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Flow-Accelerated Corrosion Investigations of Trace Chromium

Technical Report

Flow-Accelerated Corrosion Investigations of Trace Chromium

1008047

Final Report, December 2003

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This report describes research sponsored by EPRI.

The report is a corporate document that should be cited in the literature in the following manner:

Flow-Accelerated Corrosion Investigations of Trace Chromium, EPRI, Palo Alto, CA: 2003. 1008047.

REPORT SUMMARY

This study used new laboratory and plant data to examine models for determining the impact of chromium content in predicting the rate of flow-accelerated corrosion (FAC) of carbon and low-alloy steels. These data show that the FAC resistance of materials containing small amounts of chromium increases with time, in qualitative agreement with the theory proposed by Bouchacourt.

Background

Flow-accelerated corrosion causes wall thinning of piping, vessels, and components. Wall thinning results from dissolution of the normally protective oxide layer (magnetite or hematite) that forms on the surface of carbon and low-alloy steels when exposed to flowing water or wet steam. The problem is widespread in all types of nuclear and fossil power plants including boiling-water reactors (BWRs), pressurized-water reactors (PWRs), heavy-water reactors (HWRs), and graphite-moderated reactors. Wall thinning rates as high as 0.125" (3 mm) per year have been observed. If thinning is not detected in time, either leaks or instantaneous complete ruptures can, and do, occur.

It has been generally accepted for the last 20 years that the chromium content of a fitting is an important parameter affecting the rate of FAC. The chromium model used, for example, in the CHECWORKS™ and predecessor programs, is based on laboratory work done in the early 1980s. Recently, plant experience has challenged this laboratory work and the resultant models.

Objectives

- To examine the latest available laboratory and plant information on the parametric influence of chromium content
- To recommend possible improvements to the existing chromium models.

Approach

The research team gathered the most recent information available, which included data from the openly available literature, proprietary laboratory data made available by the Atomic Energy of Canada Ltd (AECL), and plant data from the members of the CHECWORKS™ Users Group (CHUG). The team plotted the new laboratory data against the Ducreux correlation currently in use in the CHECWORKS™ Steam/Feedwater Application (SFA). The team then examined and screened the plant data and determined from the inspection data a wear rate for each component selected.

When possible, they compared the wear rate to a similar component known or believed to have minimal chromium and plotted the resulting ratios against the Ducreux correlation in use in the SFA.

Results

The data evaluation showed that the Ducreux correlation is quite conservative for both single- and two-phase conditions. A revised correlation that better agrees with the data has been proposed.

The evaluation of the AECL data shows that the transient model proposed by Bouchacourt agrees qualitatively with the test data. This observation also supports the proposition that the Ducreux model is conservative when compared to long-term plant data.

EPRI Perspective

Many utilities worldwide use the CHECWORKS™ SFA to predict the rate of flow-accelerated corrosion in their piping systems and to assist in managing its control. The development of a revised factor for the chromium content will improve the accuracy of these models. The efficiency of inspection programs should increase as a result of having a more accurate model to predict FAC.

Keywords

Flow-accelerated corrosion
Chromium content
CHECWORKS™ SFA

ABSTRACT

The chromium model, currently used in the predictive algorithm of the CHECWORKS™ Steam Feedwater Application, has been challenged by plant data that suggest that it is overly conservative in the range of chromium between 0.04 and 0.2% under single-phase conditions.

Literature, laboratory and plant information were gathered, reduced and compared to the currently used Ducreux correlation. The two main questions to be answered by this work were:

- Is the current model good, or is an updated model needed?
- Should there be different models for single-phase conditions and two-phase conditions?

Evaluation of the plant and laboratory data showed that the resistance of material containing chromium increases with time. This is in qualitative agreement with the theory proposed by Bouchacourt. This observation further supports the proposition that the Ducreux correlation, which is based on short-term tests, is conservative when used to predict long-term plant data.

As a result of this work, a revision to the model is proposed. In addition, no significant difference between the single- and two-phase plant data appears to exist.

ACKNOWLEDGEMENTS

The following individuals are recognized for providing plant information:

- Ian Breedlove, Dominion Generation – North Anna Units 1 & 2, and Surry Units 1 & 2
- Steve Ewens, AmerenUE - Callaway
- Lee Goyette, Pacific Gas & Electric Company – Diablo Canyon Units 1 & 2
- Juri Kaplan, Nuclear Research Institute – Dukovany Units 2 & 3
- Erwin Prather, Wolf Creek Nuclear Operating Company – Wolf Creek
- Sherman Shaw, Southern California Edison – San Onofre Units 2 & 3

Without this plant information, this work would not have been possible.

The contributions of Joe Donell and Harold Crockett of Exelon, and Tim Giles of Constellation Energy are acknowledged.

The cooperation of AECL is also acknowledged, especially that of Dr. John Pietralik.

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1 INTRODUCTION

Flow-accelerated corrosion (FAC) has been a continuing concern for operators of nuclear and fossil power plants. A compilation of the knowledge concerning FAC can be found in a 1998 EPRI publication [1].

It has been long recognized that the alloy content of the corroding metal is an important factor in predicting the rate of FAC. In particular, a great deal of work indicates that chromium is the most important alloying element in protecting components from FAC.

This report presents the result of a study reviewing possible improvements to the algorithm used in the Steam Feedwater Application for CHECWORKS™ [2]. This study was performed by assembling all known information concerning the effects of chromium on the rate of FAC. In particular, laboratory papers were assembled and reviewed. Additionally, plant information from both domestic and foreign plants was obtained and evaluated.

This report is organized as follows:

- Chapter 2 presents the historical background of the chromium model used in the CHEC® family of computer codes.
- Chapter 3 presents the historical laboratory data and the laboratory data obtained in this project.
- Chapter 4 describes the plant data obtained in this project.
- Chapter 5 describes the approach taken in reviewing these data sources.
- Chapter 6 presents recommendations for a revised correlation for use in the SFA.

2
HISTORICAL BACKGROUND

In 1987, EPRI responded to the accident at the Surry nuclear plant by developing a method to predict the rate of FAC and a computer program, CHEC® [3], to transfer this technology to the utility members.

When CHEC® was written, the development team used available information to formulate the predictive model. The team chose the model of Ducreux to account for the presence of the three most important alloying elements – chromium, copper and molybdenum [4]. This model was slightly modified for use in the program and has remained unchanged as the program evolved to CHECMATE™, CHECWORKS™ Version 1.0x, and finally to the CHECWORKS™ SFA.♣ The predictions of the model on the impact of alloy content on the rate of FAC are presented in Figure 2-1.

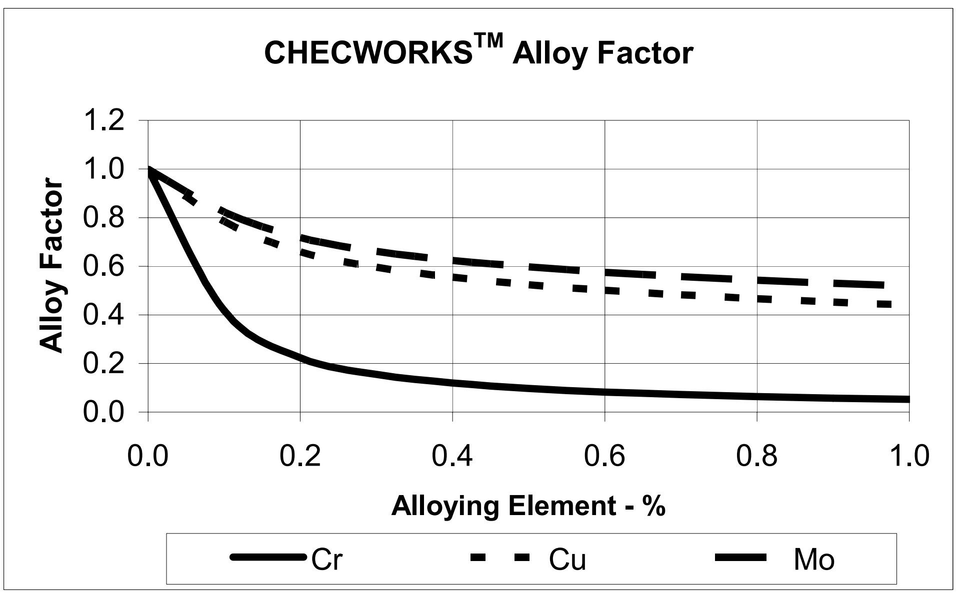

Figure 2-1
CHECWORKS™ Alloy Factor Model
(Note for illustration purposes, the contribution of each element is shown with the other two alloys set to zero.)

♣ The chromium algorithm, like all other algorithms in the CHEC® family of codes, was designed to provide a best estimate prediction of the rate of FAC. This decision was made since the FAC process is quite complicated with a large number of parameters. If a bounding approach were to have been taken, the predicted results would be so conservative that they would not be useful. Rather, the approach taken was to make the predictions as accurate as possible, and to apply conservatism at the end of the process (e.g., factor of safety on the predicted lifetime).

For convenience, the factor for chromium only is presented on a semi-logarithmic plot in Figure 2-2. This figure is useful for evaluating the plant and laboratory data.

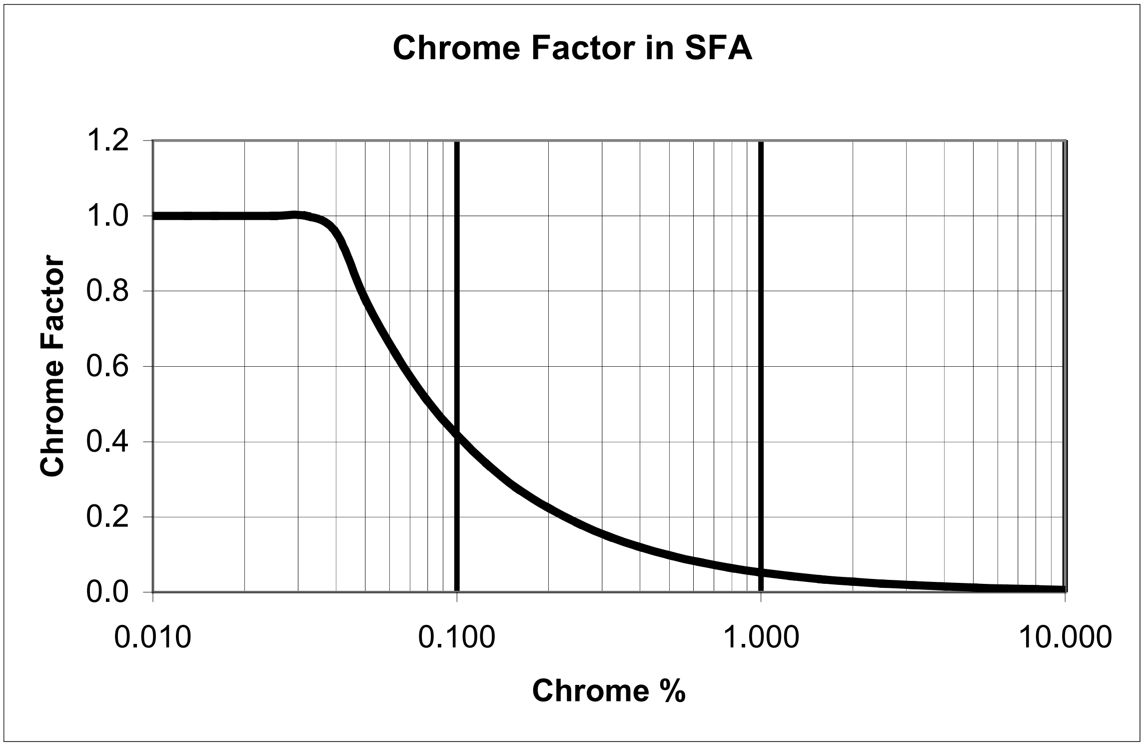

Figure 2-2
Chromium Factor Used in CHECWORKS™ SFA

In the early nineties, this model was called into question by plant observations in the United States and France. These observations indicated that chromium content as low as about 0.1% effectively inhibited FAC from occurring under single-phase conditions. It is to be noted that the information presented in Figures 2-1 and 2-2 indicates that appreciably higher amounts of chromium (>1%) are required for such inhibition. It should be stressed that this observation was made only for **single-phase** conditions. As far as is known, similar findings have not been reported for two-phase (i.e., steam-water) conditions.

