Technical Letter Report on The General Electric PLEDGE Code for the Prediction of Environmentally Assisted Crack Growth Rates

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Summary

Comparison with the available experimental data shows that PLEDGE provides conservative predictions of crack growth rates in unirradiated sensitized materials provided that an appropriate value is chosen for the parameter used to characterize the sensitization denoted by EPR. For applications to unirradiated weldments a value of EPR = 15 C/cm^2 would appear appropriate and yields a moderate degree of conservatism. With this value for EPR, PLEDGE should give somewhat conservative predictions for IGSCC under constant and cyclic loads and provide a conservative estimate for environmentally assisted fatigue, i.e., transgranular crack growth, under cyclic loading. The choice of EPR = 15 C/cm^2 ought to provide sufficient conservatism in application to weldments that the predictions can also be applied to irradiated components with fluence < 5×10^{20} n/cm^2. For environmentally assisted fatigue in unsensitized materials, the choice of EPR = 0 C/cm^2 may not give conservative estimates in the low conductivity water chemistries characteristic of current BWR operation. Some additional margin appears appropriate. This could be provided again by assuming EPR = 15 C/cm^2, but other approaches (e.g., an appropriate multiplier) could be used, but would have to be justified by comparison with appropriate data.

PLEDGE appears to overestimate the deleterious effect of impurity additions and its predictions become more conservative for conductivities > 0.2 μS/cm. It also appears to overestimate the deleterious effect of sensitization as characterized by EPR, at least for EPR values > 20 C/cm^2. Because current BWRs generally operate with conductivities much lower than 0.2 $\mu S/cm^2$ and most weldments will have sensitization levels < 15 C/cm^2, these shortcomings of the model are of limited importance. However, it is important to recognize that comparing PLEDGE predictions with data for high conductivities or high EPR could give a misleading picture of the degree of conservatism in PLEDGE predictions. Appropriate estimates of the mean error, i.e., the mean value of the ratio of the predicted crack growth rate to the observed crack growth rate, for PLEDGE predictions are provided by the results for low conductivity data given in Table 3 of this report.

1 Introduction

The PLEDGE code is based on the work done by Ford and Andresen and their colleagues at General Electric (GE) on environmentally assisted cracking. This work has been described in many papers and presentations and a recent survey paper by Ford[1] contains many references. More details of the supporting experiments and the model are given in a limited distribution EPRI report (2).

The Ford–Andresen model assumes that the crack growth rate (CGR) can be correlated with the oxidation that occurs when the protective film at the crack tip is ruptured.[1] Faraday's Law can be used to relate the oxidation charge density (Q) to the amount of metal transformed from the metallic state to the oxidized state or dissolved. In reactor systems, the protective oxide rapidly reforms at the bared surface, and crack advance can be maintained only if the crack tip is being strained so that the film rupture process can be repeated. The frequency of rupture is $\dot{\varepsilon}_{ct}/\varepsilon_f$ where ε_f is the fracture strain of the oxide and $\dot{\varepsilon}_{ct}$ is the crack tip strain rate. The average CGR is then

$$v = \frac{M}{z\rho F}\frac{Q}{\varepsilon_f}\dot{\varepsilon}_{ct} \quad (1)$$

where M and ρ are the atomic weight and density of the crack–tip metal, F is Faraday's constant, and z is the number of electrons involved in the overall oxidation of an atom of metal. The oxidation charge can be obtained by integrating over time the oxidation current that occurs after the rupture event, which is assumed to follow a power law relationship of the form:

$$i = i_o \left[\frac{t}{t_o} \right]^{-n} \tag{2}$$

where i_o and t_o are constants that depend on the material, potential, and environment. Integrating Eq. (2) and eliminating Q from Eq. (1) gives:

$$v \approx \frac{M}{z\rho F} \frac{i_o t_o^n}{(1-n)\varepsilon_f^n} \dot{\varepsilon}_{ct}^n \tag{3}$$

To use Eq. (3) to obtain quantitative predictions of CGR, Ford and Andresen have carried out three types of experiments and calculations:

i. Definition of the crack tip alloy/environment in terms of material composition, electrochemical potential (ECP), anion content, and pH.

   These are related to the corresponding bulk water chemistry parameters through modeling of potential driven transport and experiments on simulated crevices. The models and experiments suggest that the potentials at the crack tip are low and that the impurity concentrations (SO_4^{2-}) at the crack tip are 100–200 times greater than those in the bulk solution. The crack tip material is characterized in terms of the degree of chromium depletion. For example, solution-annealed material corresponds to Fe18Cr8Ni, sensitized material corresponds to a lower chromium content such as Fe12Cr10Ni or Fe8Cr10Ni, and highly sensitized material is bounded by assuming that the grain boundary is chromium free, i.e., Fe.

ii. Measurement of the oxidation current that is produced when the protective film on a material corresponding to crack tip material is ruptured in an environment corresponding to the crack tip environment.

   Ford and Andresen have made these measurements through experiments where the protective film on a thin wire specimen is removed by first applying a reducing potential and then quickly pulsing the specimen to the potential of interest and measuring the current flow as a function of time. The parameters i_o, t_o, and n are determined as functions of the material, potential, and environment by fitting the resulting current decay curves with a power law of the form Eq. (2).

iii. Definition of the crack tip strain rate $\dot{\varepsilon}_{ct}$, which controls the rate of rupture of the protective film at the crack tip in terms of parameters like crack tip stress intensity factor K and the frequency.

   Under constant load $\dot{\varepsilon}_{ct}$ is usually assumed to be proportional to K^m. The proportionality constant and m are determined empirically. For cyclic loading Shoji has shown that $\dot{\varepsilon}_{ct}$ is proportional to the CGR in an inert environment (air).[3] The proportionality constant is determined empirically. The crack growth contributions from the cyclic and constant loads are summed,

$$v = v_{air} + A\left(\dot{\varepsilon}_{ct_{cyclic}}\right)^m + A\left(\dot{\varepsilon}_{ct_{const}}\right)^m$$

rather than summing the crack tip strain rates, i.e.,

$$v = v_{air} + A\left(\dot{\varepsilon}_{ct_{cyclic}} + \dot{\varepsilon}_{ct_{const}}\right)^m.$$

The general description of the stress corrosion cracking process that underlies PLEDGE is now widely accepted. It provides the conceptual framework in which most workers in this area discuss their results or refine models for certain aspects of problem,[3-5] although some of assumptions related the crevice electrochemistry have been a matter of discussion.[6–9] A comprehensive independent survey of some related studies has been provided by Turnbull and Psaila-Dombrowski.[7]

The actual implementation and development of the model is considered proprietary by GE. It is clear that the processes involved are complex and a number of assumptions and approximations must be introduced. Many of the parameters involved are somewhat uncertain. In addition to the experiments necessary to determine the oxidation current, etc., PLEDGE also needs a purely empirical calibration to determine, e.g., the constants needed to define $\dot{\varepsilon}_{ct}$. In order to use this code for regulatory purposes (and probably anything else) the uncertainties in these predictions due to uncertainties in the assumptions of the models used to develop the code and the uncertainties in the quantitative parameters used in the code must be addressed. It is unrealistic to expect that this can be done on a "first principles" basis by identifying the uncertainties in each part of the model and then propagating those uncertainties through the model. The only practical approach is through comparison with relevant experimental measurements of CGRs.

In this report, PLEDGE predictions are compared with experimental data collected by the BWRVIP,[10] data developed at ANL as part of USNRC sponsored research, data provided by P. L. Andresen of GE,* data used to develop the original USNRC disposition curve, and other data gathered from the literature.[11-18] Some of the data provided by Andresen were developed at GE, while other data were developed at ABB and VVT as part of a SCC CGR round robin sponsored by the Swedish nuclear regulatory authority SKI. For some of the older ANL data at high dissolved oxygen (DO) levels (7–8 ppm) and some data from the literature such as the data used to develop the original USNRC disposition curve, ECP measurements were not available. These data were included using assumed values for the ECP. This was felt to be reasonable because at these high oxygen levels the ECP is only a weak function of the dissolved oxygen level.

2 Overall Comparisons with Experimental Data

PLEDGE predictions have been compared with experimental results in many presentations and papers by GE. However, virtually all of these comparisons are presented in graphical terms without tabular data, and it is often difficult to determine the precise conditions of the comparison. See, for example, the comparisons shown in Fig. 1, which were taken from Ref. 1, but which have appeared in several other publications. The "Theory" referred to in the figures may be an earlier version of PLEDGE. The predictions of the version supplied to the NRC are

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* Personal Communication, P. L. Andresen (GE) to W. J. Shack (ANL), October, 1998.

labeled “PLEDGE” and are significantly different from the theoretical results, which a reader would presumably assume to be based on PLEDGE. The actual experimental conditions are unclear. The high CGR data in (a) and (b) appear to be identical. In one case they are identified as EPR=30 C/cm^2 and in the other as EPR=15 C/cm^2. Additional examples of such confusion can be found in other comparisons of data with PLEDGE in various GE reports. Since the data are not presented in tabular form with a precise statement of the actual experiment conditions, it is difficult to make independent comparisons.

A comparison based on large set of data (340 pts) purportedly covering a wide range of environmental and material conditions is shown in Fig. 2. The figure was taken from Ref. 1, but also has appeared in many other papers. The only information available about the data is that shown in the graph. However, even if these data were to be documented, it is very unlikely that they would provide an adequate benchmark to demonstrate the adequacy of PLEDGE and estimate the uncertainties associated with PLEDGE predictions of SCC CGRs. Under typical BWR conditions, SCC CGRs are less than 3.5×10^{-10} m/s (5×10^{-5} in/h). This value has in fact been used as a conservative bound for NRC assessments. Only about 20 of the 340 data points in Fig. 2 appear to be obtained under conditions that give CGRs less than this value. There are about 20 more data with CGRs $<1 \times 10^{-9}$ m/s where it could be argued that the environmentally induced cracking was at least some reasonable fraction of the mechanically driven CGR. The remaining ≈300 data points must have been obtained under cyclic loading conditions in which the scatter in the mechanically driven fatigue CGRs is at least as large as the environmentally induced CGRs (and for CGRs $>10^{-8}$ m/s much larger). They are fatigue tests and would give similar results whether conducted in air or in water. Indeed PLEDGE itself predicts that under the cyclic loading conditions required to produce these high growth rates, there is little difference in the CGRs in air and in the environment.

A database of experimentally determined CGRs under conditions considered more representative of BWR conditions was developed from data reported in BWRVIP-14[10] and from data developed at ANL as part of USNRC funded research on environmentally assisted cracking and from data supplied by P. L. Andresen. The database is available as an Excel spreadsheet and in the case of the ANL data includes references to the original ANL reports from which the data were obtained. The BWRVIP-14 database is considered proprietary. About 40% of the data are from constant load tests; the remainder are from cyclic load tests with load ratios R between 0.9 and 0.95 and frequencies of 0.08 Hz or less. The tests cover a wide range of sensitization conditions, conductivities, electrochemical potentials, and stress intensity factors. The BWRVIP database contains data for temperatures from 240–289°C. Only the data with temperatures greater than 262•C were compared with PLEDGE, because PLEDGE does not include temperature as a variable. None of the materials are from actual weldments. The materials were sensitized by furnace heat treatment.

