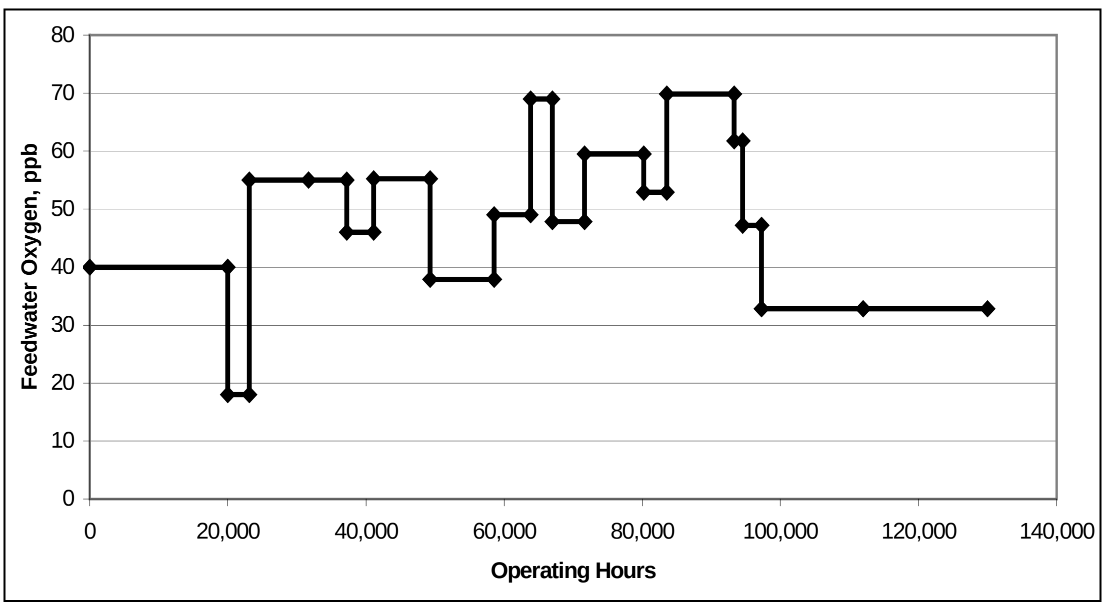

Figure A-5
LaSalle Unit 1 Feedwater Oxygen History

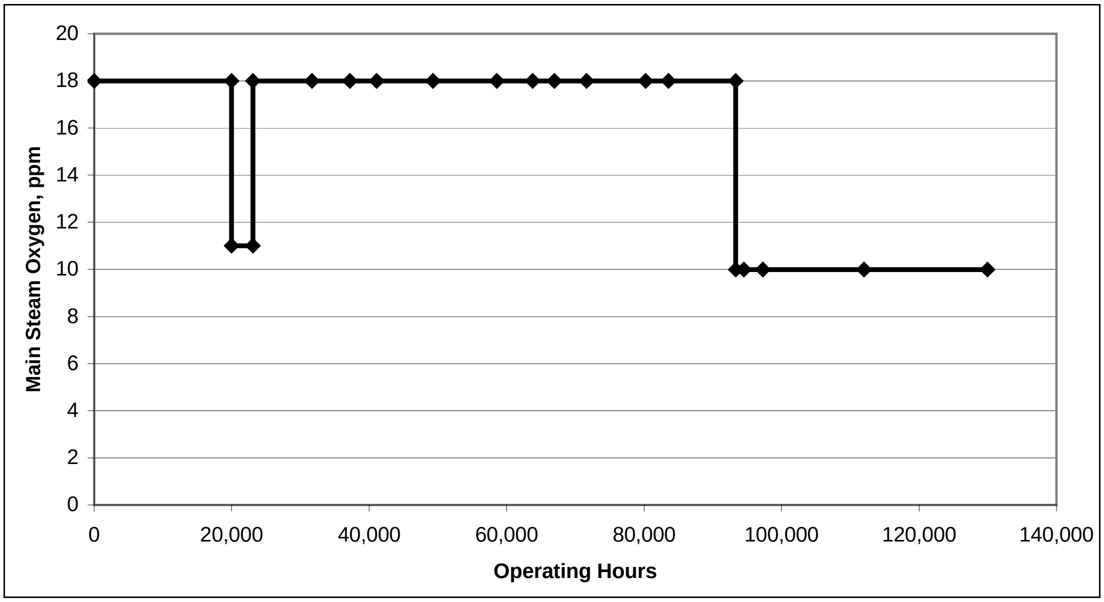

Figure A-6
LaSalle Unit 1 Main Steam Line Oxygen History

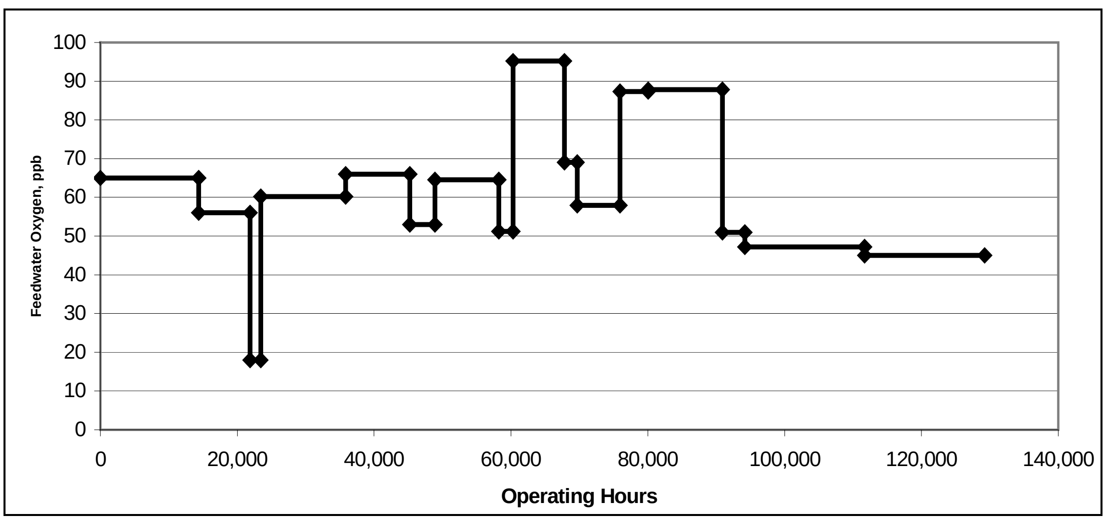

Figure A-7
LaSalle Unit 2 Feedwater Oxygen History

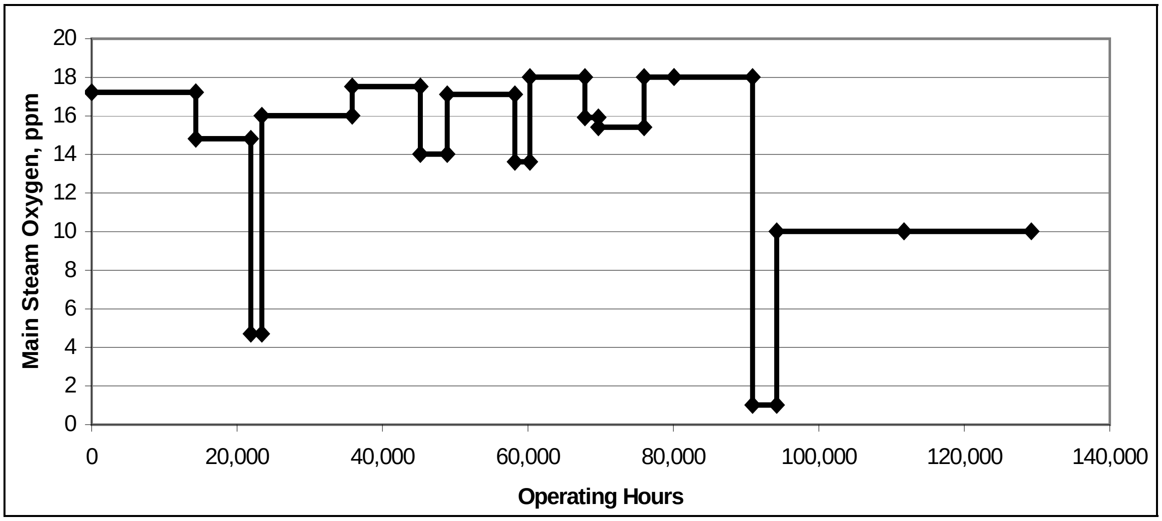

Figure A-8
LaSalle Unit 2 Main Steam Line Oxygen History

A.4 Databases for Blind Test

Databases from Columbia and Fermi were used for the blind test.

The Columbia unit did not have the vent rates tuned to match the plant measurements of oxygen concentration. Figures A-9 and A-10 present the history of the final feedwater and steam line oxygen concentrations.

The Fermi unit did not have the vent rates tuned, although the default vent rates were not used. Figures A-11 and A-12 present the history of the final feedwater and steam line oxygen concentrations.