In the mid-nineties, Bouchacourt [5] developed a transient model to determine the impact of chromium on FAC. The results of this model are presented in Figure 2-3 together with two pieces of plant data. It is to be noted that the Ducreux relationship corresponds to the highest (i.e., the 100 hour) curve on this figure. In other words, the model states that steel with chromium contents of greater than about 0.04% become more protective with time. This observation is not apparent in any of the existing sets of laboratory data.

As mentioned previously, the Bouchacourt Model applies to single-phase conditions, as two-phase conditions were not specifically included in his model.

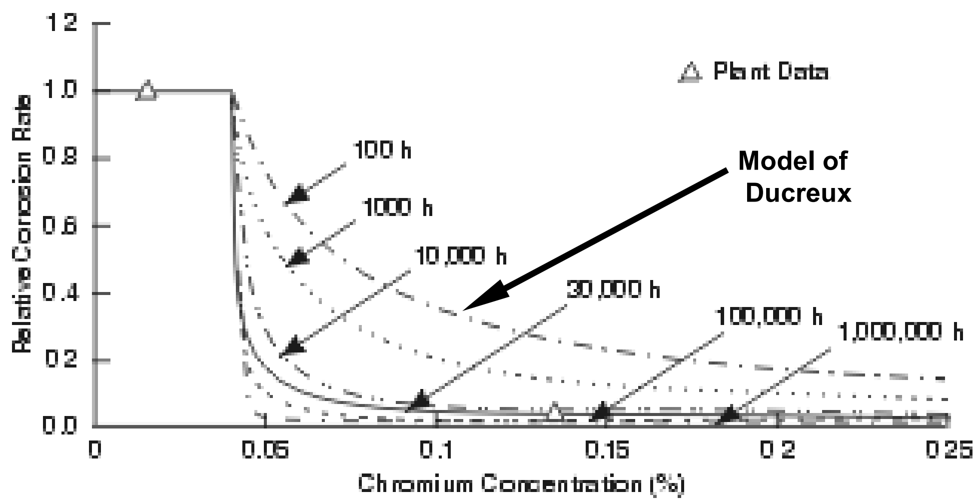

Figure 2-3
Model of Bouchacourt

It should be mentioned that there is another materials model in fairly common usage. It is the Kastner Model [6] in the WATHEC computer program of Siemens. This model differs from the Ducreux Model in that the materials parameter that is correlated is the sum of the chromium and molybdenum contents.

The Kastner model is presented in Figure 2-5 against high-velocity single-phase data at 356ºF (180ºC). Note that the test duration was 200 hours. Figure 2-6 compares the Kastner model to the Ducreux Model for a molybdenum content of zero. As can be seen, the Ducreux Model is less conservative (i.e., greater influence of chromium in reducing FAC) than the Kastner Model.

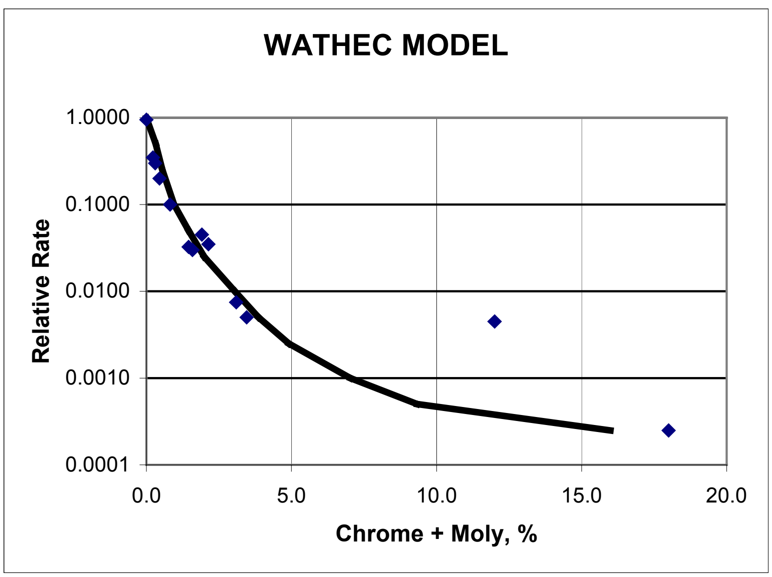

Figure 2-4
Kastner Model and Data

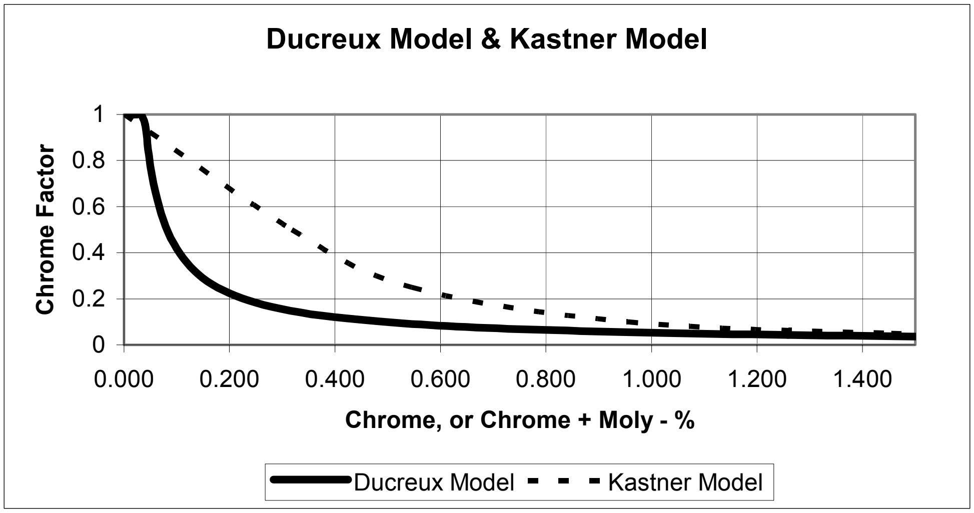

Figure 2-5
Kastner and Ducreux Models

3 LABORATORY INFORMATION

There are several sources of laboratory information on the subject of chromium and FAC as discussed below.

3.1 Ducreux Data

In the early eighties, Ducreux, working for EDF, conducted tests to determine the importance of alloying elements in protecting against FAC. He performed these tests by directing a high-velocity stream of steam and water at a temperature of ~355ºF (180ºC) on various samples and measuring weight loss. The test duration was between 30 and 300 hours. Ducreux developed an empirical correlation based on this information. As mentioned above, this correlation has been used in CHEC® and the successor codes. A curve fit through the Ducreux data for chromium was presented in Figures 2-1 and 2-2.

Correlations based on this data are used in EPRI's CHECWORKS™ SFA program as well as in EDF's BRT-CICERO program [7].

3.2 Huijbregts Data

Also in the early eighties, Huijbregts in the Netherlands determined the impact of alloy content on FAC [8]. The tests were done in a manner similar to those of Ducreux in that a high velocity jet of steam/water was directed at small test coupons. Test duration was 100 hours. Figure 3-1 presents the data of Huijbregts together with his curve fit as normalized by Shack [9].

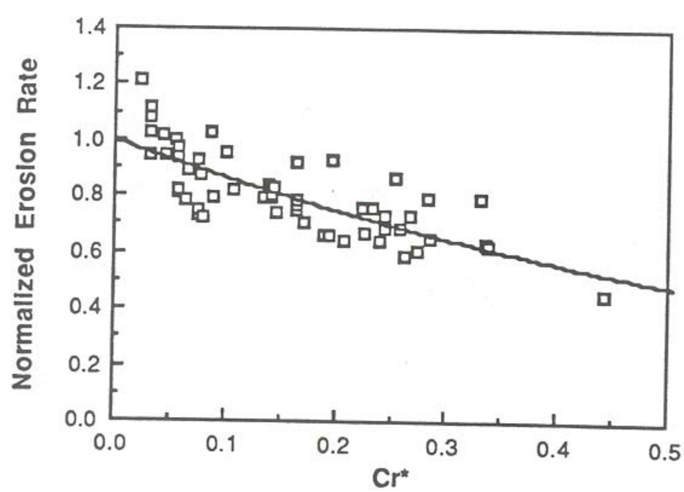

Figure 3-1
Data of Huijbregts as Normalized by Shack [9]

3.3 Kastner Data

Kastner, working for Siemens/KWU, obtained similar alloy data. This data was obtained by flowing single-phase water over plate samples within a pipe. The test duration was 200 hours [10]. A correlation based on this data was presented in Figure 2-5

3.4 AECL Data

Much more recently, Atomic Energy of Canada Ltd (AECL) obtained chromium data. This data was taken in response to thinning reported in CANDU® feeder pipes. The feeder pipes are the pipes that connect inlet and outlet headers with the inlet and outlet of the pressure tubes that cool the core. FAC has been observed in outlet feeders [11] [12]. As part of the investigation into this problem, AECL conducted tests into the influence of chromium on FAC under high-velocity, single-phase conditions.

The AECL test data were different from the other works presented in that they were obtained under CANDU primary circuit conditions in a loop circulating high-temperature light water where the pH was controlled by lithium hydroxide [13]. They also differ from the earlier work in that the measurements were all made in high temperature single-phase water and that the test duration was much longer. The FAC rate was determined by weight change after the appropriate corrections for oxide loading were made.

Two sets of tests were conducted addressing the feeder wall thinning issue [13]. One test, the "in-reactor" test, was performed in a fueled loop in the NRU research reactor in Chalk River, Ontario, where the purified light water was kept unsaturated with respect to dissolved iron by the choice of pH and the temperature rise across the core. The temperature of the water was about 585ºF (~307ºC). The test duration was a total of 611 days. Two materials, with chromium contents of 0.013% and 0.24%, were tested.