The comparison was limited to tests with $20 \leq K \leq 40$ $MPa \cdot m^{1/2}$. The upper limit on K was introduced to ensure validity of the CGR measurements from a fracture mechanics standpoint. The lower limit on K was introduced to try to minimize confounding of data for active crack growth with data that show a dramatically different K dependence as illustrated schematically in Fig. 3. PLEDGE does not attempt to predict behavior in region of steep K dependence below the threshold value for active crack growth (nor does any other model of which we are aware). The threshold K depends on material and environmental conditions. Although it can be quite low for very heavily sensitized materials in aggressive environments, experience suggests that values of 20-25 $MPa \cdot m^{1/2}$ are reasonable for the conditions in these tests. Inclusion of data below the threshold will contribute to scatter—the models will tend to greatly overpredict CGRs in these cases. Inclusion of such data in a statistical fitting procedure such as was done in BWRVIP-14 could lead to underprediction of CGRs in the active growth region. At the February 18, 1997 meeting at ANL, R. M. Horn of GE presented a screening of the BWRVIP-14 data from a slightly different perspective, but was somewhat similar in spirit.

All of the data in the BWRVIP-14 and Andresen databases were assumed to represent intergranular cracking. Many of the data in the ANL represent transgranular cracking under cyclic loading. For comparison with PLEDGE, the ANL data were split into two groups, one in which the cracking was intergranular, the other in which the cracking was transgranular.

There is considerable scatter in all the data sets. This reflects the experimental difficulties in measuring the low crack growth rates of practical interest and in measuring ECPs in a dissolved oxygen regime where the ECP is particularly sensitive to the dissolved oxygen level. The crack tip strain rates are also sensitive to thermomechanical loading history and the detailed microstructure. There is considerably more scatter for the BWRVIP data than for the ANL data or SKI round robin data. This is not unexpected. The BWRVIP data were obtained under constant load conditions, which tend to produce more scatter than the low amplitude "ripple" loading used to develop most of the ANL data or the long rise time cyclic loading in the SKI tests. In addition, the SKI round robin showed that the "normal" testing procedures used by the laboratories in the round robin, who contributed heavily to the BWRVIP data base, led to a wide range of scatter and uncertainty in the CGRs and ECPs.[19] The data provided by Andresen were developed after the procedures at the laboratories in the round robin were revised to provide more consistent and reproducible results. The requirements for "good" SCC data identified by Andresen include comparison of inlet and outlet conductivities, identification of the species responsible for the measured conductivity, relation of inlet and outlet dissolved oxygen, position of the reference electrode, and verification of the measured CG by posttest fractography. To these we would add the confounding introduced by the failure to distinguish between below threshold behavior and active growth. It is difficult to assess the validity of the BWRVIP data in these terms on the basis of the information available. The ANL data meets most of these requirements except for the direct measurement of ECP on the specimen. Scatter in SCC testing is undoubtedly significant and larger than in mechanical fatigue testing.

An important input to PLEDGE is the EPR (electropotentiokinetic reactivation), a measure of the degree of sensitization of the material. Variations in EPR value over the range of 0–30 C/cm^2 result a factor of ≈ 50 change in the crack growth rates predicted by PLEDGE as shown in Fig. 4 at high ECP. EPR provides a characterization of the grain boundary chromium level. Unfortunately the correlation between EPR and grain boundary chromium content is subject to significant uncertainty. Because EPR depends on both the width and the depth of the chromium depleted zone, the EPR value depends strongly on the overall thermal history and not just on the grain boundary chromium content. For example, low temperature aging tends to produce narrower depleted zones than high temperature aging treatments, so that an EPR value for a low temperature aged material corresponds to a lower grain boundary chromium concentration than that corresponding to the same EPR value for a high temperature aged material. The calculations with PLEDGE used reported values of the EPR except for ANL data which used a two step sensitization process involving a low temperature aging step. In this case the value reported by ANL was 2 C/cm^2. Because this would underestimate the EPR value that be be observed for the same grain boundary chromium level in a material with a high temperature treatment a value of 15 C/cm^2 was initially assumed in the calculations. Since EPR as used in PLEDGE is not truly a measured quantity (it really reflects the analysts judgment as to the degree of chromium depletion at the grain boundary), the strong dependence on EPR makes it a potent “adjustable” parameter. Post–hoc adjustments of the EPR value would permit PLEDGE predictions to be “tuned” to experimental data.

The PLEDGE predictions are compared with the Andresen, ANL IGSCC, and BWRVIP data bases in Fig. 5. Although there is considerable scatter in the results, in almost all cases the PLEDGE prediction is conservative. PLEDGE predictions are compared with ANL TGSCC in Fig. 6. In this case the appropriate EPR value is 0; and there is no particular bias to the predictions. The number of conservative predictions are about the same as the number of nonconservative predictions.

In Figs. 7 and 8, the predictions of the BWRVIP–14 disposition model are compared with the Andresen, ANL, and BWRVIP data. Unlike PLEDGE, which is intended to predict CGRs under both constant load and cyclic loading conditions, the BWRVIP model was developed only for the constant load case. Much of the available data base consists of data with high R (≥ 0.9) loading. Even if the intended application of the model is only for constant load situations, it is useful to extend the BWRVIP model to include cyclic loading to develop increased confidence in its predictions of the effects of material and environmental variables. This was done by using an approach similar to that described by Ford,[1] and the development is described in Appendix 1. The predictions of the modified BWRVIP–14 model are conservative for the ANL and BWRVIP data bases, but are not consistently conservative for the Andresen data.

In Fig. 9 the predictions of PLEDGE and the BWRVIP model are compared with the BWRVIP–14 data base as screened by R. Horn of GE. The predictions of the BWRVIP model at low ECP are very conservative compared to those from PLEDGE and the screened data. PLEDGE predicts somewhat higher crack growth rates at high potentials.

The predictions of the models with data for high dissolved oxygen levels from ANL and Refs. 11 and 12 are shown in Figs. 10. Both the PLEDGE and BWRVIP models are conservative in most cases, In Fig. 11 comparisons are shown with cyclic CGR data from ANL and Refs. 13-18. With an EPR value of 15 C/cm^2 the PLEDGE predictions are conservative for both sensitized and nonsensitized materials. When the EPR value is set to 0 as would be appropriate for nonsensitized materials, the results are no longer necessarily conservative.

PLEDGE appears to provide conservative predictions of crack growth rates in sensitized materials provided that an appropriate value is used for EPR. For applications to weldments a value of 15 C/cm^2 would appear appropriate and yields a moderate degree of conservatism. For environmentally assisted fatigue for which the growth is expected to be transgranular, the choice of EPR = 0 gives reasonable values for the mean behavior, but does not bound much of the data. Some additional margin appears appropriate. This could again be provided by assuming EPR = 15 C/cm^2.

Table 1. Mean difference between PLEDGE predictions of CGR and experimental measurements for the four data sets

	BWRVIP	ANL IGSCC	Andresen	ANL TGSCC
Upper 95% ME	10.5	6.3	1.8	0.8
Mean Error (ME)	8.3	5.2	1.6	0.7
Lower 95%ME	6.5	4.4	1.4	0.6

Table 1 shows the mean error (ME) (i.e., the mean value of the ratio of the predicted crack growth rate to the observed crack growth rate) for the four data sets. An ME > 1 implies the PLEDGE predictions are conservative. As noted previously from examination of Figs. 5, 6, 10, and 11, PLEDGE is generally conservative for all the data sets with intergranular cracking and slightly nonconservative for the transgranular cracking data.

The predictions are worst both in terms of the mean error and the scatter for the BWRVIP data set. This set, which is comprised of data from GE Crack Arrest Verification (CAV) tests and laboratory data from ABB, appears to be biased towards low crack growth rates. As noted by Andresen[19] there is an inherent bias in experimental data on SCC towards low crack growth rates—there are more reasons crack growth can be retarded than accelerated. Even in the SKI Round Robin, the observed scatter in the data under conditions that were supposedly tightly controlled covered three orders in magnitude and many tests were reported to give no SCC under material, environmental, and loading conditions for which SCC would be expected and had been observed in other tests.[19] To try to remove some of this bias, the BWRVIP data base was screened to eliminate data where the CGR seemed unreasonably (> order of magnitude) low for the nominal conditions of the test. No CGR data were screened out because they were too high. The results for the screened set are summarized in Table 2 and shown in Fig. 12(a). The mean error for the screened set is a factor of two smaller than that for the original BWRVIP data set.

As noted previously, the ANL specimens with EPR = 2 C/cm^2 were sensitized using a low temperature heat treatment which would be expected to give narrower, deeper Cr depletion zones than the higher temperature heat treatments used in most of the other reported data. Somewhat arbitrarily an EPR of 15 C/cm^2 was used in the initial PLEDGE calculations instead of the value of 2 to make the ANL results more consistent with other reported results. If instead the actual reported values are used, the mean error decreases as shown in Table 2 and Fig. 12(b). This again emphasizes the sensitivity of PLEDGE predictions to the choice of EPR value. In most cases EPR values will not be available and even if they are available it may be difficult to identify the appropriate correspondence with the values used by PLEDGE, which depend on the time–temperature histories used by Ford and Andresen to determine the EPR/Cr depletion/CGR correlation. Although the use of the reported EPR gives better agreement with the PLEDGE predictions, the fundamental meaning of EPR in PLEDGE says that the EPR value obtained using the ANL low temperature heat treatment should be increased when making comparisons with PLEDGE calculations. The choice of the appropriate value is a matter of engineering judgment. A value of EPR = 15 C/cm^2 should be conservative for most welds and the ANL heat treatment. All references to comparisons of the ANL IG data with PLEDGE outside of Table 2 are based on EPR = 15 C/cm^2 for the low temperature heat treatments.

Table 2. Mean difference between PLEDGE predictions of CGR and experimental measurements for the screened BWRVIP data set and the ANL IGSCC data set using reported EPR values.

	BWRVIP screened	ANL IGSCC No EPR adjustment
Upper 95% ME	5.3	1.3
Mean Error (ME)	4.2	1.0
Lower 95%ME	3.2	0.8

3 Comparison of Specific Dependencies on EPR, Conductivity, and ECP

The errors were plotted as a function of the conductivity, ECP, EPR, and K to determine whether there was any correlation between these variables and the magnitude of the errors in the PLEDGE predictions. Examples of these graphs are shown in Figs. 13–16. These results suggest that errors are most strongly correlated with the conductivity. To examine this more rigorously, the data were sorted into two categories: low conductivity data with conductivities ≤ 0.2 μS/cm and high conductivity data with conductivities ≥ 0.2 μS/cm. As shown in Table 3, the PLEDGE predictions for the high and low conductivity data are significantly different for all the data sets. In each case, the PLEDGE predictions are more conservative for the high conductivity data than for the low conductivity data, i.e., PLEDGE overestimates the effect of increases in conductivity on increases in CGRs.