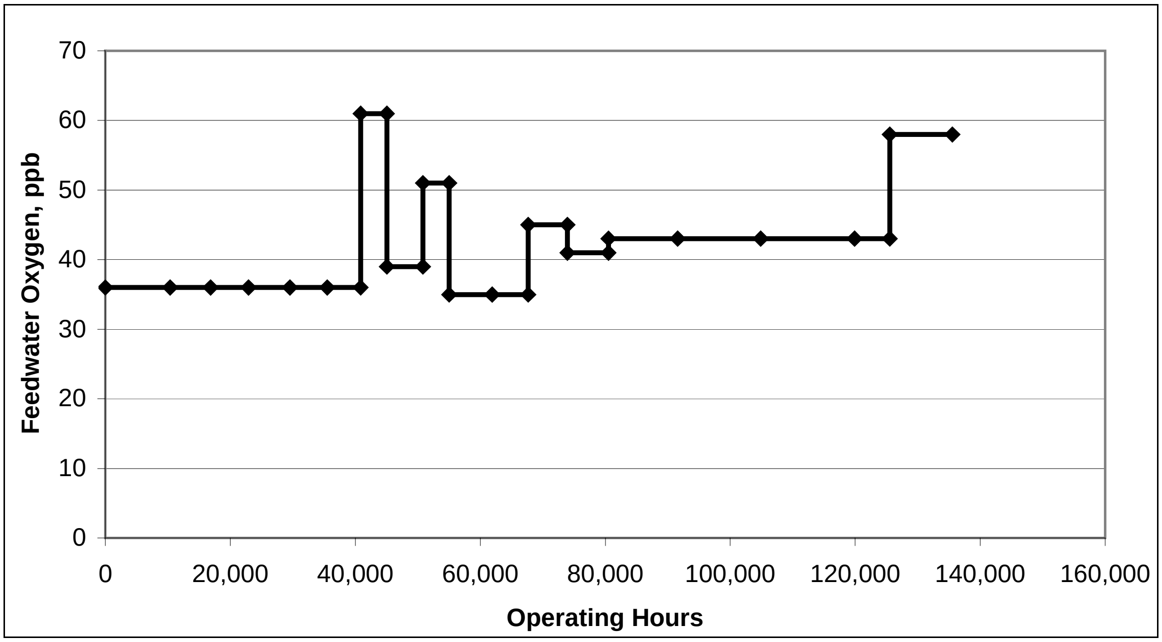

Figure A-9
Columbia Feedwater Oxygen History

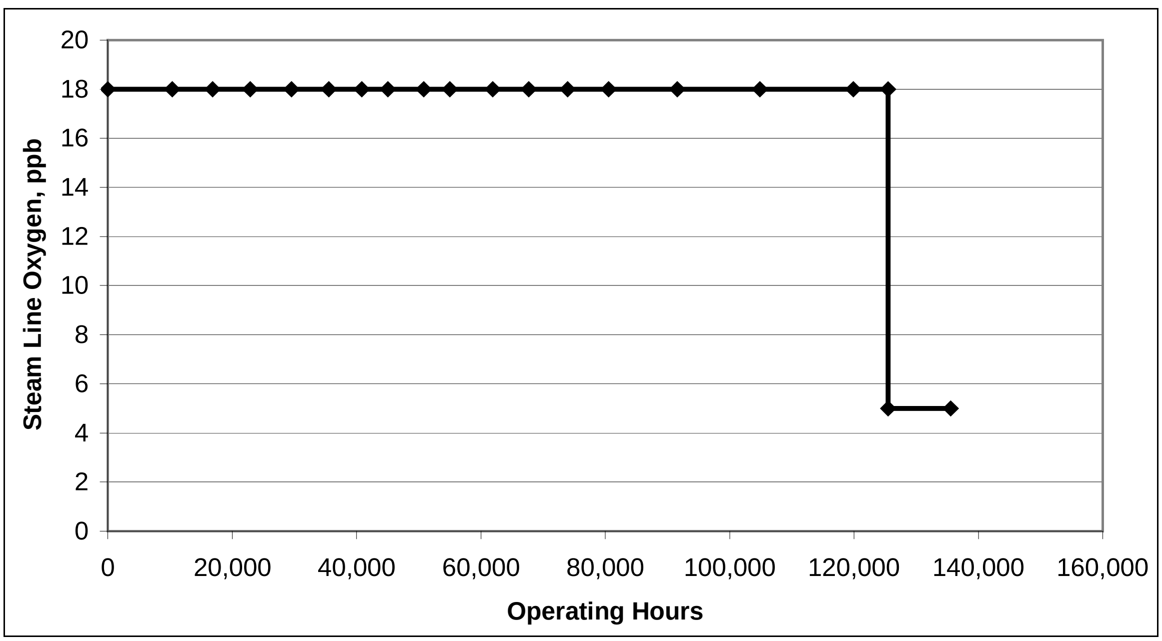

Figure A-10
Columbia Main Steam Line Oxygen History

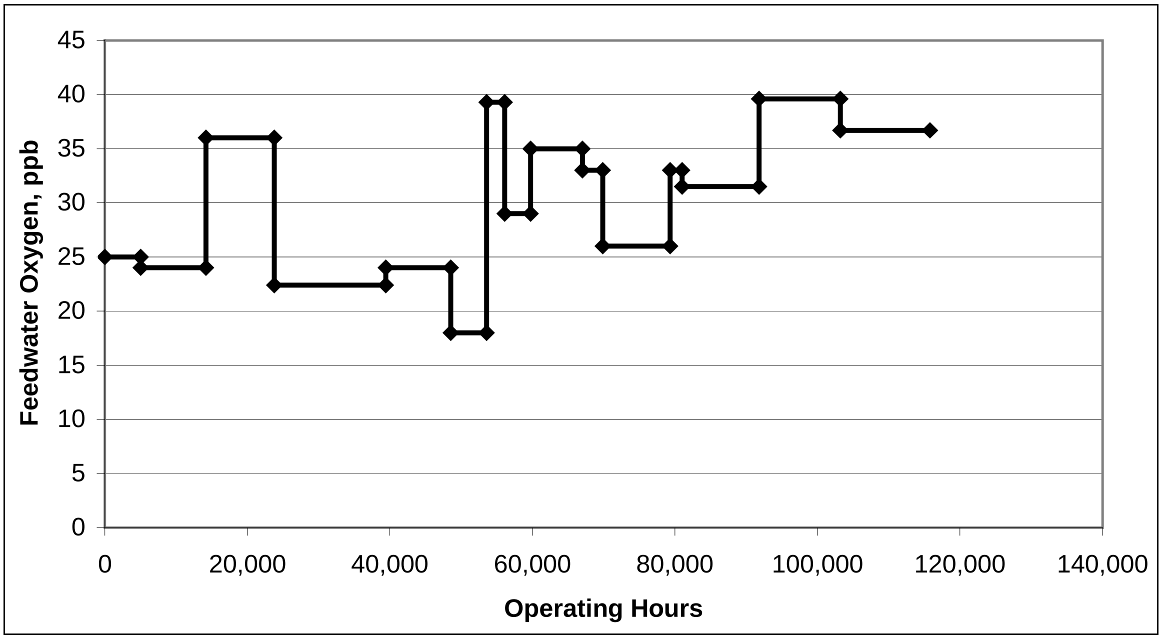

Figure A-11
Fermi Feedwater Oxygen History