The second test was conducted in the recirculating stainless steel H-2 loop at about 575ºF (~302ºC), where the dissolved iron concentration was kept low by a high flow purification system [13]. Three materials with chromium contents of 0.02, 0.24, and 0.33 % were tested. The test duration was 110 days.

A third series of tests [14] were conducted in the HTR loop at Chalk River Laboratories addressing FAC under saturated dissolved iron conditions and hydrazine/ammonia chemistry at about 350°F (~180°C) to address chemistry conditions in the steam cycle. The loop was constructed of 304 stainless steel with no carbon steel present other than the test samples. The loop did not have a full-flow purification to remove the iron produced during the tests. A side purification stream was employed to maintain steady-state all-volatile chemistry. Three samples with chromium contents of 0.02, 0.05, and 0.140 % were tested. A probe containing 2.3% Cr and 0.9% Mo was used as a blank. The corrosion rates were established from measured changes of the electrical resistance of tubular probes. In this way, a record of the average thickness of the specimen versus time was obtained.

The lack of a full-flow purification system implies that the loop water became saturated or nearly saturated in dissolved iron. Accordingly, crud particles were observed to be generated in the loop. The basic understanding of FAC is that there is dissolution of ferrous ions from the metal and oxide surfaces, and that this dissolution is driven by the concentration gradient between the bulk water and the surfaces, thus the FAC rates should have been very small. This work appears to contradict this, but as the data from this loop appears reasonable it is assumed that this data is valid. This issue is further discussed in Reference [14].

The HTR data are presented in Figure 3-2 together with the Ducreux correlation. It should be noted that this data is normalized to the corrosion rate at 0.05% chromium.

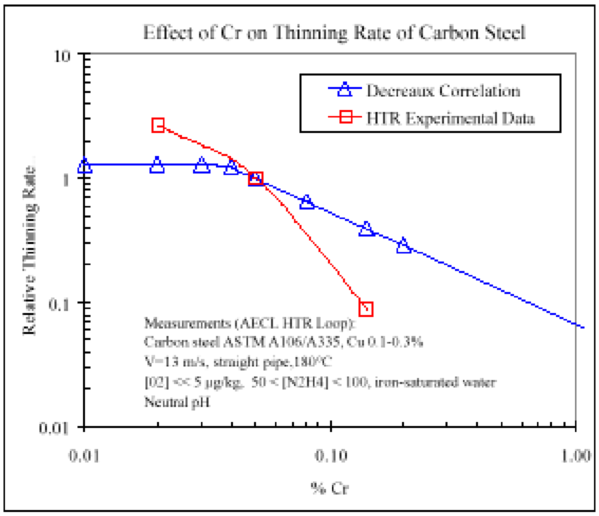

Figure 3-2
AECL Out-of-Reactor Results

Transient Results. One very significant aspect of the AECL data obtained under lithium hydroxide chemistry is that the transient corrosion of the specimens was monitored. It is generally accepted that steels experiencing FAC display a linear corrosion rate with time. Bouchacourt theorized, as presented earlier, that the corrosion rate of steels containing more than about 0.04% chromium should show a decreasing rate of corrosion with time.

Figure 3-3 shows the results of the calculated weight loss versus time for the in-reactor tests. Similar results were obtained for the H-2 loop tests. The bending downward of the high chromium samples shows the decreasing corrosion rate. From this, and the sister graph for the H-2 loop data, a plot of the relative FAC rate as a function of time can be obtained. Figure 3-4 shows the data from both the in-reactor and the H-2 out-of-reactor tests under lithium hydroxide chemistry at ~580ºF. For conservatism, the highest of the family of three curves for the in-reactor case was chosen. Also plotted on this figure is the Bouchacourt prediction for chromium content of 0.24%. The Bouchacourt prediction exhibits the same shape as the data, but is much lower.

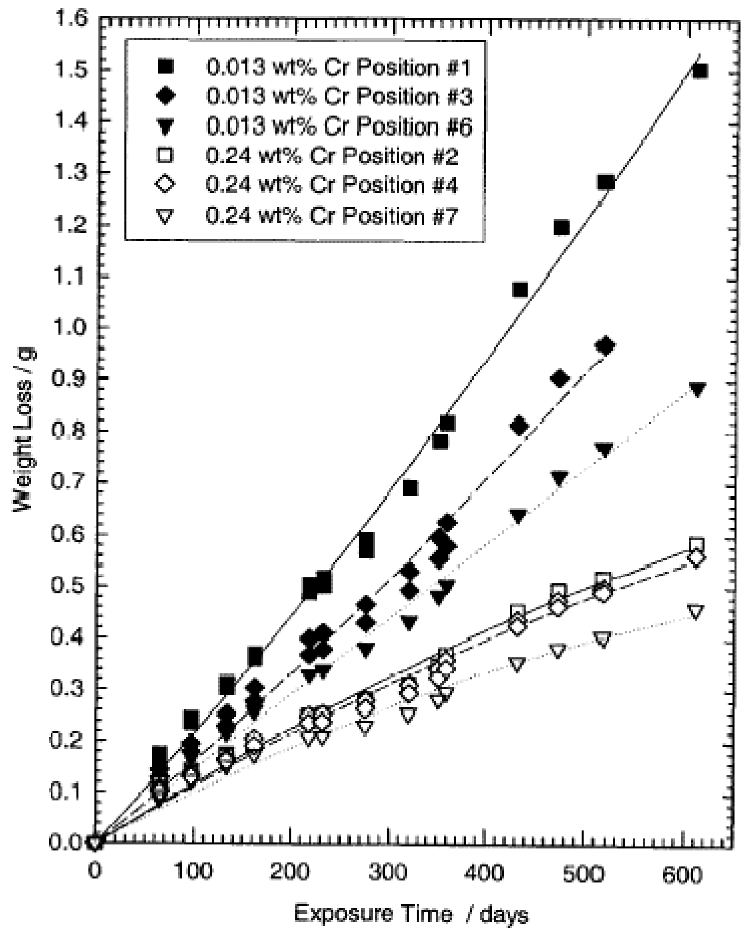

Figure 3-3
In-Reactor Data Showing Transient Behavior

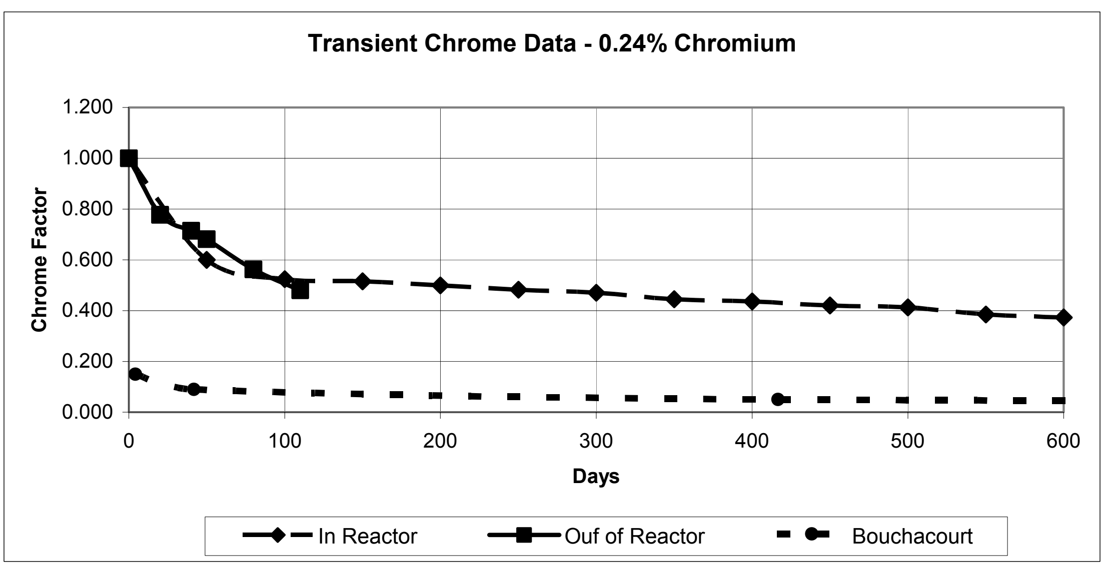

Figure 3-4
AECL Transient Data at 580°F with Bouchacourt Prediction

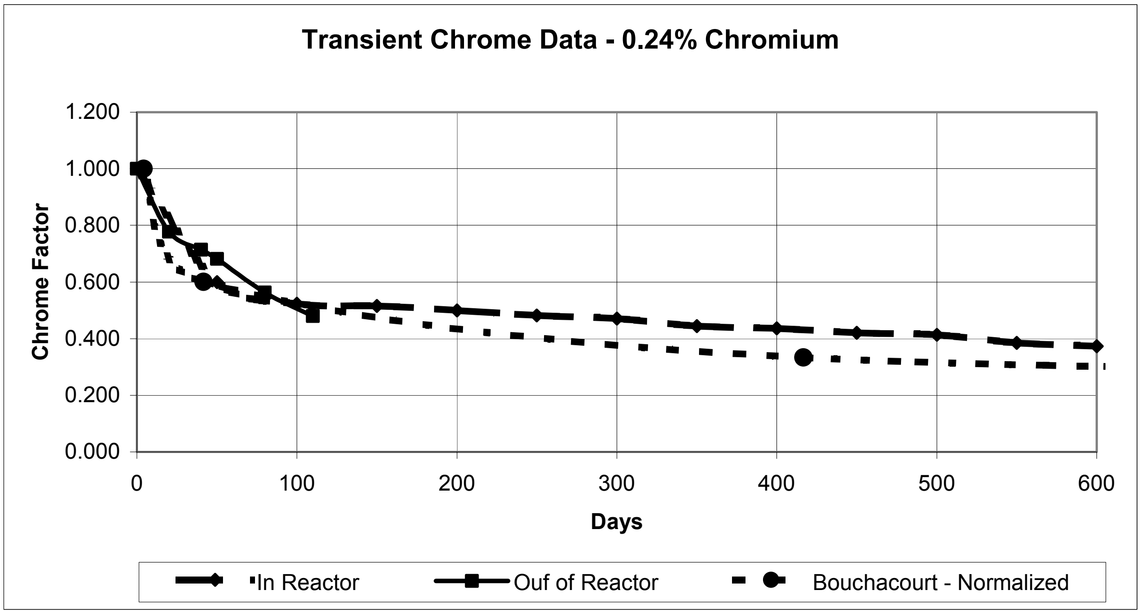

Figure 3-5
AECL Transient Data at 580°F Compared to Normalized Bouchacourt Prediction

To compare the shape of Bouchacourt prediction with the two data sets, the Bouchacourt prediction was normalized to unity at zero time. This comparison is presented in Figure 3-5. As can be seen, the agreement is excellent.

4 PLANT DATA

It should be stressed that it is difficult to estimate from plant data the chromium content when FAC is completely inhibited. This is because the determination of small amounts of wear is difficult. Thus, it is possible to say that a given component does not seem to be wearing, but it is difficult to say that it is wearing at a rate of less than 1% of a similar fitting. This observation will be discussed in the next chapter.