This has a significant impact when assessing the degree of conservatism associated with PLEDGE predictions. For modern BWRs only the low conductivity data are really relevant and Table 3 shows the conservatism of the PLEDGE predictions is about a factor of 2 less than would be implied from the results for the complete data sets shown in Table 1.

Table 3. Effect of conductivity on mean difference between PLEDGE predictions of CGR and experimental measurements for 4 data sets

	Andresen Low Conductivity	Andresen High Conductivity	ANL IG Low Conductivity	ANL IG High Conductivity
Upper 95% ME	1.1	4.6	4.3	10.4
Mean Error (ME)	1.0	4.1	3.2	9.3
Lower 95%ME	0.9	3.6	2.5	8.4
	BWRVIP Low Conductivity	**BWRVIP High Conductivity**	**ANL TG Low Conductivity**	**ANL TG High Conductivity**
Upper 95% ME	3.4	10.4	0.3	5.0
Mean Error (ME)	2.6	6.9	0.3	3.9
Lower 95%ME	2.0	4.6	0.2	3.1

Because of the fairly large effect of the conductivity on the errors associated with the PLEDGE predictions, attempts were made to examine effects of other variables were based on examination of the data sets for either low or high conductivity rather than the combined data bases. Unfortunately, the number of data available are too few in most cases to be able to get statistically significant comparisons. The screened BWRVIP database does contain enough low conductivity data with differing degrees of sensitization to get some information on the effect of EPR as shown in Table 4, which show that the PLEDGE calculations are more conservative for the more highly sensitized specimens, i.e., PLEDGE appears to overestimate the effect of EPR.

Table 4. Effect of EPR on the mean difference between PLEDGE predictions of CGR and experimental measurements for the screened BWRVIP data sets.

	EPR 13–15 C/cm^2	EPR 20–30 C/cm^2
Upper 95% ME	2.3	6.3
Mean Error (ME)	1.5	4.6
Lower 95%ME	0.9	3.4

Estimates of the effect of ECP were made using the low conductivity portions of the ANL TG and Andresen data bases. These results are summarized in Table 5. No significant effect of ECP could be seen in the ANL TG data, but the results from the Andresen data suggest that the PLEDGE calculations are somewhat more conservative for very low ECP and very high ECP.

Table 5. Effect of ECP on mean difference between PLEDGE predictions of CGR and experimental measurements for low conductivity data in Andresen and ANL TG data sets

	Andresen ECP<–400	Andresen 53<ECP<140	Andresen ECP>140	ANL TG 75<ECP<140	ANL TG ECP>140
Upper 95% ME	1.6	0.8	1.5	0.3	0.4
Mean Error (ME)	1.2	0.7	1.3	0.3	0.3
Lower 95%ME	0.9	0.6	1.2	0.2	0.3

Data from other sources were also examined to try to determine dependence on conductivity, sensitization, and ECP. The data of Kawakubo et al.[11] comparing crack growth rates in materials with EPR = 0 and 15 C/cm^2 are shown in Fig. 17(a) along with the corresponding PLEDGE predictions in Fig. 17(b). The prediction is about 3 times as that observed at a stress intensity of K = 27 $MPa{\cdot}m^{1/2}$. Data with EPR of 10–15 and 30 C/cm^2 used to develop the NRC disposition curve[12] are shown in Fig. 18(a) along with the corresponding PLEDGE predictions in Fig. 18(b). There is large scatter in the data, but nominally the difference is again about a factor of 3 at a stress intensity of K = 27 $MPa{\cdot}m^{1/2}$. These results are consistent with the results determined from the BWRVIP data as shown in Table 4.

Part of the reason PLEDGE may overestimate the effect of sensitization may be in the experimental models it uses to represent the material at the crack tip. In solution–annealed material the crack tip is Fe18Cr8Ni, in weld–sensitized material it is Fe8Cr10Ni, and in furnace–sensitized material it is pure Fe.[2] The actual relation between the oxidation current densities measured on these materials and the dependency on EPR built into PLEDGE is part of the proprietary "black box", but it certainly is conceivable that such assumptions would result in an over estimate of the effect of sensitization.

As noted from the examination of the databases, PLEDGE appears to predict a stronger dependence on conductivity than is observed. This is consistent with the results from a "controlled" experiment in which conductivity was systematically varied while keeping all other experimental parameters constant shown in Fig. 19. In application to operating reactors, the conductivity as defined by PLEDGE should be a conservative representation of the impurity effects. "Conductivity" in really used as a surrogate measure for harmful anions such as SO_4^{2-} and Cl^-; other anions may be much more benign. PLEDGE assumes that the conductivity is due to the "worst–case" impurity, sulfate.

Only a small sample of the experimental data upon which the dependencies on critical variables included in PLEDGE were constructed is available for review even in restricted distribution documents such as EPRI NP-5064s.[2] However, the limited data available on the effect of conductivity seems somewhat contradictory to the dependency on conductivity in PLEDGE. In Fig. 20, the effect of sulfate concentration on oxidation current density transient after a potential pulse to -420 mV in pH_{25} 2.0 solution is shown. The slope of the current transient clearly increases as the concentration is increased. In Fig. 21, the dependence on crack tip strain exponent n on corrosion potential and bulk solution conductivity for a sensitized SS, which is equal to the slope observed for oxidation current density is shown. The slope n decreases as the conductivity increases at any fixed potential, which seems to contradict the result shown in Fig. 20.

The predicted dependence of CGR on ECP is shown in Figs. 22 and 23. In this case the dependency is quite sensitive to the loading condition. Under R=1 loading the CGR essentially vanishes; under the R=0.95 loading, the mechanically driven CGR places a floor on how low the rate can go and so the relative change is smaller. The reductions predicted by PLEDGE are hard to verify experimentally, because the CGRs so low that they are extremely difficult to measure. The much more modest reductions predicted by the BWRVIP model are probably skewed by unavailability and scatter in CGRs at such low levels. Many of the ANL tests in hydrogen water chemistries are not reported as CGRs, simply because they were so low that it would take an inordinate amount of time to obtain a valid CGR. However, Ruther and Kassner carried out a series of tests on a thermally aged cast SS,[23] which showed a high susceptibility to environmentally assisted cracking, in which the tests were continued until the CGRs could be measured with some confidence, Their measurements are also shown in Fig. 22. They suggest that the BWRVIP model is very conservative at low ECPs, but that the PLEDGE model predicts the overall trends reasonably well. These results together with the results in Table 5 suggest that the PLEDGE model predicts the variation of the CGR with ECP fairly well overall, although it may overestimate somewhat the increases in CGR associated with increase in ECP above 140 mV.

4 Conclusions

The basic physical description of stress corrosion cracking that underlies the PLEDGE model is consistent with the basic anodic dissolution model of SCC developed by Parkins and his colleagues for several decades. The detailed mathematical description of the model and the experimental data used to develop the correlations used in PLEDGE are proprietary. However, the acceptability of PLEDGE for modeling stress corrosion cracking behavior can be established by comparison with the extensive data on SCC in BWR environments available in the literature. Based on this comparison, it can be stated that PLEDGE provide conservative predictions of crack growth rates in unirradiated sensitized materials provided that an appropriate value is chosen for the EPR. For applications to unirradiated weldments a value of 15 C/cm^2 would appear appropriate and yields a moderate degree of conservatism. With this value for EPR, PLEDGE should give somewhat conservative predictions for IGSCC under constant and cyclic loads and provide a conservative estimate for environmentally assisted fatigue, i.e., transgranular crack growth, that may occur under cyclic loading. For environmentally assisted fatigue in unsensitized materials, the choice of EPR = 0 C/cm^2 may not give conservative estimates in the low conductivity water chemistries characteristic of current BWR operation. Some additional margin appears appropriate. This could be provided again by assuming EPR = 15 C/cm^2, but other approaches (e.g., an appropriate multiplier could be used, but would have to be justified by comparison with appropriate data). The choice of EPR = 15 C/cm^2 ought to provide sufficient conservatism in application to weldments that the predictions can also be applied to irradiated components with fluence < 5 x 10^{20} n/cm^2.

PLEDGE appears to overestimate the deleterious effect of impurity additions and its predictions become more conservative for conductivities > 0.2 µS/cm. It also appears to overestimate the deleterious effect of sensitization as characterized by EPR, at least for EPR values > 20 C/cm^2. Because current BWRs generally operate with conductivities much lower than 0.2 $\mu S/cm^2$ and most weldments will have sensitization levels < 15 C/cm^2, these shortcomings of the model are of limited importance. However, it is important to recognize that comparing PLEDGE predictions with data for high conductivities or high EPR would give a misleading picture of the degree of conservatism in PLEDGE predictions. Thus the implied conservatism in the values of the mean errors in Table 1 is misleading and a more appropriate comparison with experimental data is provided by the results for the low conductivity data given in Table 3.

The choice of an appropriate degree of conservatism in the development of a disposition curve is to some extent not a technical question. However, we believe that the use of a 95% confidence limit on the predictions is overly conservative. There is inevitable scatter in SCC measurements, and the focus should be on the main trends not the scatter in the tails. The James and Jones approach of adopting a 95% confidence limit on the mean[21] has been adopted here as a appropriate method to compare the model predictions with the experimental data.

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Figures

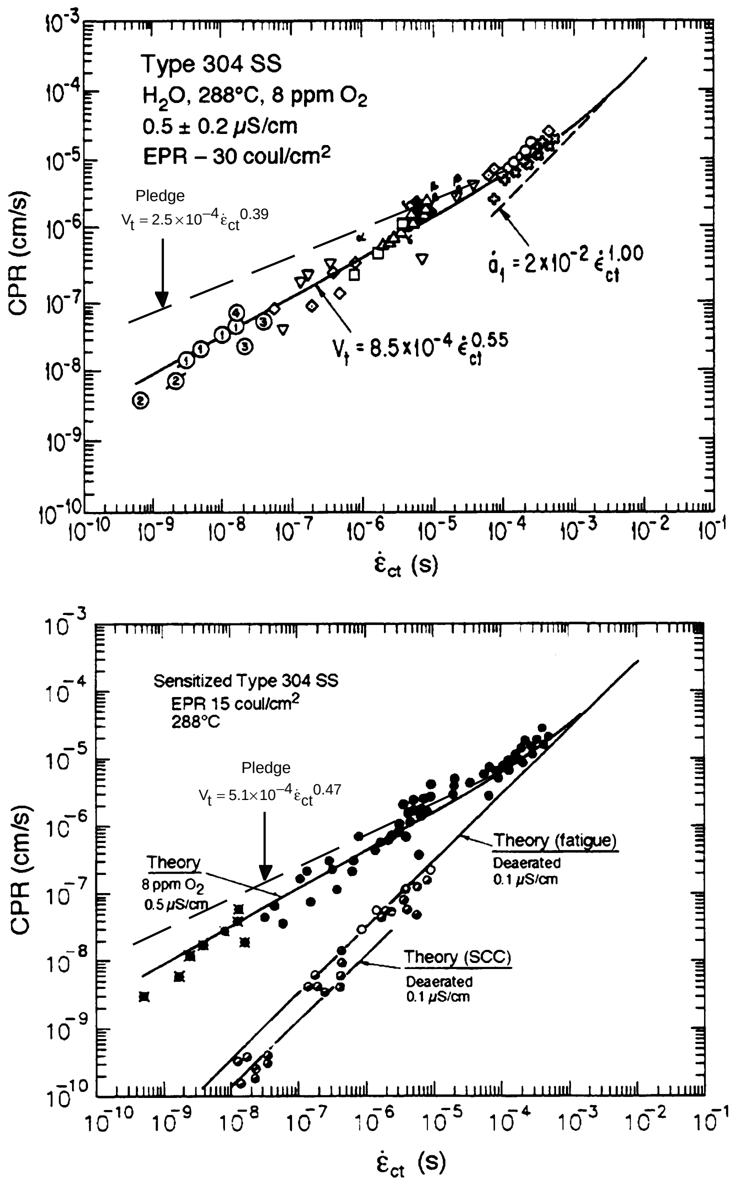


Figure 1.
(a) Comparison of experimentally observed CGRs with predicted values. The "Theory" referred to in the figures may be an earlier version of PLEDGE. The predictions of the version supplied to the NRC are labeled "PLEDGE". The actual experimental conditions are unclear. The high CGR data in (a) and (b) appear to be identical, although the symbols are different. In one case they are identified as EPR=30 C/cm^2 and in the other as EPR=15 C/cm^2.