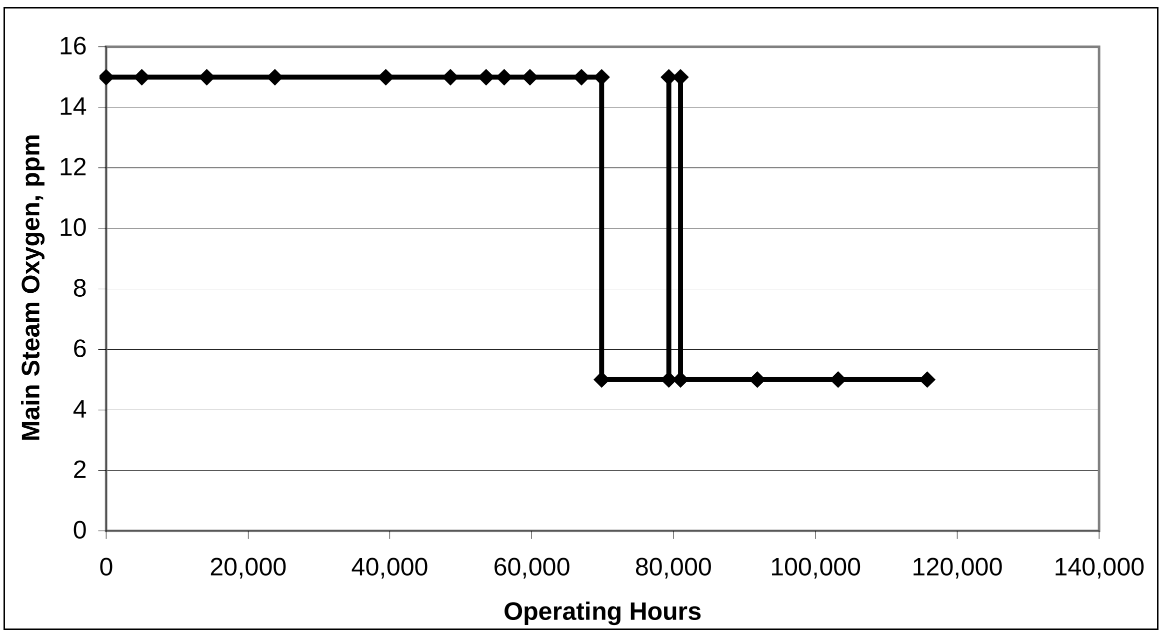

Figure A-12
Fermi Main Steam Oxygen History

B
DEVELOPMENT OF A REVISED CORRELATION

B.1 Original Correlation

The original correlation of oxygen factor versus dissolved oxygen dates from the development of CHEC® in the late 1980s [B-1]. The correlation is in the form of a series of curve fits covering the range of 0 to 2,000 ppb. Above 2,000 ppb, the factor is set to zero. Figure B-1 presents a plot of this correlation versus dissolved oxygen.