An additional difficulty is that relatively few components have multiple inspection data and measured chromium data. A request for chromium data was made to members of CHUG (i.e., the CHECWORKS™ User Group), with data received from the following plants.

4.1 Diablo Canyon

Diablo Canyon is a two-unit Westinghouse PWR plant located on the coast of California. Historically, this plant has experienced a great deal of damage caused by FAC primarily because of relatively poor water chemistry (i.e., poor with respect to FAC). This problem has been especially severe in the feedwater system where there is a combination of high wear caused by the chemistry and small structural margins (difference between actual thickness and the code required minimum thickness). Because of this, a large number of inspections have been made in this system. Fortunately, sample examinations found that there were significant amounts of trace chromium present in many components of this system. The combination of the high wear, low margin, and trace chromium led to an aggressive program to determine the amount of chromium present in each inspected component.

4.2 Dominion Power

Dominion Power operates two two-unit PWR sites in Virginia – Surry and North Anna. Both of these sites use PWRs designed by Westinghouse. Since the Surry accident in 1987, Dominion Power has had a robust FAC program.

4.3 Callaway

Callaway is a single unit Westinghouse PWR. Because of relatively poor water chemistry (i.e., poor with respect to FAC), there have been a large number of inspections performed over the years. A drain line failure in 1999 increased the emphasis on FAC inspections.

4.4 Wolf Creek

Wolf Creek is a single unit Westinghouse PWR. It is a sister plant to the Callaway plant.

4.5 San Onofre

San Onofre is currently a two-unit PWR site designed by Combustion Engineering. (Unit 1 has been decommissioned.)

4.6 Dukovany

The Dukovany Nuclear Power Plant is a four-unit VVER plant of Russian design. In concept, the VVER reactors are similar to PWRs. Each Dukovany unit is rated at 440 MWe. Because of extremely poor water chemistry by Western standards, there has been a great deal of damage caused by FAC. Fortunately, it has been found that the piping components at Dukovany have a higher percentage of chromium than that usually found in Western plants.

For convenience, the Dukovany experience will be divided into two parts.

1999 Paper

In 1999, personnel from the Nuclear Research Institute presented a paper describing the FAC program at Dukovany [15], which included a program to measure trace chromium. The approach taken was to compare the measured rates of FAC for similar components with and without trace chromium. It is stated *"Data fit well with the Ducreux model in the range of Cr (i.e., chromium) contents between 0.04 and 0.1%. At higher values, it seems that Ducreux model overpredicted slightly the wear rate"*.

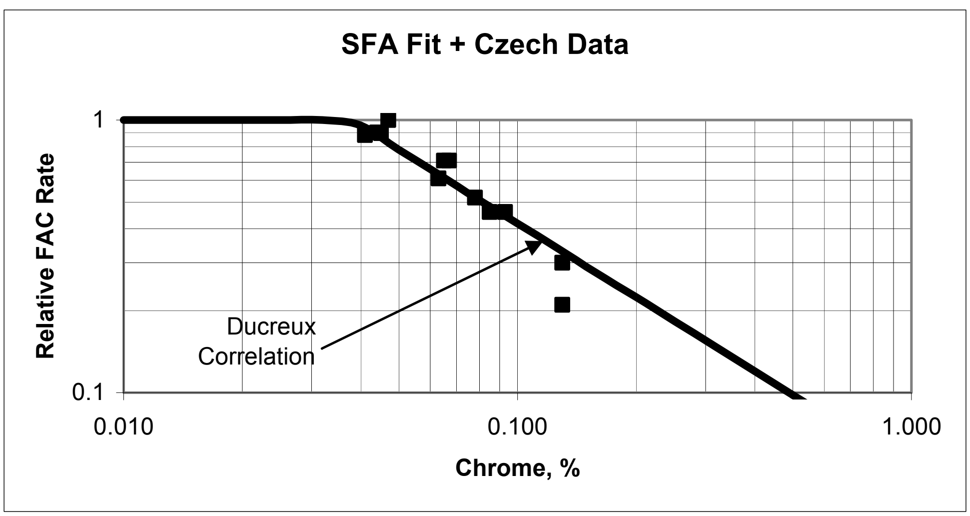

Figure 4-1
Czech Data from Ruščák, et al.

The data presented is summarized in Figure 4-1. As can be easily seen, all but one of the data points agrees quite well with the Ducreux model. It should be noted that the data shown in Figure 4-1 is for single-phase conditions on straight pipes in the feedwater system [16].

Recent Data

More recent data was obtained from NRI concerning the Dukovany plant. This data was interpreted in the same manner as the data of the US plants previously discussed.

4.7 J-Tube Experience

J-tubes are anti-water hammer devices found in the inlet portion of some steam generators. In the early eighties, it was found that the some of the J-tubes at a number of plants were severely attacked by FAC. This experience led to investigations designed to determine why some J-tubes were attacked while other J-tubes in other locations were not attacked. These investigations determined that trace alloy content, particularly trace chromium was responsible for the protection observed.

Virtually all of the information is proprietary, and is not discussed further.

4.8 Miscellaneous Experience

In addition to the plant data mentioned above, there are many reports in the literature concerning chromium and FAC. Unfortunately, these reports do not allow a quantitative estimate of the impact of chromium and are not discussed here. The interested reader is referred to Reference 1.

5
DATA ANALYSIS

The two types of data obtained were analyzed in different ways.

5.1 Laboratory Data

The only laboratory data used in this project was the Canadian data from AECL described in Section 3.4. This data was used directly as presented in the report [13] and accompanying letter [14]. The only data analysis performed was deducing the transient impact. This was done by evaluating the data presented in Figure 3-3 and the data from the out-of-reactor tests. At each point of interest, the loss rate of the high chromium component was divided by the loss rate of the low chromium component. The resulting data was then plotted against time.

5.2 Plant Data

The analysis of the plant data was much more complicated. The plant information was generally in the form of a CHECWORKS™ database with sometimes supplemental information containing chromium measurement data. As there are many thousands of components present in a typical database, there was a great deal of information to be evaluated. To do this, the following general procedure was used:

1. A small FORTRAN program was written to examine the database output and select components with chromium content in the range from 0.04 to 1%.

2. The outputs of this FORTRAN program were imported into an EXCEL spreadsheet for further processing. One spreadsheet was developed for each unit examined.

3. The next step was to compare the generated list of components with chromium in the range of interest with a list of measured chromium content if such a list was available. This was done to ensure that all components with measured chromium were accounted for.

4. The unit databases were used to populate the spreadsheet in categories of component type (e.g., elbows, tees, nozzles, straight pipe, etc), single- or two-phase operating conditions, and number of inspections performed.

5. Next, all of the components with zero or one inspection were removed from the list. Also removed were components that did not have identical grids for their inspections. Identical grids are necessary for accurate point-to-point determination of the wear. At this point, only components with suitable data from two or more outages remained to be considered.

6. As far as possible, components from this culled list were matched with “sister” components from the database. To qualify as a sister component, the following criteria had to be satisfied:
   - The component came from the same line or a parallel line with the same operating conditions
   - The component was of the same geometry type
   - Two or more sets of inspection data were available for the sister component.

   Additionally, it was desirable that the chromium content of the sister component had been measured, but this was not a requirement for selection.

7. The ratio of the wear rates of the component with chromium and its sister component were made, and entered in the spreadsheet together with the name of the two components, the chromium content(s), and whether or not the components experienced single- or two-phase conditions.

8. In some cases, when two or (usually) more sets of inspection data showed what was judged to be zero wear, then the points were entered into the result spreadsheet with a notation that the determination was not based on a sister component.

9. The results from the different units were assembled, evaluated and plotted.

It is to be noted that in most cases there were few components left after the data analysis process was completed.

5.3 Results

The results from the new plant data are presented in Figure 5-1. The results are subdivided as single-phase results in Figure 5-2, and two-phase results in Figure 5-3. It is to be noted that the correlation used in CHECWORKS is plotted in each of these figures, but that the Dukovany data is not plotted. This will be discussed below. Data plots for all of the plants are presented in Appendix A.

In Figure 5-1 through 5-3, the points that had “zero wear” are located on the abscissa. All of the other points (i.e., the points that had some relative FAC) were derived from “sister components.” Obviously, there was more scatter in the points from the sister category, but that is just a result of the data analysis method.