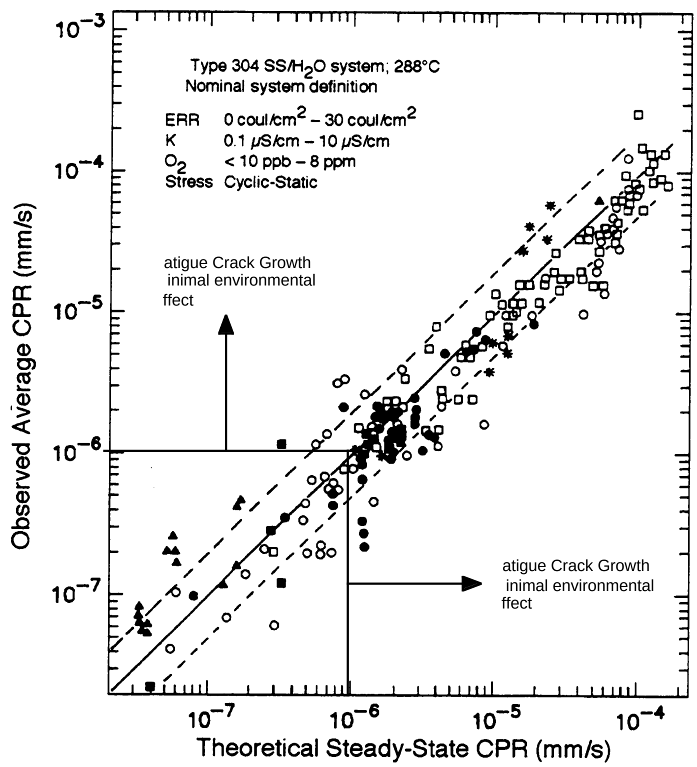


Figure 2.
Comparison of CGRs predicted by PLEDGE with experimentally observed CGRs. The comparison is of little use in establishing the validity of PLEDGE because relatively few of the data are taken under conditions in which environmentally enhanced cracking is significant.

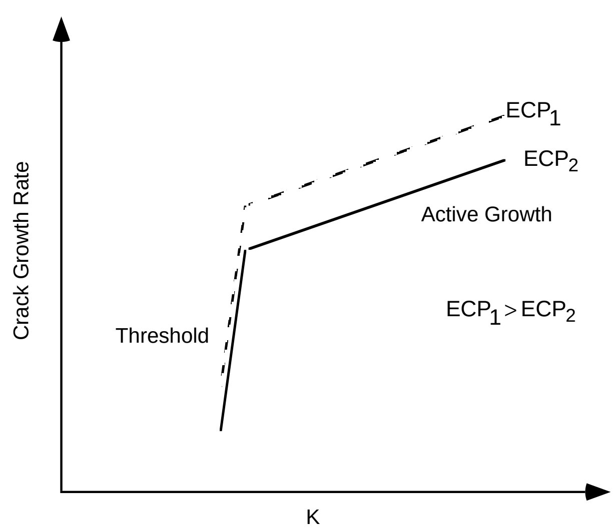


Figure 3
PLEDGE (and all other current models) only tries to predict CGRs in the active growth region above some lower threshold in stress intensity K. Data taken from the threshold region for ECP_1 would confound results because it would suggest that CGRs were lower for ECP_1 than for ECP_2.

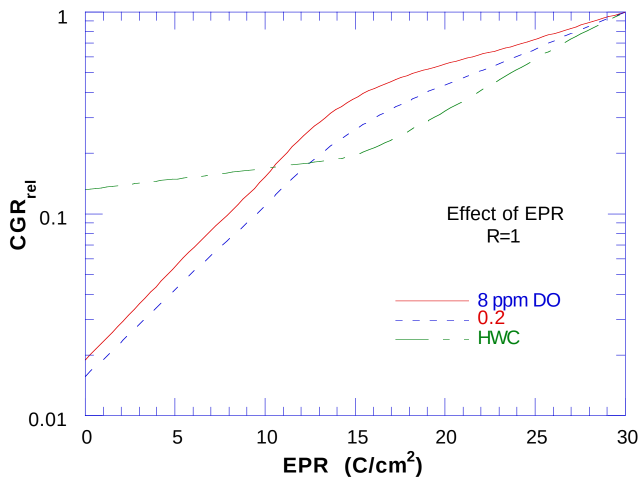


Figure 4
Predicted effect of variation in EPR on CGR for constant loads at different ECP levels.

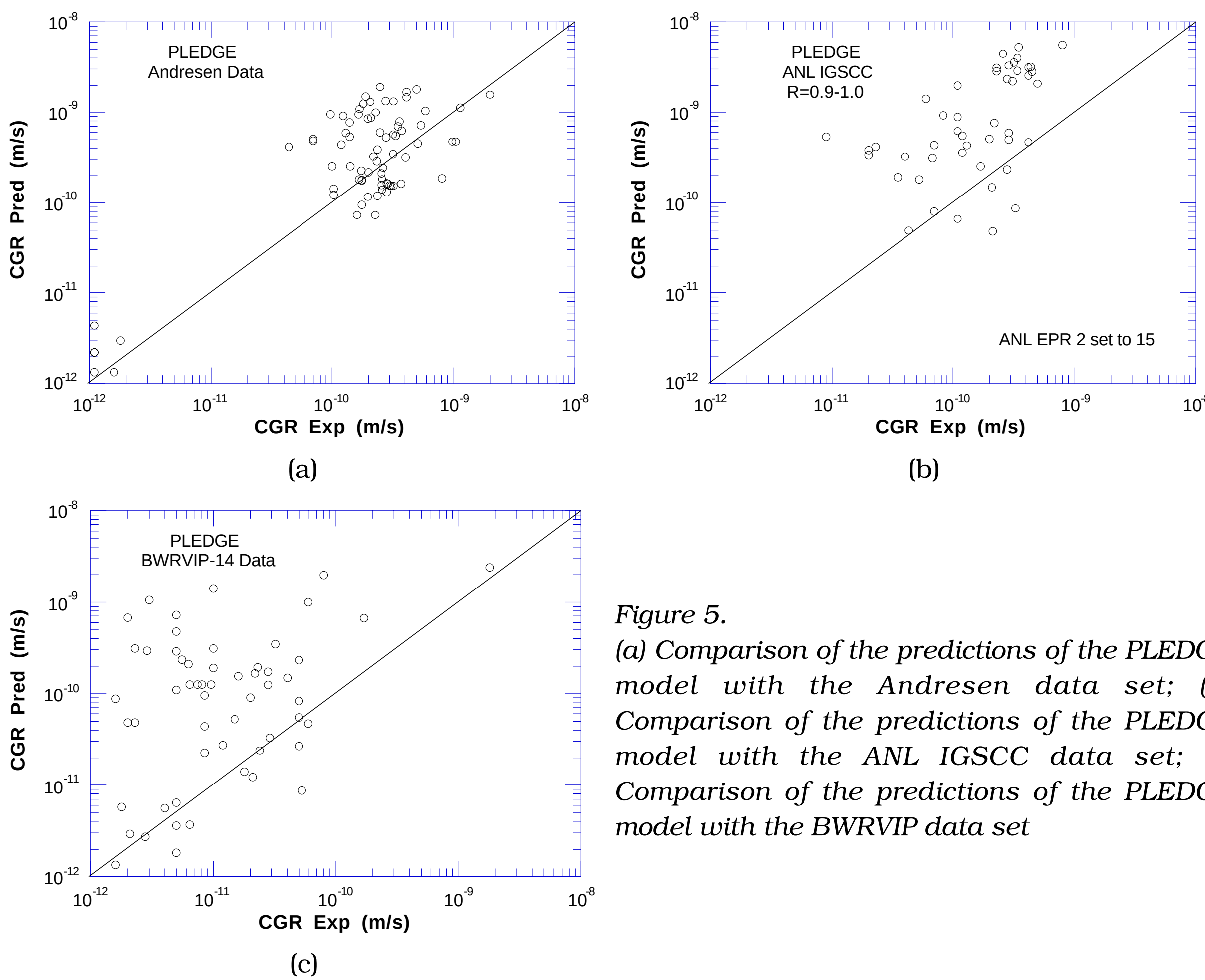


Figure 5.
(a) Comparison of the predictions of the PLEDGE model with the Andresen data set; (b) Comparison of the predictions of the PLEDGE model with the ANL IGSCC data set; (c) Comparison of the predictions of the PLEDGE model with the BWRVIP data set