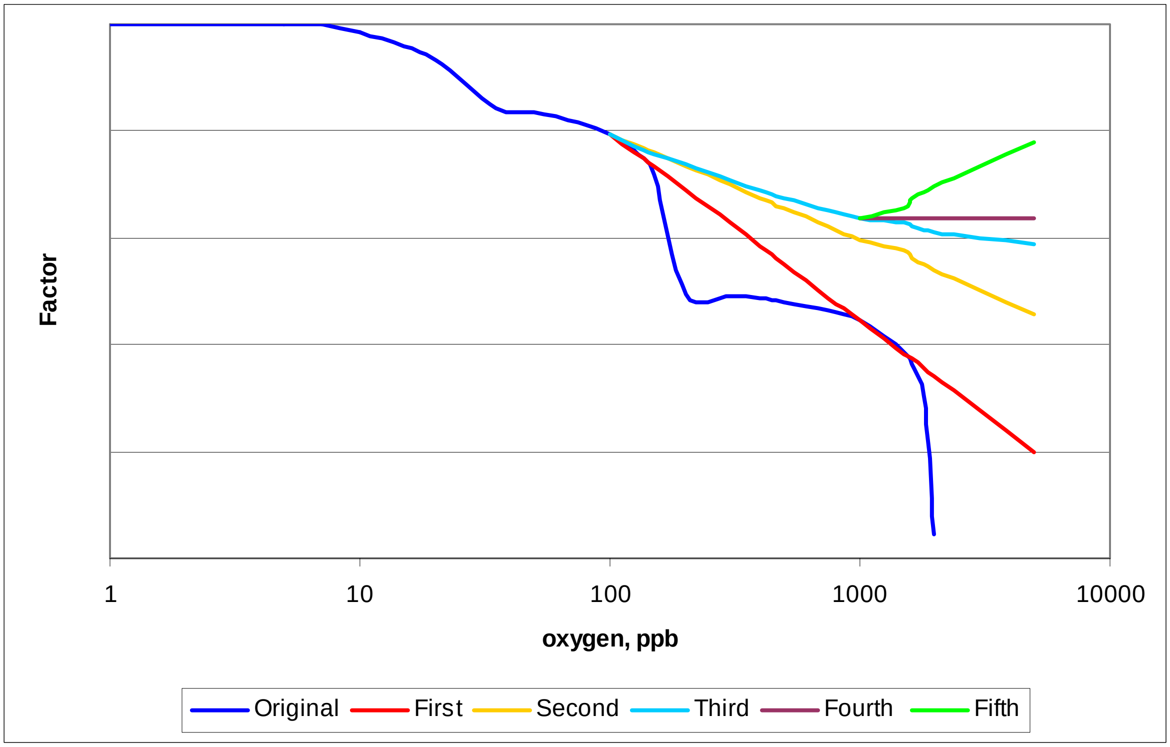

Figure B-1
Evolution of Oxygen Factors

B.2 Revised Correlations

Based on the results of the earliest trials, two facts seemed evident:

1. The correlation had to be extended past 2,000 ppb,
2. The correlation was substantially underpredicting (i.e., the oxygen factor was too low) at values of the dissolved oxygen greater than about 100 ppb.

To improve the predictions, a series of revised correlations were tested against the laboratory and plant data.

B.2.1 First Version

The first trial was designed to smooth out and extend the original correlation. This correlation was non-zero at all levels of oxygen, but was still underpredicting both the laboratory and plant data. Figure B-1 presents the original correlation and the first version versus dissolved oxygen.

B.2.2 Later Versions

The remaining trial correlations were designed to overcome the underpredicting, particularly of the plant data, while not overpredicting the laboratory data. The shapes of these correlations are presented in Figure B-1.

Note that in the fourth version of the correlation, the oxygen factor above 1,000 ppb no longer is monotonic, rather it plateaus at a constant value.

Finally, the final version has a minimum oxygen factor at 1,000 ppb and a linear increasing curve thereafter.

B.3 Final Version

The final version of the correlation departed from earlier versions in that it was no longer monotonically decreasing. Rather at 1,000 ppb, it ramped linearly upward. Further attempts to use even higher values of the factor at higher oxygen values resulted in very poor agreement with the high-oxygen laboratory data. Thus, this version was a compromise between the laboratory data and the limited amount of high-oxygen plant data.

B.4 Reference

B-1. CHEC® Computer Program Users Manual. NSAC-112L, Rev.1, EPRI, July 1989.

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