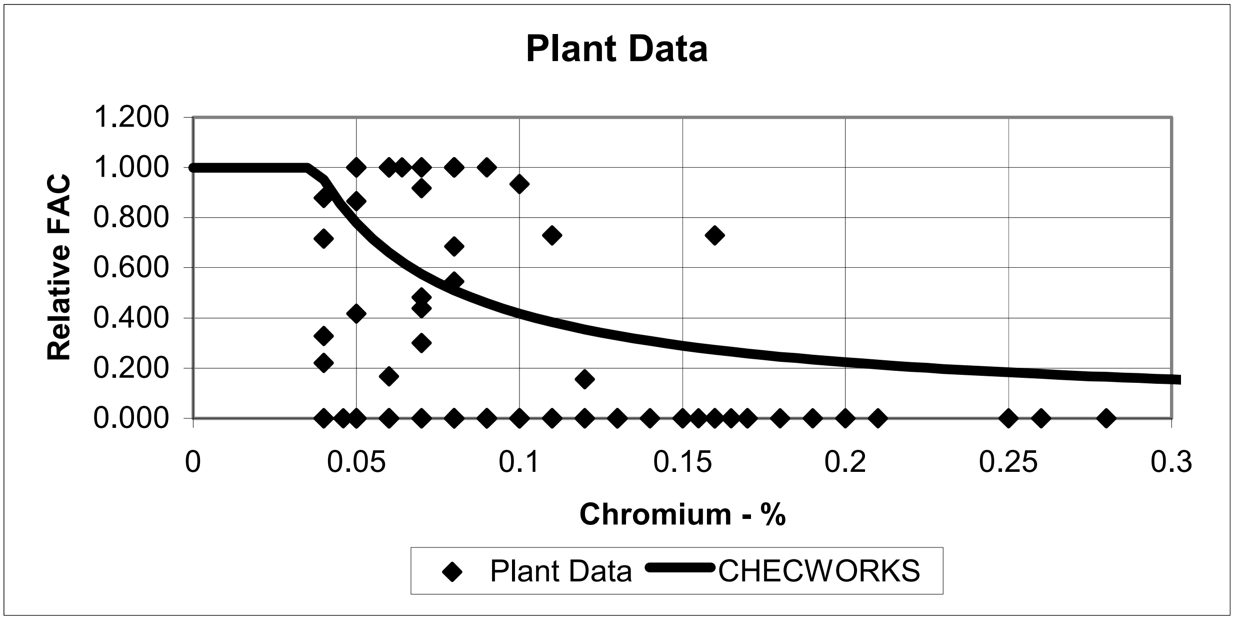

Figure 5-1
Plant Data

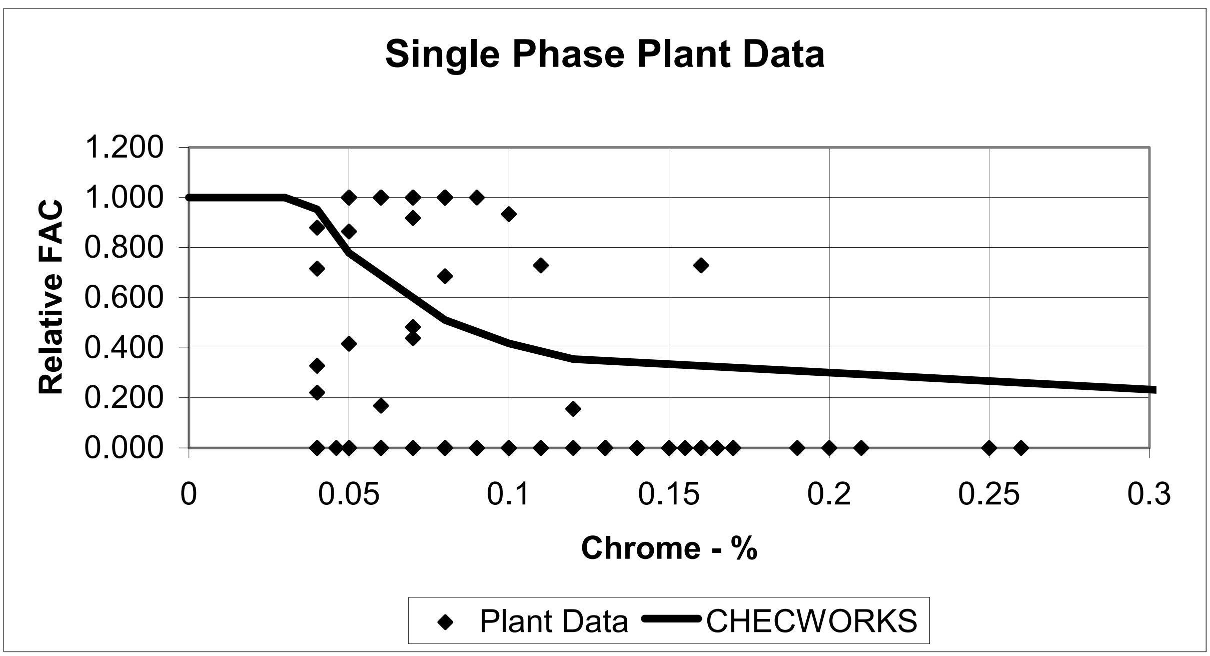

Figure 5-2
Single-Phase Plant Data

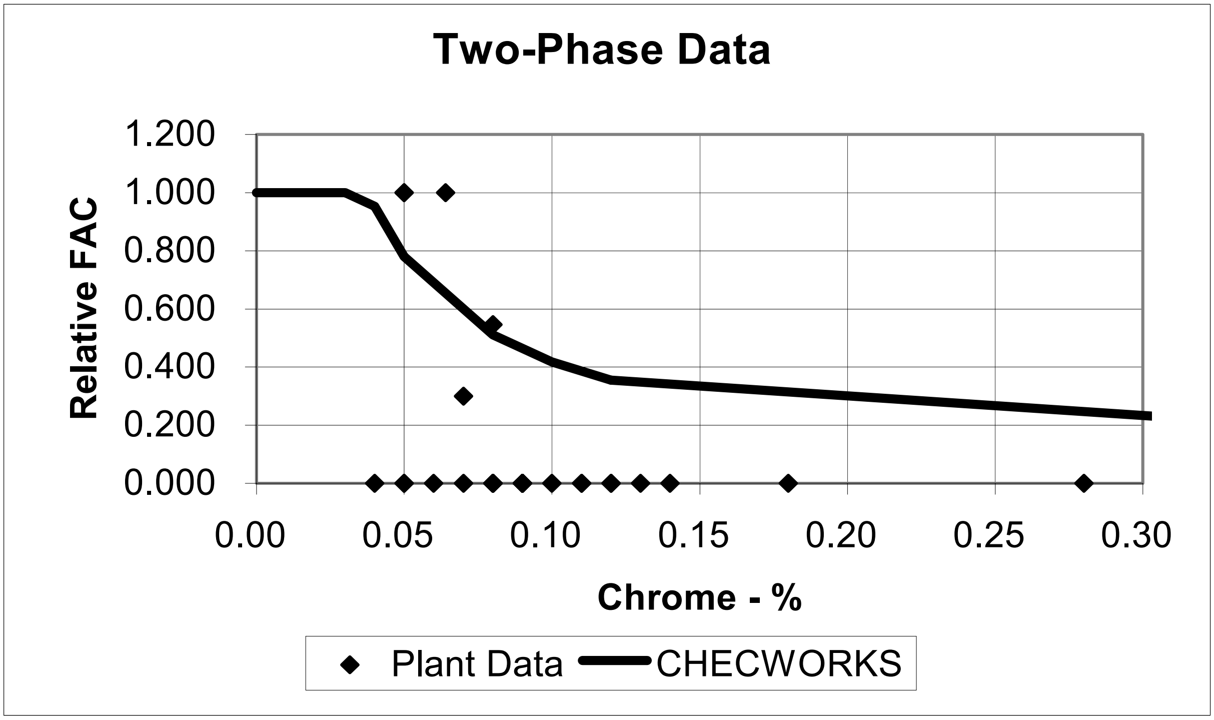

Figure 5-3
Two-Phase Plant Data

5.4 Discussion of Results

Scatter

As expected, there was a great deal of scatter present in the data. Some of the reasons for the scatter are:

- Imprecision of the inspection measurements.
- Inaccuracies in the chromium measurement
- Difficulties in comparing the subject component with a “sister” component.

These issues will be discussed in the next section.

Exclusion of the Dukovany Data

When all of the data were first plotted, there was a tremendous amount of scatter present. When the data were plotted on a plant basis, it was readily apparent that the Dukovany data contributed a large amount of the scatter.

To understand this scatter, the Dukovany CHECWORKS™ databases were examined. There were two obvious differences between the data from Dukovany and the data from the US plants:

1. The grids used at Dukovany had a wider spacing (i.e., less data around and along the length of the components), and

2. There were fewer data points per component, particularly for pipes upstream and downstream of components. The Dukovany upstream and downstream pipe data consists of only one row of grid points per straight pipe. The US plants had at least two rows of data.

This difference in NDE technique may explain why the Dukovany data exhibited more scatter than the US plants considered, and were thus excluded from the evaluation.

Single-Phase versus Two-Phase

Looking at the plots of the data, Figures 5-1 through 5-3, and keeping in mind that there are more single-phase than two-phase points plotted, there does not seem to be any significant difference between the two sets.

5.5 Measurement Issues

Although it is intellectually satisfying to use plant information as a basis for a predictive model, there are difficulties in the implementation. Some of the difficulties in using plant data were mentioned above. To illustrate these difficulties, let us examine the procedure used to extract "plot-able" data from the raw information. "Plot-able" data is defined as sets of measured chromium content and relative wear believed to be accurate enough for inclusion on a summary plot.

As stated above, a datum became plot-able when one of two criteria was met. Either a judgment was made that there was zero wear, or a comparison was made with a sister component. These two cases will now be examined.

Zero Wear

In most cases, there was not a clear-cut distinction between zero wear and small amounts of wear. This was complicated by the inherent imprecision in the NDE data and the statistical nature of the data interpretation process. In any set of component measurements, there are tens to hundreds of individual readings. Two or more sets of data are subtracted to produce a point-to-point difference at every measurement location. These differences are further examined.

As an example, let us consider a fitting that has a nominal thickness of 0.500" (12.7 mm). The accuracy of NDE data is normally assumed to be ±5% of the thickness. Thus, even assuming that there is no difference due to corrosion in the thickness profile between the inspections, then there will be differences on the order of 0.025" (0.7 mm) due to measurement uncertainty. This should be obvious. But what is not usually obvious, until one has examined data, is that there will be a great number of "negative wear" points. That is, there are points where the thickness has apparently increased (i.e., grown). As this is physically impossible, this observation is suspect even though it should be anticipated.

Judgment is clearly necessary to make the determination that there is zero wear. If any error in this judgment is made, the error will tend to be in favor of increasing the impact of chromium. This is because the wear cannot be less than zero, so an error will never be made by ascribing zero wear when actually a small amount of wear is present.

Although these points were plotted as zero, it would be more correct to ascribe a small number to them. The difficulty is deciding which number to apply. So, for convenience, zero was used although it was realized that a small number would have been more accurate.

Sister Components

The second method that "plot-able" data was determined - comparing with sister components, is discussed below. Although this method seems straightforward, there are three main difficulties.

- **Locating a sister.** A sister component could not be located for all cases. This was because a sister component had to have been inspected at least twice and be of the same geometry type as the component with measured chromium. What happened when a sister was not located is to be noted. There was a component with chromium content greater than 0.04% with measured wear that was excluded from the data. Thus the impact of trace chromium on reducing the rate of FAC was probably over-stated by ignoring the data for components without sisters. This is because the "high-chromium" components were wearing at a non-zero rate (otherwise they would not be in this category), and that wear rate could be appreciable compared to a hypothetical sister.
- **Unknown alloy content.** For cases where an appropriate sister component was located, the alloy content of the sister was often unknown. In some cases, the sister was observed to be wearing less than the subject component. Although this was an extreme situation, the presence of chromium in the sister component would under-state the impact of trace chromium. This is because a "high-chromium" component is compared to a component containing some amount of chromium, not zero-chromium which is implicitly assumed.
- **Non-identical local conditions.** Local operating conditions for a component and the sister component can be somewhat different. As examples, the connecting welds may protrude into the flow stream differently; there may be differing amounts of counterbore; there may be differing local flow patterns due to different upstream influences (instrument taps, lengths of pipe between elbows, etc.), or differences in chemistry or temperature (e.g., differing amounts of tube plugging of upstream heat exchangers, differing amine, hydrazine, or oxygen concentrations, differences in steam quality, etc).

Chromium Measurements

Although there are several methods available, most plant chromium measurements were made with a spark emission tester such as the ARC-MET™ series of instruments manufactured by Metorex [17]. The claimed accuracy of the ARC-MET™ 900 and 930 is presented in Table 5-1 [18]. This accuracy should be sufficient to evaluate the impact of trace chromium on FAC. However, it has been observed that if the metal surface is not properly cleaned, traces of zinc chromate primer will remain. This type of primer contains about 6% chromium, and will cause erroneous (high) readings on the surface of the component [19]. This effect has been observed at several US plants.

Table 5-1
Quoted Accuracy of ARC-Met™ 900 Series Instruments for Low Alloy Steels (Reference 18)

	Chromium
Concentration Range	0-5%
Standard Error of calibration (% absolute), 1 σ	0.03 (<2%)
	0.10 (>2%)
Precision % absolute @ given concentration (1 σ of typically 10 consecutive measurements)	0.001 @ 0.02%
	0.005 @ 0.30%
	0.020 @ 3.00%

In examining the plant data, there were some components whose chromium level was apparently over-stated. This was apparent when a component with a very high value of measured chromium (e.g., > 0.4%) had as much wear as a plain carbon steel component.