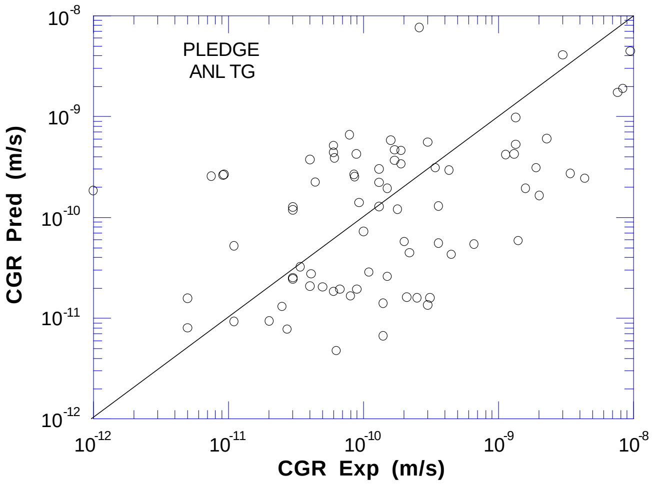
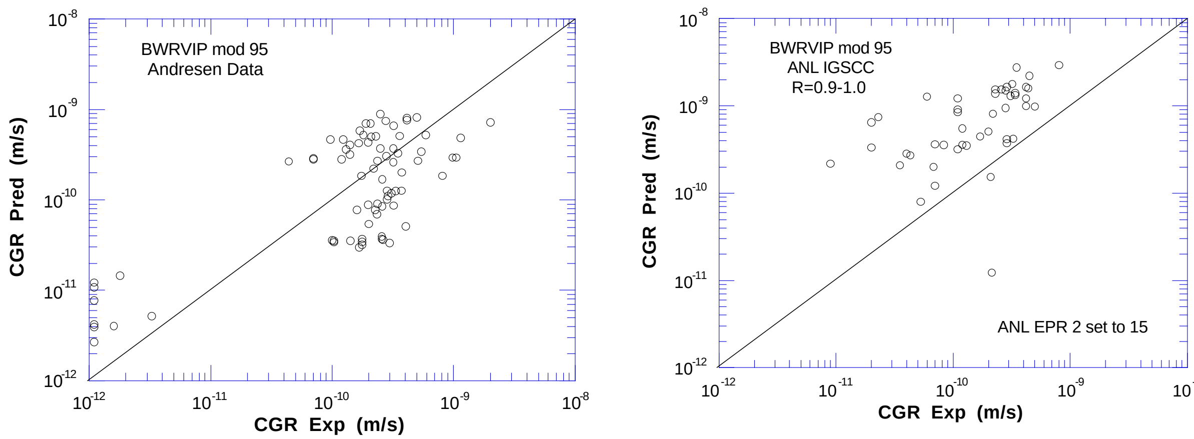
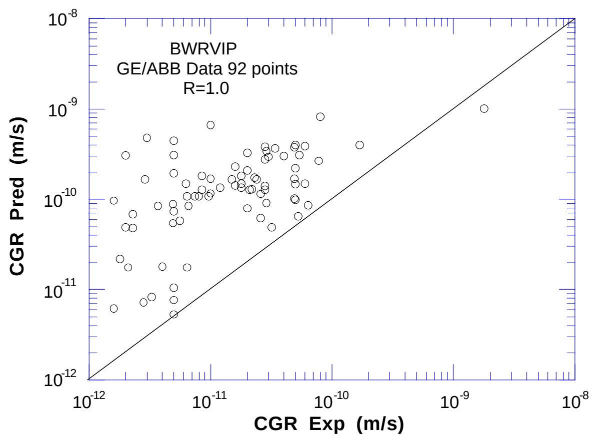


Figure 6.
(a) Comparison of the predictions of the PLEDGE model with the ANL TG data set



(a)

(b)



(c)

Figure 7.
(a) Comparison of the predictions of the BWRVIP 95 model with the Andresen data set; (b) Comparison of predictions of the BWRVIP model 95 modified to account for cyclic loading with the ANL IGSCC data; (c) Comparison of the predictions of the BWRVIP 95 model with the BWRVIP data set

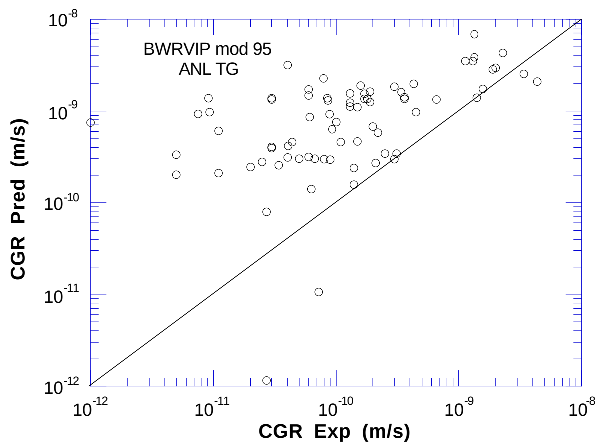
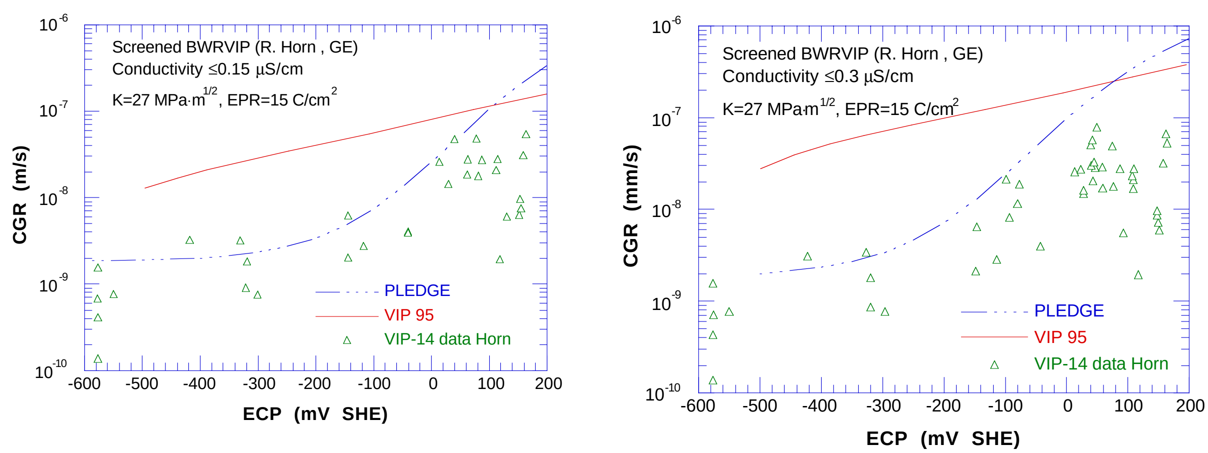


Figure 8.
Comparison of predictions of the BWRVIP model modified to account for cyclic loading with the ANL TG data.

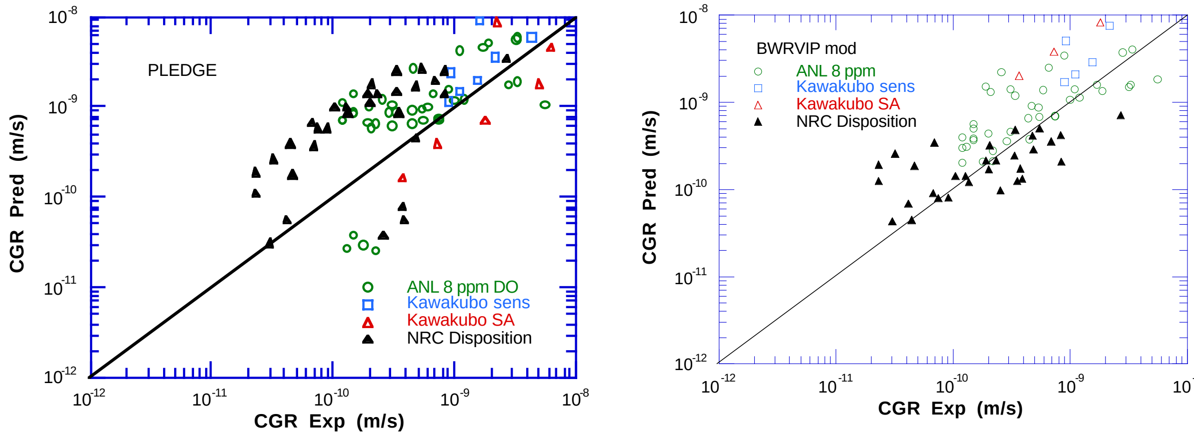
(a)

(b)



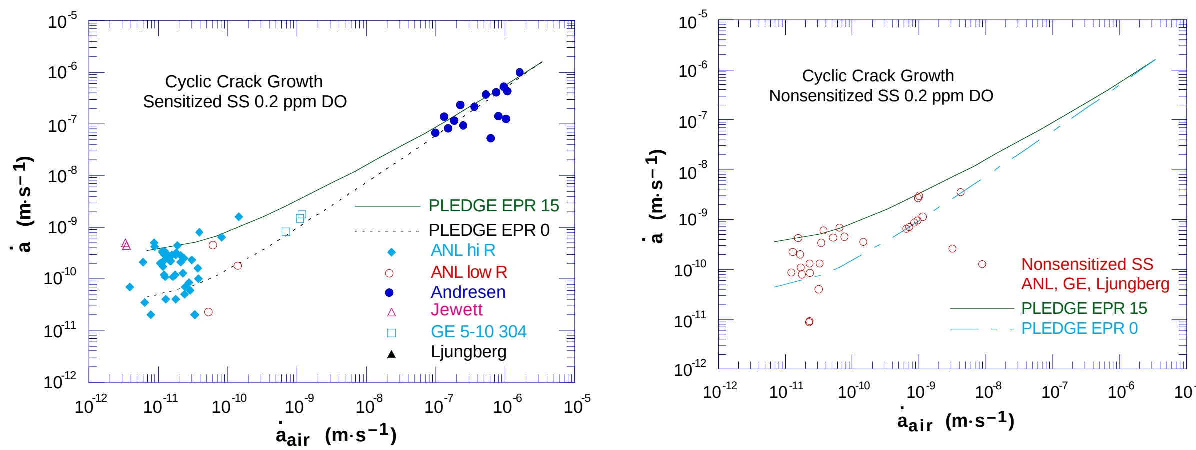
(a) (b)

Figure 9 *Comparison of BWRVIP data after screening by R. M. Horn with models (a) Conductivity ≤0.15 µS/cm; (b) Conductivity ≤0.3 µS/cm. The BWRVIP 95% confidence limit is very conservative for the screened data (scatter is reduced at low potentials.*

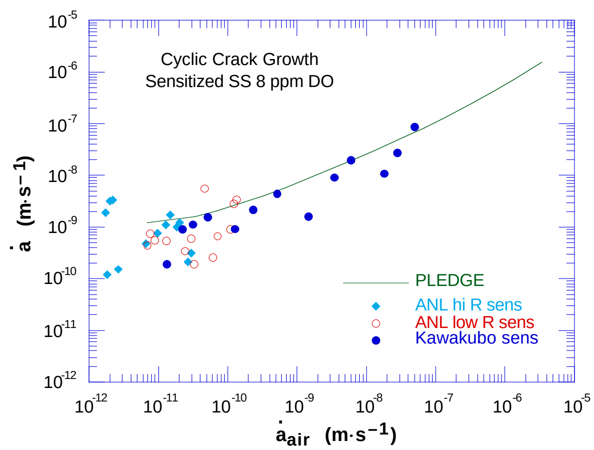


(a) (b)

Figure 10. *(a) Comparison of the predictions of the PLEDGE model with ANL high DO data, data from Kawakubo et al.[11] and data used to develop the NRC Disposition curve; (b) Comparison of predictions of the BWRVIP 95 model modified to account for cyclic loading with the same data.*