In all cases except obvious ones, the chromium data were accepted as reported. This assumption causes a great deal of scatter at high chromium levels and high relative wear rates. This should be considered when evaluating the plant data.

5.6 Summary

Corrosion is by nature a chaotic process. Apparently identical components will often corrode at different rates. This general statement is true even in perhaps the most-predictable corrosion mechanism – FAC. It should not be surprising that separating out a parametric effect from plant data is a difficult task. All possible care was taken to analyze the data as methodically as possible. For example, all the data were reduced before any of the data were plotted to avoid prejudicing the data reduction process.

In spite of the scatter, the logic for changing the correlation seems clear. The AECL tests confirm the Bouchacourt model of corrosion rates decreasing with time for high chromium components. With this established, it is difficult to argue against lowering the Ducreux correlation that is based on short duration tests. Further, there appears that there is ample plant evidence supporting the reduction of the present correlation.

Finally, even though a reduction in the Ducreux correlation is recommended, additional data, preferably long-term laboratory data would help to further validate the recommended correlation presented in the following chapter. Hopefully, such data will come from the EDF test program, planned for 2004, designed to quantify the impact of chromium.

6
RECOMMENDATIONS

Based on the information presented in the preceding sections, the following recommendations are made:

- The correlation used in the CHECWORKS™ SFA should be modified as shown in Figures 6-1 and 6-2. Note that the single-phase comparison, Figure 6-1, includes the AECL data previously presented in Figure 3-2.
- The revised correlation used in CHECWORKS™ SFA should not distinguish between single- and two-phase conditions.
- The EDF chromium test program planned for 2004 should be followed to obtain additional information in support of this modification.

The recommended curve was developed through a comparison of the plant data with the CHECWORKS™ model, the AECL data and the transient results. Because of the uncertainty regarding the values of the points with “zero wear”, formal statistical methods were not used. The fit was based on the following observations:

- The existing CHECWORKS™ model appears conservative once the chromium content exceeds about 0.04%
- The qualitative verification of Bouchacourt’s theory confirming that the Ducreux model (i.e., model in CHECWORKS™) is overly conservative with regard to long-term behavior, and
- The quantitative results of the AECL testing.

Using these observations, several curve fits were tried. The one chosen best matched the observations noted above.

The recommended line was drawn from the existing Ducreux correlation at low values of chromium and diverged from it to a line through the data at intermediate values of chromium. The line continued at a fixed ratio of the Ducreux correlation thereafter.

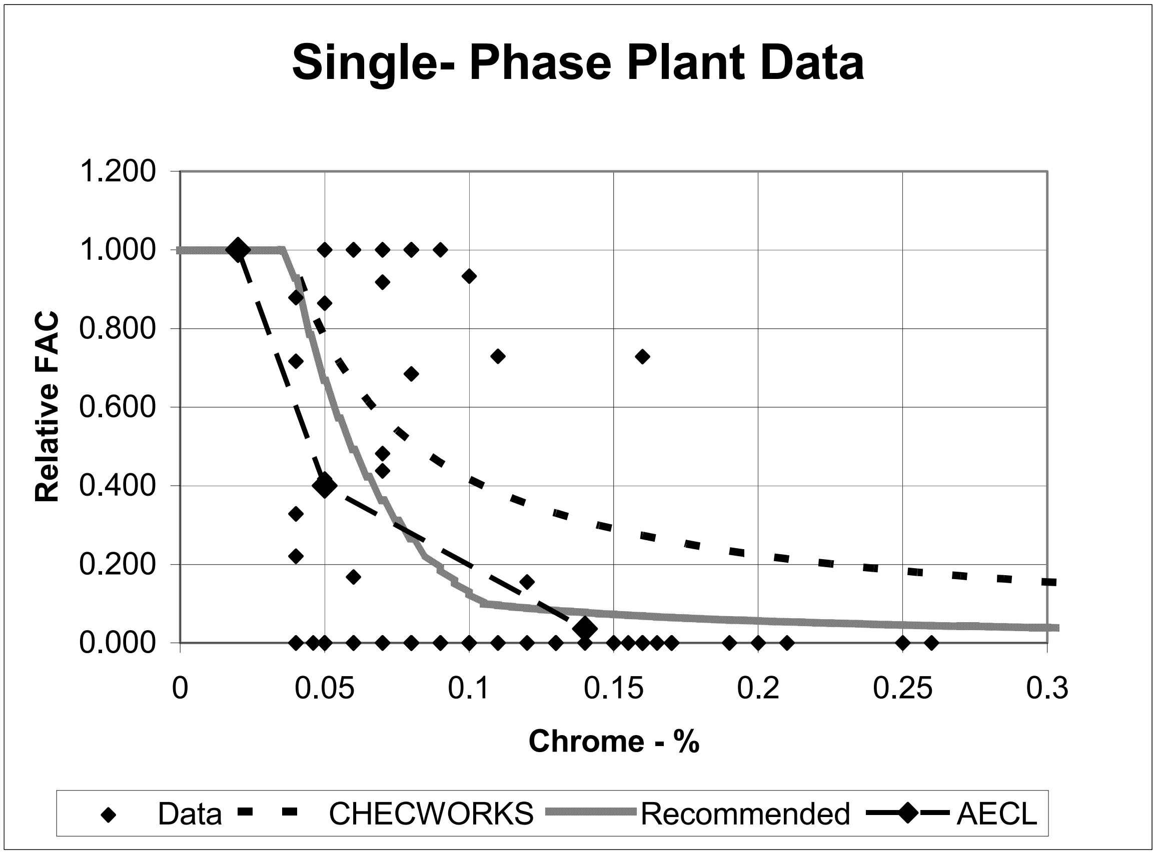

Figure 6-1
Recommended Correlation with Single-Phase Data

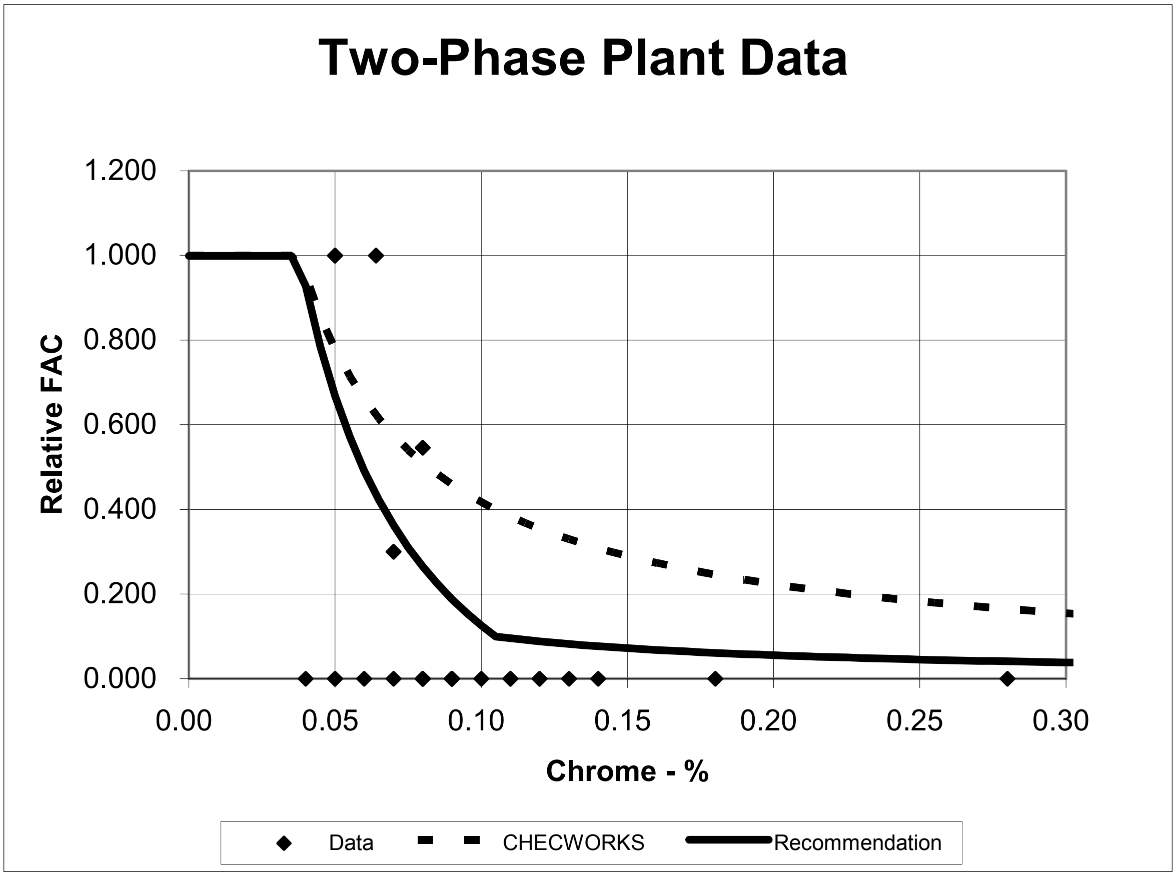

Figure 6-2
Recommendation with Two-Phase Data

7
REFERENCES

1. Chexal, B., et al., Flow-Accelerated Corrosion in Power Plants, EPRI Report TR-106611-R1, July 1998.

2. CHECWORKS™ Steam Feedwater Application Version 2.0 User Guide, EPRI Product 1002944, September 2002

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

4. Ducreux, J., "Theoretical and Experimental Investigation of the Effect of Chemical Composition of Steels on Their Erosion-Corrosion Resistance", (in French) presented at the Specialists' Meeting on the Corrosion-Erosion of Steels in High-Temperature Water and West Steam, Les Renardières, France, May 1982.

5. Chexal, B., et al., pages 3-93 – 3-96.

6. Henzel, N., Kastner, W., Stellwag., B., "Erosion-Corrosion in Power Plants Under Single- and Two-Phase Conditions – Updated Experience and Proven Counteractions", presented at the American Power Conference, Chicago, April 1988.

7. Bouchacourt, M., "BRT-CICERO: An Integrated Software to Control the Flow Accelerated Corrosion, Occurrence in Power Plants", presented at the SMiRT Post Conference Seminar, Lyon, France, 1997.

8. Huijbregts, W.M., "Erosion-Corrosion of Carbon Steel in Wet Steam", Materials Performance, October 1984.

9. Shack, W. J., "Review of Erosion-Corrosion Data in Single-Phase Flows," Materials and Components Technology Division, Argonne National Laboratory", Argonne, Illinois, undated.

10. Heitmann, H. G., Schub, P., "Initial Experience Gained with a High pH Value in the Secondary System of PWRs", *Water Chem. Nucl. React. Systems*, 1983, 3, Vol. 1, pp 243-252.

11. Lister, D. H., et al., "The Accelerated Corrosion of CANDU Primary Piping", Proceedings of the JAIF International Conference, Japan Atomic Industrial Forum on Water Chemistry in Nuclear Power Plants, 1998, pp 442'-1 – 442'-8.

12. Burrill, K. A., et al., "Assessment and Mitigation of Outlet Feeder Pipe Wall Tinning in CANDU", presented at the COG-IAEA Meeting on "The Exchange of Operating Experience of PHWRs", September 1998, Cernavoda, Rumania.