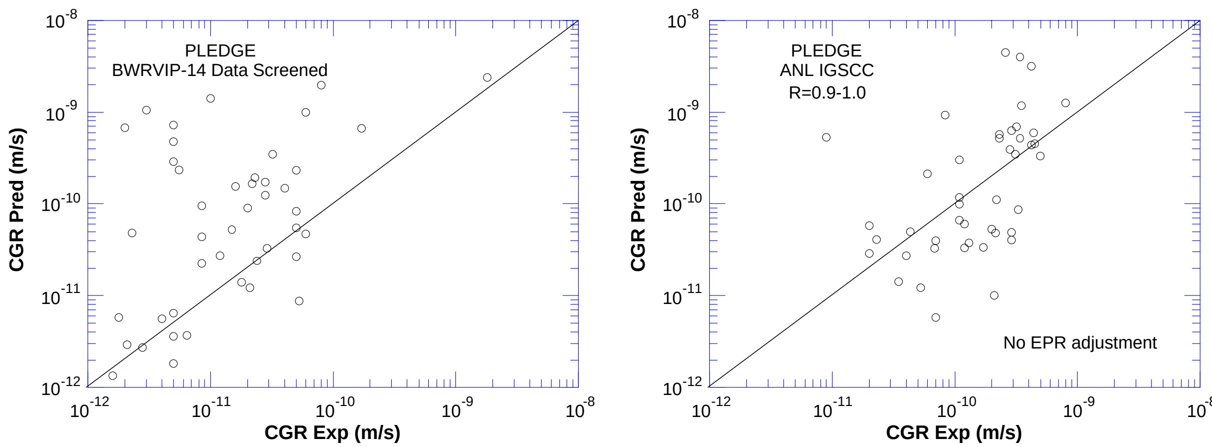


(a) (b)



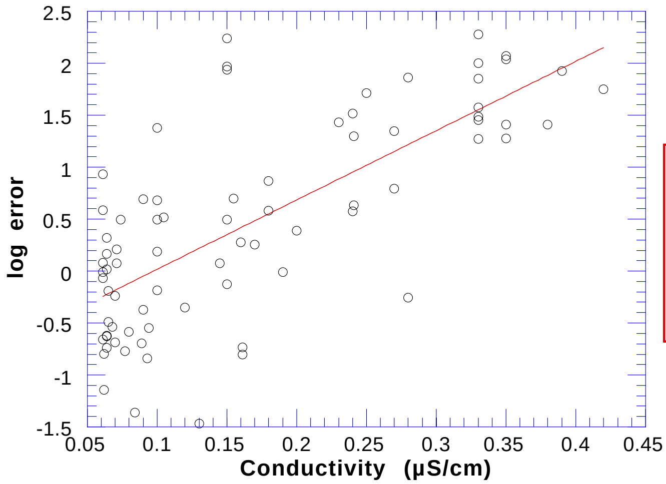
(c)

Figure 11.
Comparison of the predictions of the PLEDGE, BWRVIP, modified PLEDGE models with cyclic CGR data from the literature; (a) Data for sensitized SS in 0.2 ppm DO; (b) Data for nonsensitized SS in 0.2 ppm DO; (c) Data for sensitized SS in 8 ppm DO;



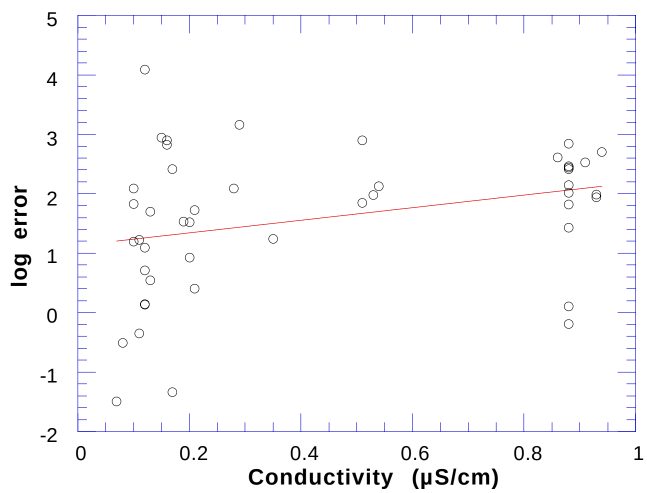
(a) (b)

Figure 12. *(a) Comparison of the predictions of the PLEDGE model with the screened BWRVIP data set; (b) Comparison of the predictions of the PLEDGE model with the ANL IGSCC data set with no adjustment to reported EPR values.*



y = m1+m2*m0		
	Value	Error
m1	-0.64935	0.14196
m2	6.6696	0.71957
Chisq	34.538	NA
R	0.72843	NA

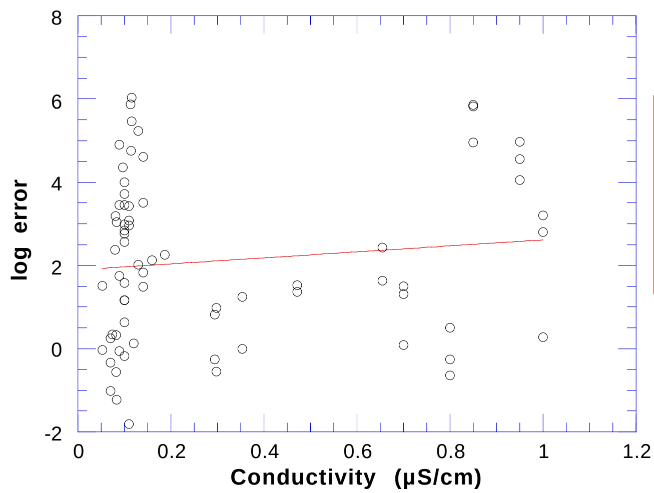
(a)Andresen



y = m1+m2*m0		
	Value	Error
m1	1.1259	0.27473
m2	1.0664	0.50141
Chisq	59.155	NA
R	0.30532	NA

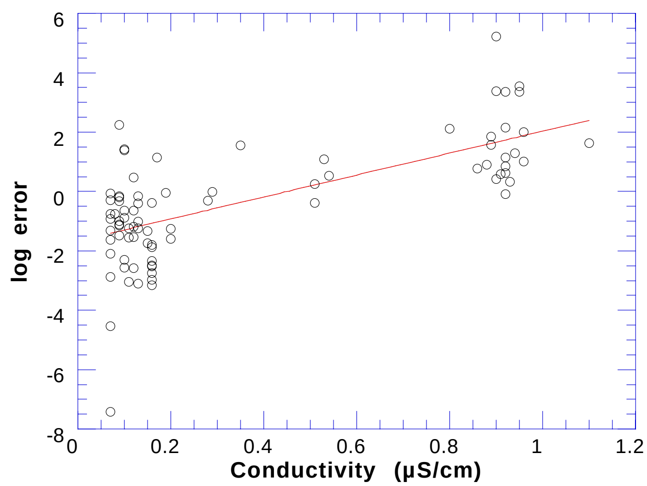
(b)ANL IGSCC

Fig. 13 *Variation of the errors in the PLEDGE predictions with conductivity for the (a) Andresen, (b) ANL IGSCC (with adjusted EPR values)*



y = m1+m2*m0		
	Value	Error
m1	1.8937	0.33202
m2	0.72292	0.75623
Chisq	276.59	NA
R	0.11433	NA

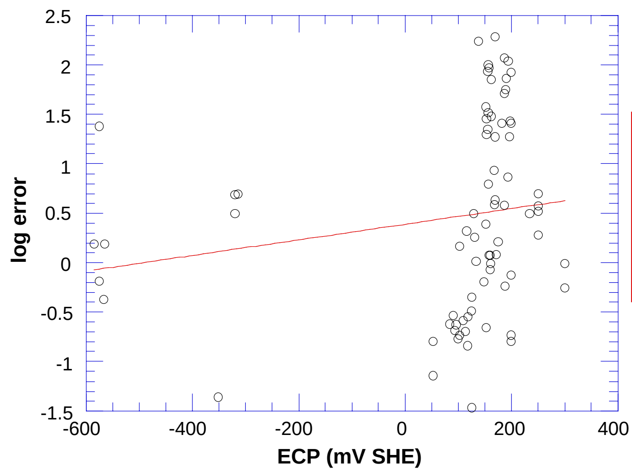
(c)BWRVIP



y = m1+m2*m0		
	Value	Error
m1	-1.6605	0.21567
m2	3.6909	0.44236
Chisq	179.55	NA
R	0.66885	NA

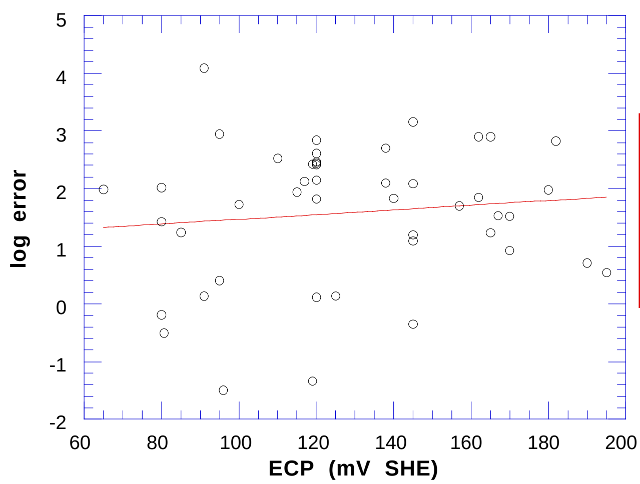
(d)ANL TGSCC

Fig. 13. (continued) Variation of the errors in the PLEDGE predictions with conductivity for the (c) BWRVIP, and (d) ANL TGSCC data sets.



y = m1+m2*m0		
	Value	Error
m1	0.38907	0.11944
m2	0.00079075	0.00052444
Chisq	71.444	NA
R	0.17043	NA

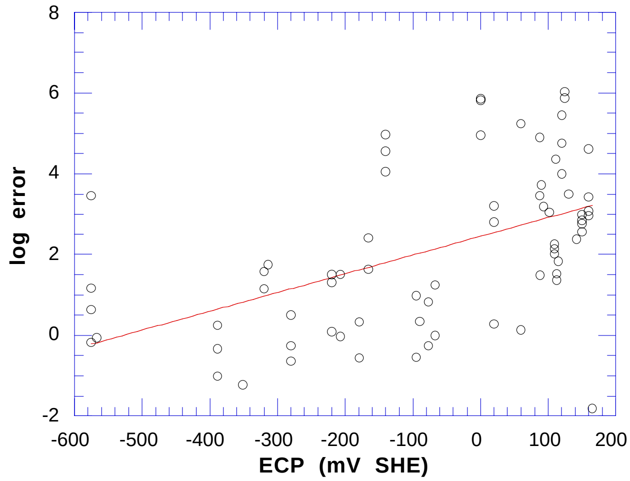
(a) Andresen



y = m1+m2*m0		
	Value	Error
m1	1.0601	0.71993
m2	0.0040725	0.0054291
Chisq	64.413	NA
R	0.11237	NA