13. Elliot, A.J., et al, "Flow-Accelerated Corrosion Studies of Carbon Steel under CANDU Heat Transport System Conditions: Reduction of Corrosion Rate with Increased Chromium Content in the Steel", AECL Report, RC-2753 FDR-33126-REPT-003 Revision 0, Proprietary, February 2003.

14. Klimas, Stan, AECL Memorandum CS-33110-021-000 to N. Subash and C.W. Turner, entitled "FAC Under Iron Saturated Conditions", Atomic Energy of Canada, Ltd. Chalk River Laboratories, Chalk River, Ontario, Canada. Proprietary, April 8, 2003

15. Ruščák, Martin, Kaplan, Jiři, & Kadečka, Petr, "Complex Approach to the Lifetime Evaluation of WWER Secondary Piping Due to Erosion-Corrosion", presented at the IAEA Specialists Meeting on Erosion/Corrosion of Nuclear Power Plant Components, Vladimir, Russian Federation, September, 1999.

16. Kaplan, J., Email to J.S. Horowitz, July 7, 2003.

17. See www.Metorex.com for product information.

18. "ARC-MET Mobile Optical Emission Analyzers", Meterox, March 1999.

19. Crockett, H., Email to J.S. Horowitz, July 29, 2003

A
APPENDIX—PLANT DATA

This appendix presents the reduced data by plant, which are shown in Chapter 4. Table A-1 presents the breakdown of data points by plant for single- and two-phase. Figures A-1 through A-5 present the single-phase plots and Figures A-6 through A-10 present the two-phase data plots.

Table A-1
Data Points by Plant

Plant	Unit	Single Phase Points	Two-Phase Points	Total Points
Callaway	-	24	13	37
Diablo Canyon	1	17	0	17
	2	35	4	39
Dukovany	2	30	17	47
	3	7	0	7
North Anna	1	5	2	7
	2	0	1	1
San Onofre	2	1	3	4
	3	4	4	8
Surry	1	1	1	2
	2	1	1	2
Wolf Creek	-	5	3	8
		130	49	179