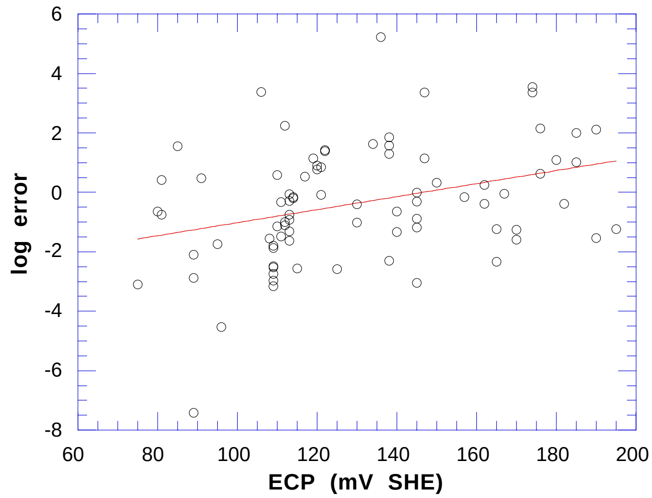
(b) ANL IG

Fig. 14. Variation of the errors in the PLEDGE predictions with ECP for the (a) Andresen, (b) ANL IGSCC (with adjusted EPR values.



y = m1+m2*m0		
	Value	Error
m1	2.4509	0.2176
m2	0.0046416	0.0009541
Chisq	208.68	NA
R	0.50537	NA

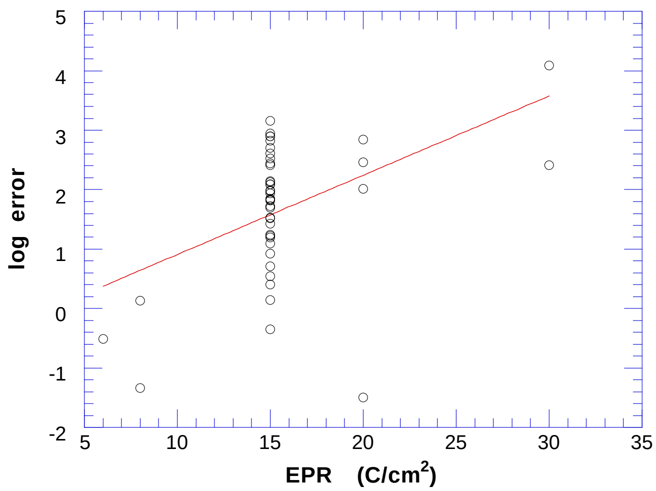
(c)BWRVIP



y = m1+m2*m0		
	Value	Error
m1	-3.2116	0.84993
m2	0.021911	0.00645
Chisq	286.46	NA
R	0.34396	NA

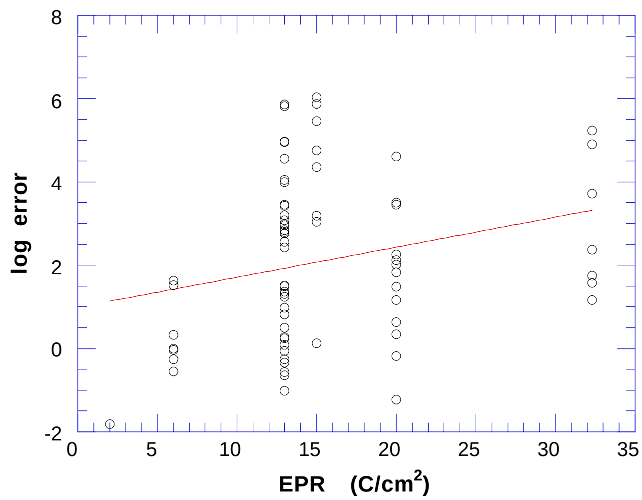
(d) ANL TGSCC

Fig. 14. (continued) Variation of the errors in the PLEDGE predictions with ECP for the (c) BWRVIP, and (d) ANL TGSCC data sets.



y = m1+m2*m0		
	Value	Error
m1	-0.42568	0.63911
m2	0.13339	0.039638
Chisq	47.012	NA
R	0.46084	NA

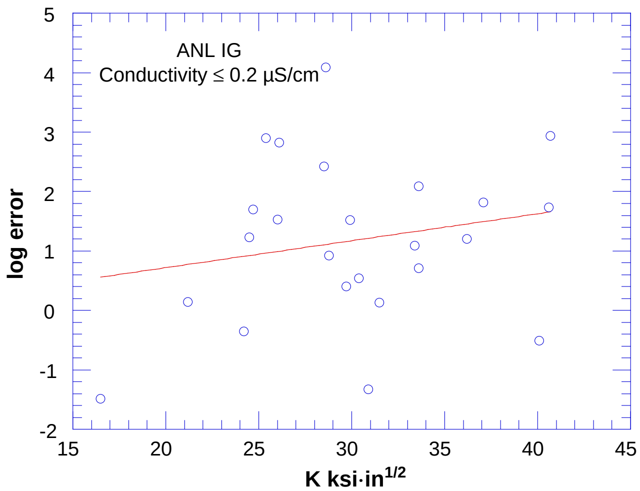
(a) ANL IG



y = m1+m2*m0		
	Value	Error
m1	0.99279	0.57971
m2	0.072127	0.034138
Chisq	263.22	NA
R	0.2465	NA

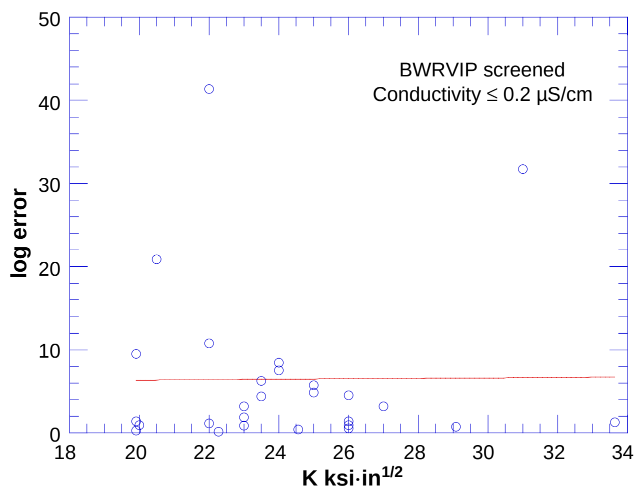
(b)BWRVIP

Fig. 15. Variation of the errors in the PLEDGE predictions with EPR for the (a) ANL IGSCC (with adjusted EPR values) and (b) BWRVI data sets.



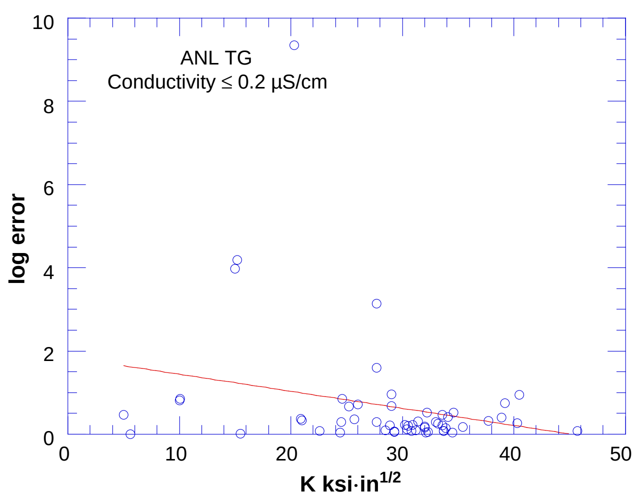
y = m1+m2*m0		
	Value	Error
m1	-0.18808	1.4244
m2	0.045353	0.046416
Chisq	41.142	NA
R	0.20394	NA

(a) ANL IG



y = m1+m2*m0		
	Value	Error
m1	5.8147	14.346
m2	0.026671	0.58886
Chisq	2529.5	NA
R	0.009058	NA

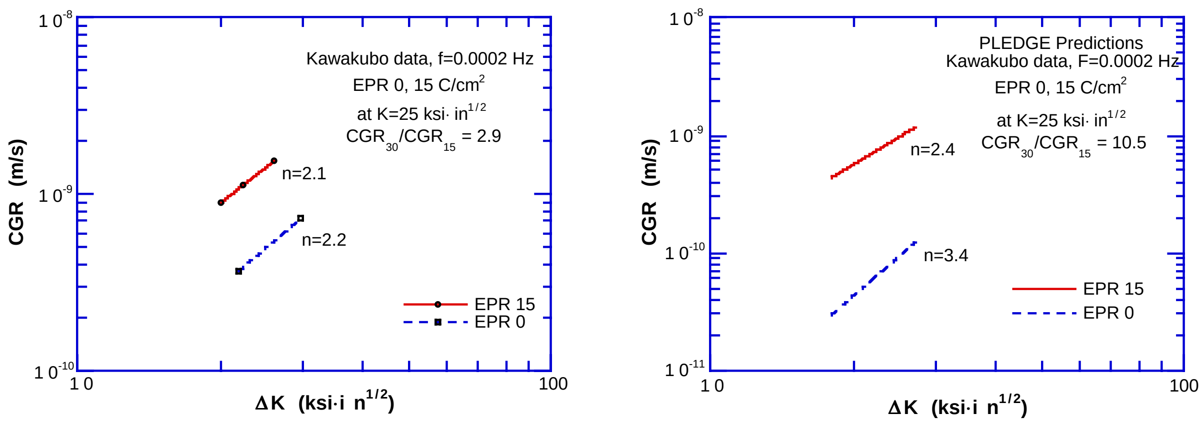
(b)BWRVIP



y = m1+m2*m0		
	Value	Error
m1	1.8539	0.55952
m2	-0.041025	0.019508
Chisq	117.15	NA
R	0.26833	NA

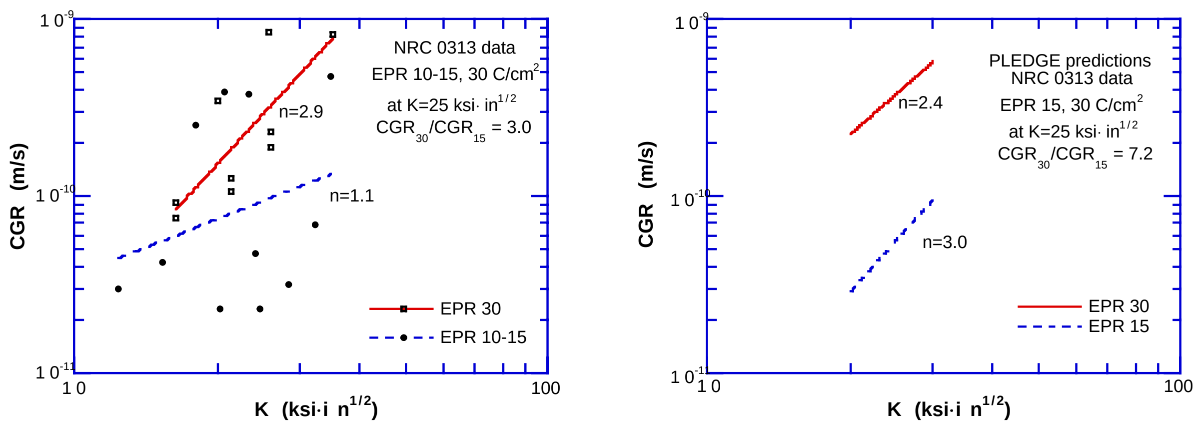
(c) ANL TGSCC

Fig. 16. Variation of the errors in the PLEDGE predictions with EPR for the (a) Andresen, (b) ANL IGSCC (with adjusted EPR values), (c) BWRVIP, and (d) ANL TGSCC data sets.