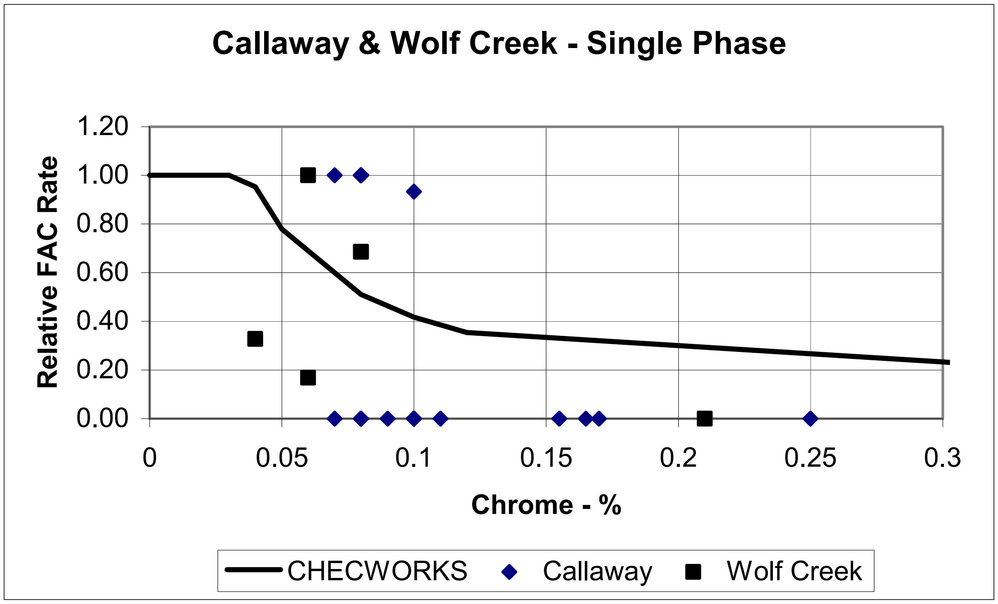

Figure A-1
Single-Phase Plant Data from Callaway and Wolf Creek

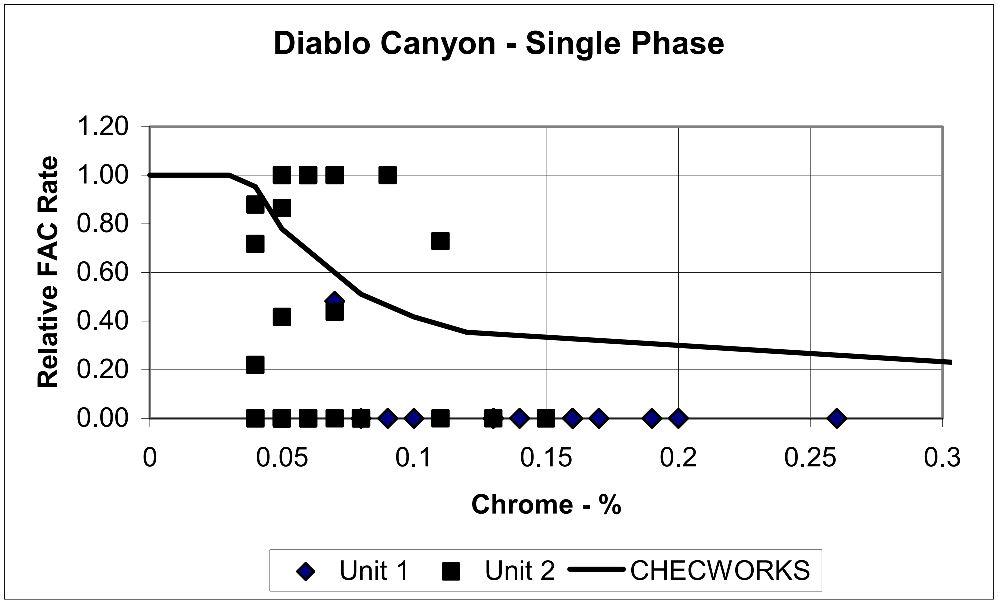

Figure A-2
Single-Phase Plant Data from Diablo Canyon

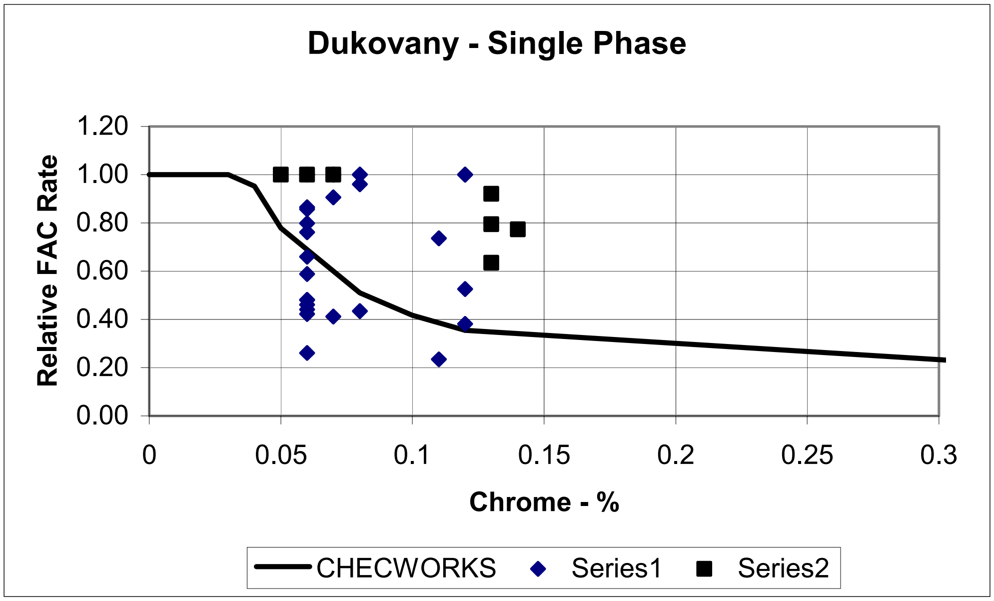

Figure A-3
Single-Phase Plant Data from Dukovany

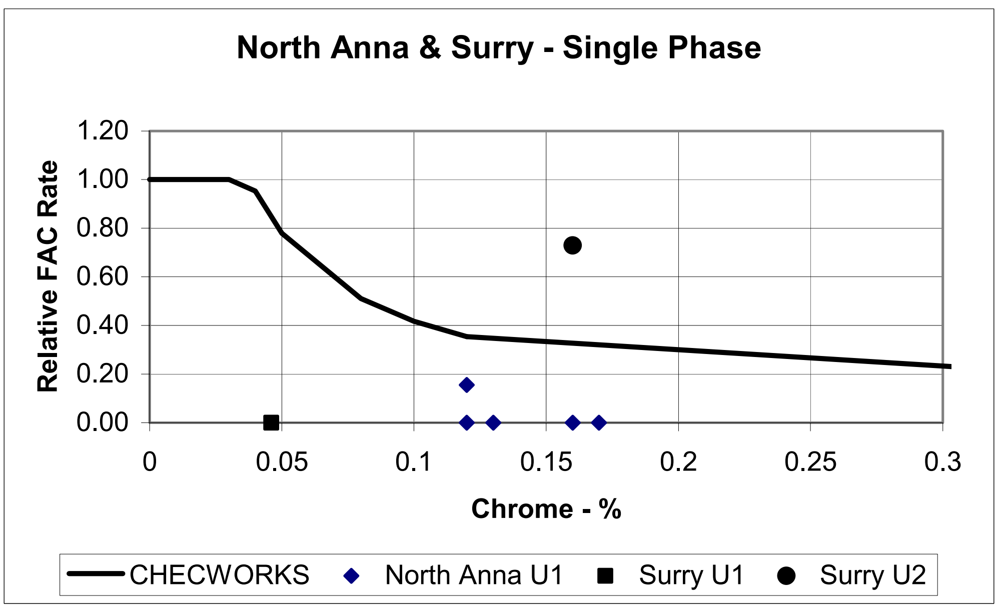

Figure A-4
Single-Phase Plant Data from North Anna and Surry

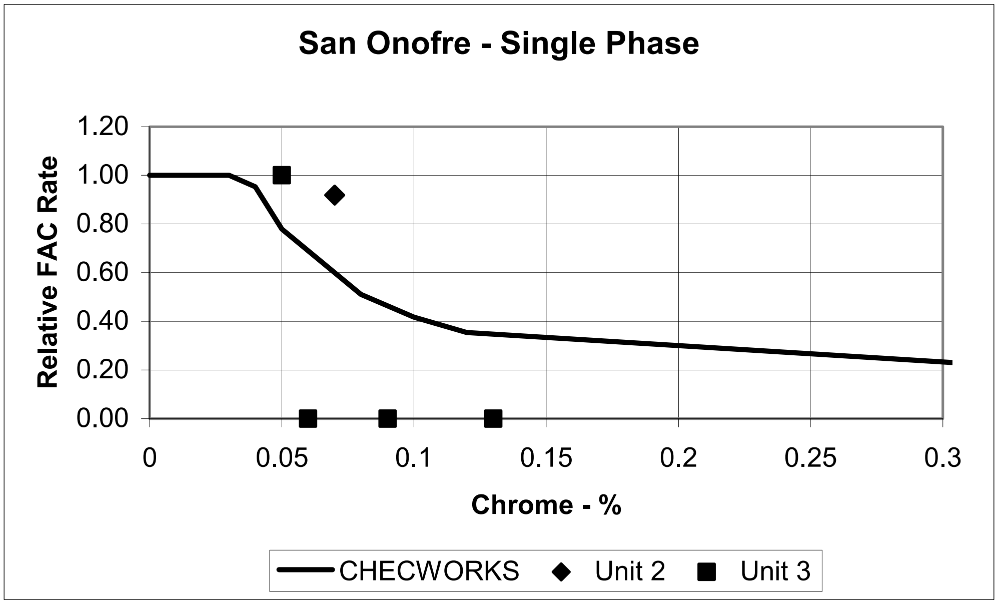

Figure A-5
Single-Phase Plant Data from San Onofre

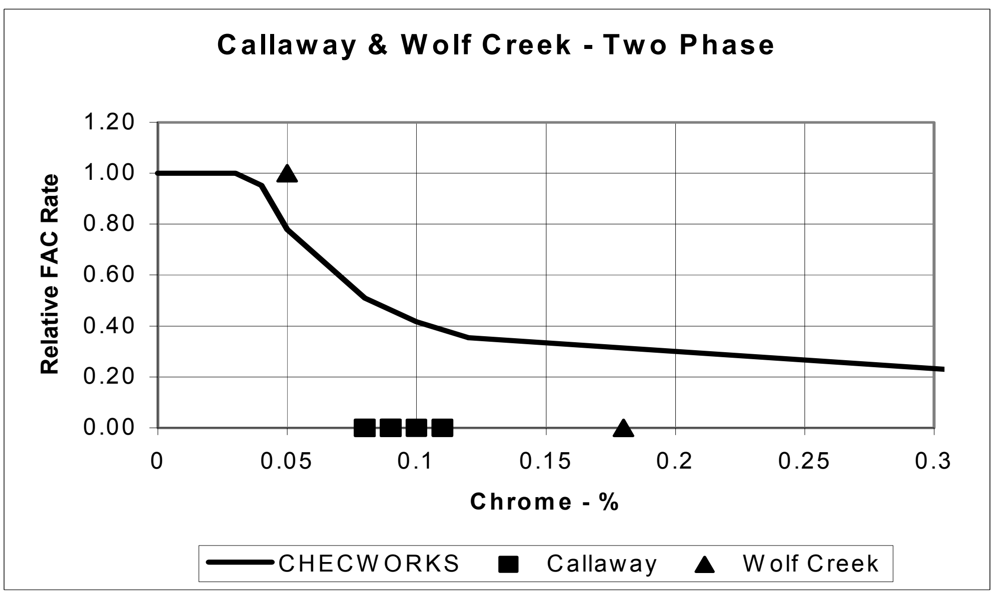

Figure A-6
Two-Phase Data from Callaway and Wolf Creek

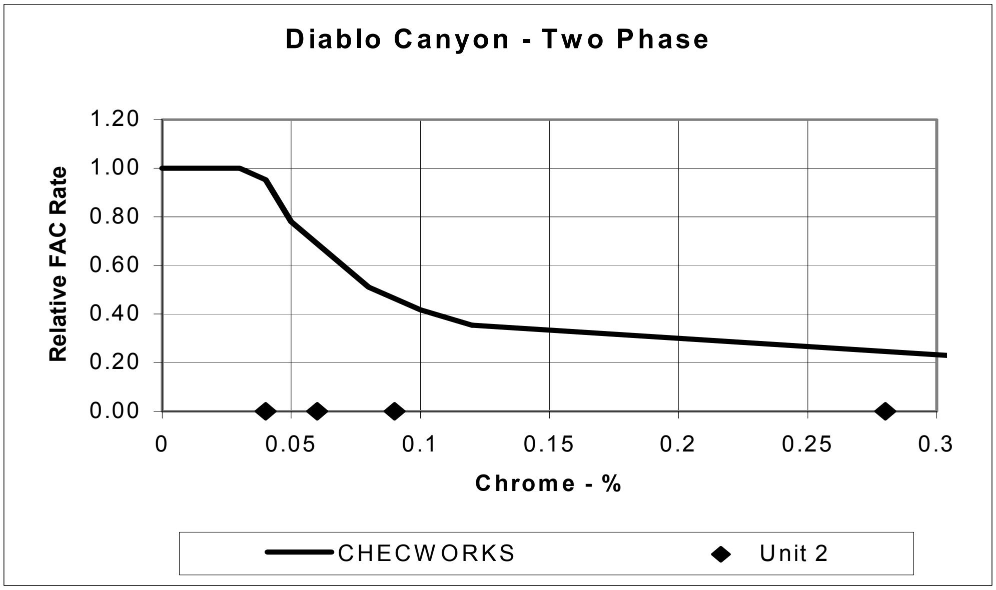

Figure A-7
Two-Phase Data from Diablo Canyon

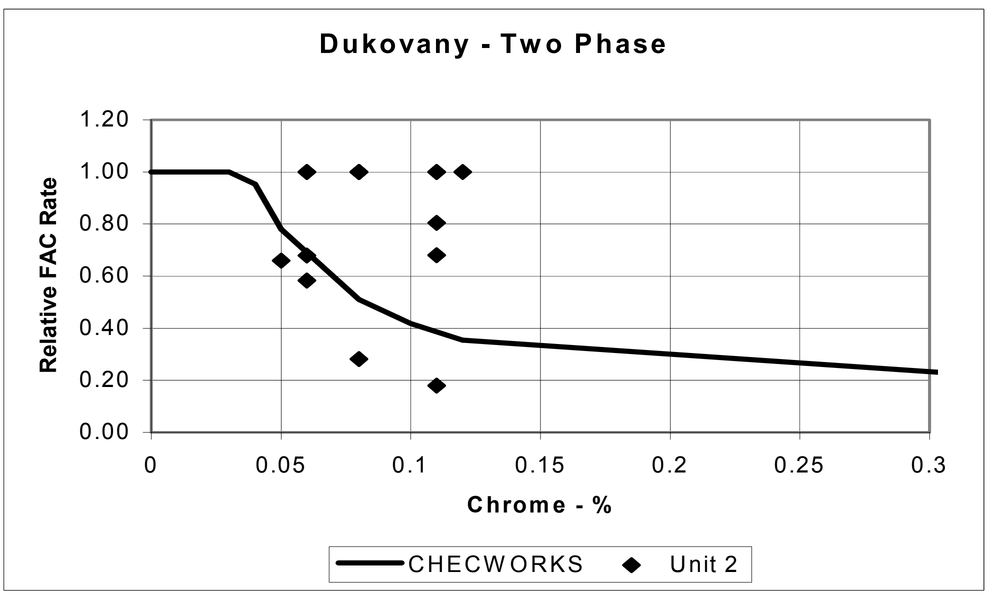

Figure A-8
Two-Phase Data from Dukovany

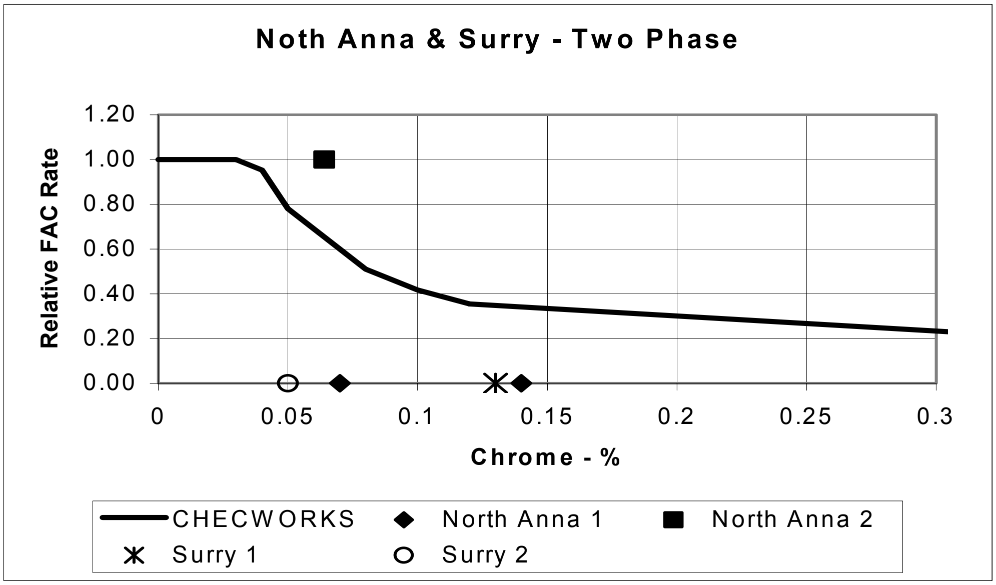

Figure A-9
Two-Phase Data from North Anna and Surry

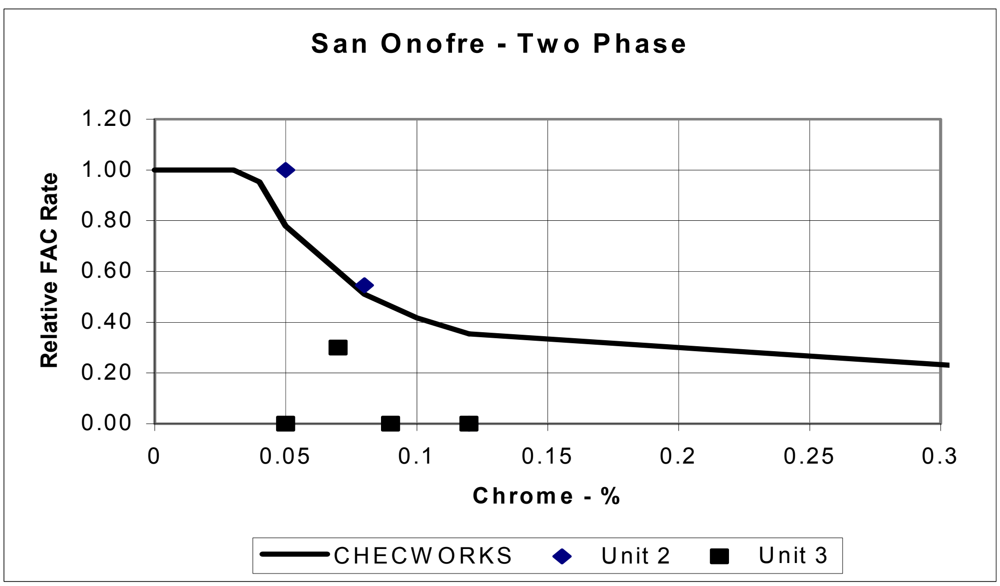

Figure A-10
Two-Phase Data from San Onofre

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