(a) (b)

Figure 17 (a) Effect of sensitization on CGR observed in cyclic load tests of Kawakubo et al.[11] (b) PLEDGE prediction of change in CGR due to change in sensitization.



(a) (b)

Figure 18 (a) Effect of sensitization on CGR observed in cyclic load tests used for NRC disposition curve[12] (b) PLEDGE prediction of change in CGR due to change in sensitization.

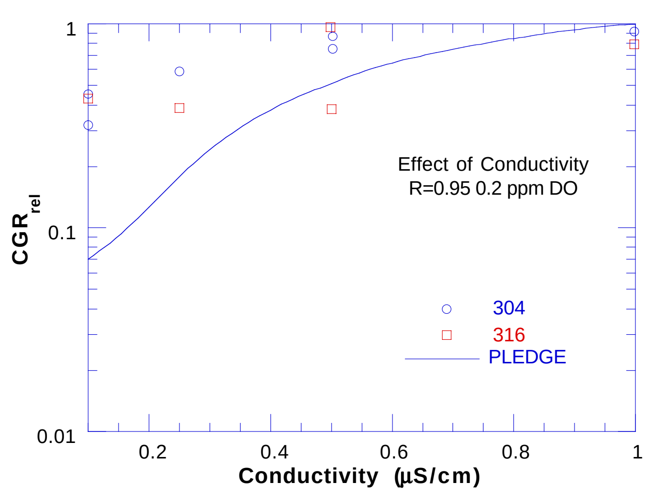


Figure 19 Predicted effect of variation in conductivity on CGR for R=0.95 loading. Data shown are from a controlled test where conductivity was varied keeping all other variables constant

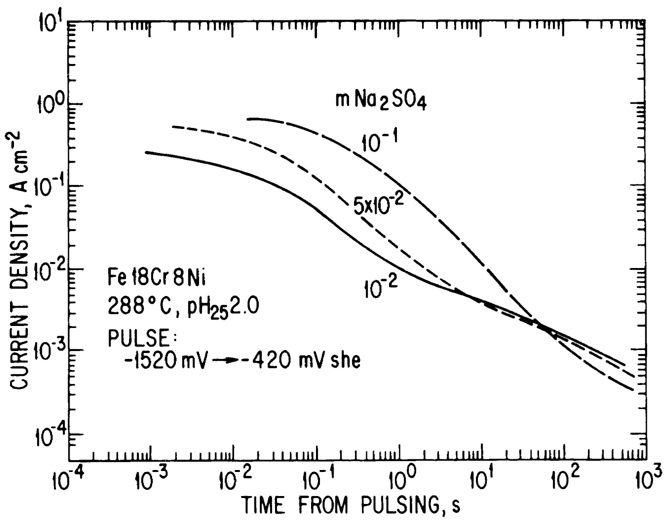
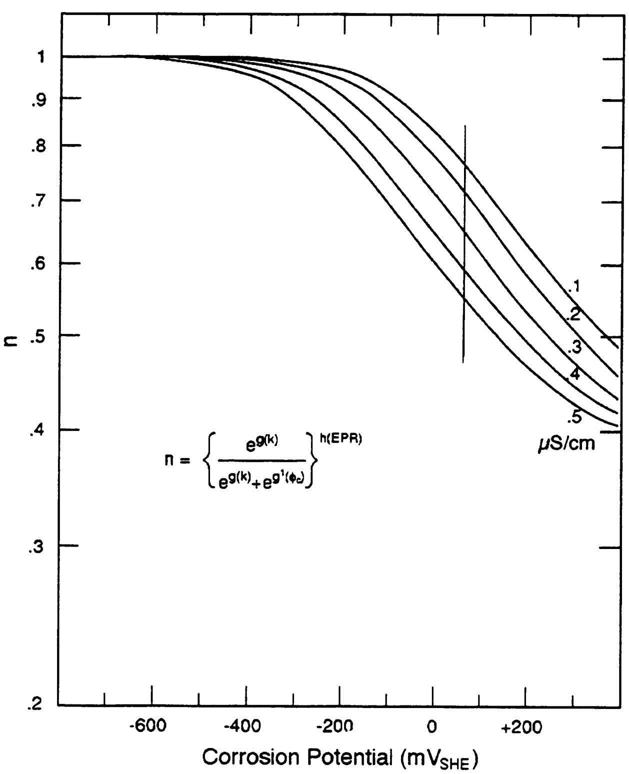


Figure 20
Effect of sulfate concentration on oxidation current density transient after a potential pulse to -420 mV in pH_{25} 2.0 solution. The slope increases as the concentration is increased.



$$n = \left\{ \frac{e^{g(k)}}{e^{g(k)} + e^{g'(\phi_c)}} \right\}^{h(EPR)}$$

Figure 21
Dependence on crack tip strain exponent n on corrosion potential and bulk solution conductivity for a sensitized SS. The slope n decreases as the conductivity increases at any fixed potential. From Ref. 1.

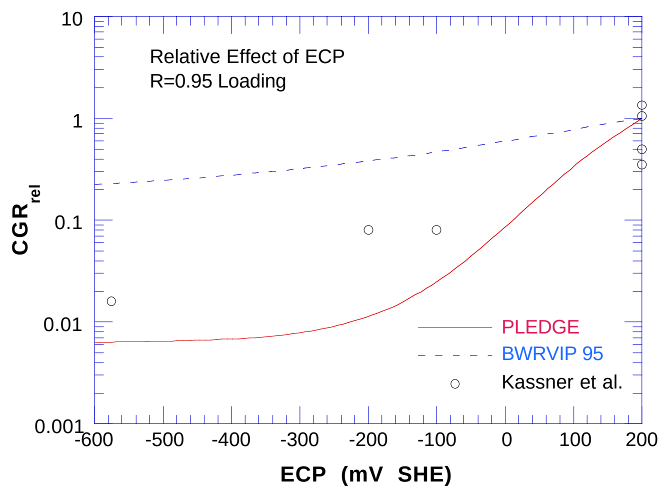


Figure 22 Predicted effect of variation in ECP on CGR for R=0.95 loading. Data shown are from a controlled test where ECP was varied keeping all other variables constant.

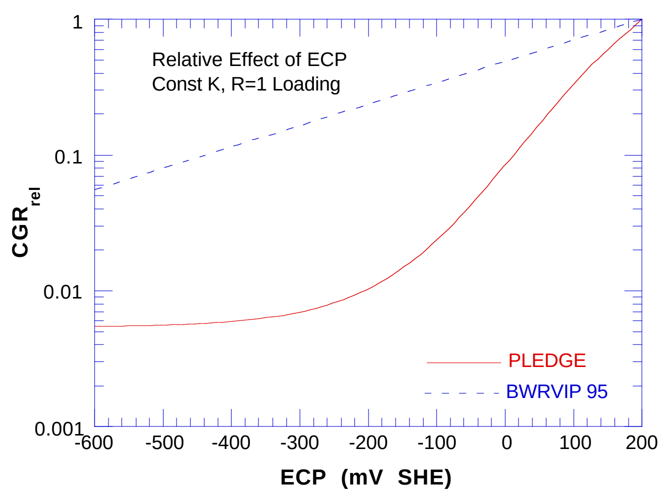


Figure 23 Predicted effect of variation in ECP on CGR for R=1 loading.

Appendix: Extension of BWRVIP Model to Include Cyclic Loading

The BWRVIP model is of the form:

$$\dot{a} = C K^n \qquad (1)$$

where C is function of conductivity, temperature, and electrochemical potential and K is the fracture mechanics stress intensity factor. However, under static loading, K is widely considered to be a surrogate for a more fundamental parameter, namely, the crack tip strain rate, $\dot{\varepsilon}_{ct}$. Ford et al.[2] have proposed an empirical relation between $\dot{\varepsilon}_{ct}$ and K of the form:

$$\dot{\varepsilon}_{ct} = B K^4, \qquad (2)$$

where B is a constant. The BWRVIP model can then be expressed in terms of $\dot{\varepsilon}_{ct}$ and new constants $\hat{C}$ and $\hat{n} = n/4$.

$$\dot{a} = \hat{C} \dot{\varepsilon}_{ct}{}^{\hat{n}}. \qquad (3)$$

The dependence of $\hat{C}$on electrochemical potential, conductivity is exactly the same as in the original BWRVIP model.

For cyclic loading there is an additional contribution to the crack tip strain rate. Shoji has argued that the crack tip strain rate is proportional to the CGR under cyclic loading in an inert environment (air). That is

$$\dot{\varepsilon}_{ct} \propto \dot{a}_{air} = \frac{1}{t_R} \frac{da}{dN}, \qquad (4)$$

where it is assumed that all of the crack growth during a cycle occurs during the rising load portion of the cycle of duration t_R. Two expressions for da/dN were examined. One is that used by Ford et al.[2]; the other is that developed by James and Jones,[21] which has been used as the basis for the ASME Section XI fatigue crack growth curves. Differences between the two models are fairly small at low R, but quite large for high R (>0.8) as shown in Fig. A1. Both models were examined for use with the BWRVIP model. The James and Jones correlation seems to give somewhat better results and has been used for the current studies. The proportionality factor in Eq. (4) can be inferred from some of Shoji's finite element results or can be treated as a fitting parameter. We initially chose the value proposed by Ford et al.[2]

$$\dot{\varepsilon}_{ct} = \frac{50}{t_R} \frac{da}{dN}, \qquad (5)$$

where a is in cm, t in sec, but then adjusted the numerical constant by a factor of 3 to improve the fit to the data.

The BWRVIP model modified to include cyclic loading can then be written as

$$\dot{a} = \hat{C} \left(\frac{150}{t_R} \frac{da}{dN} + B K^4 \right)^{\hat{n}}. \qquad (6)$$

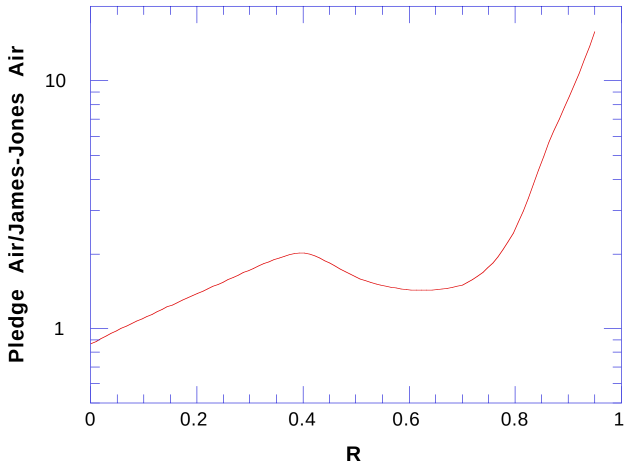


Figure A1
Ratio of fatigue CGR predicted by PLEDGE model to the predicted by the correlation developed by James and Jones. The CGRs are similar for R ≤0.8, but diverge for high R.