ELECTRIC POWER RESEARCH INSTITUTE

Environmentally Assisted Fatigue Gap Analysis and Roadmap for Future Research

Roadmap

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Environmentally Assisted Fatigue Gap Analysis and Roadmap for Future Research

Roadmap

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ABSTRACT

Crack growth test data indicate that significant environmental enhancement of fatigue crack growth can occur under some light water reactor (LWR) environmental conditions, but established fatigue initiation life curves do not explicitly account for the effect of these conditions on steels exposed to high temperature water environments. In response, the NRC has prescribed new assessment rules for fatigue initiation life of new nuclear power plantsNPP in the United States and ASME is developing Code Cases that reflect these regulatory changes. Application of these rules will result in higher fatigue usage factors for some LWR components and can represent a significant challenge in justifying safe long term NPP operation. However, the more onerous rules for lifetime assessments, intended to account for environmental effects, appear inconsistent with the relatively few reported fatigue failures of components in existing LWRs. Consequently there is a perception that the rules are excessively conservative. There is a need to resolve current uncertainties and knowledge gaps to improve the understanding and treatment of environmentally assisted fatigue (EAF) for lifetime justification of LWR components.

This report, which builds on an earlier knowledge gap analysis (EPRI report 1023012) addresses this situation by proposing a Roadmap that provides a sequence by which knowledge gaps could be addressed. It also provides more detail on the work packages that will be needed to resolve each knowledge gap. The intention is to prioritize the knowledge gaps to maximize the short-term benefit to designers and in the longer term, lead to assessment procedures and fatigue management programs that avoid undue conservatism, are supported by mechanistic understanding, and are fit-for-purpose.

Keywords

Environmentally-assisted fatigue
Corrosion fatigue
Fatigue initiation life
Fatigue crack growth

EXECUTIVE SUMMARY

Background

Established fatigue initiation life curves, such as those given in Section III of the American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code, provide the design basis for nuclear power plant (NPP) components. These curves do not explicitly account for the effect on fatigue initiation life of the high temperature water environments to which components of the reactor coolant system in light water reactors (LWRs) are typically exposed. Additionally, crack growth test data indicate that significant environmental enhancement of fatigue crack growth can occur under some LWR environmental conditions; the definition of in-service inspection programs may be compromised if the assessment of fatigue crack growth is unrealistic.

Low Cycle Fatigue data, obtained by laboratory testing of small specimens, has demonstrated that substantial reductions in fatigue life may occur in LWR environments. The Nuclear Regulatory Commission (NRC), in Regulatory Guide 1.207, has prescribed new assessment rules for fatigue initiation life of new NPP in the U.S. These rules were developed by Argonne National Laboratory based on a review of small specimen fatigue initiation life test data and introduce an environmental penalty factor, F_{en}, by which fatigue lifetime is reduced in LWR environments compared to air. ASME is developing Code Cases for assessing fatigue life in LWR environments, either using an approach similar to that prescribed by the NRC, or using fatigue curves fitted to the experimental data in water environments. Application of these rules results in higher fatigue usage factors for some LWR components, as compared with calculations based on current design codes. This can represent a significant challenge in justifying safe long term NPP operation.

The more onerous rules for lifetime assessments, intended to account for environmental effects, appear inconsistent with experience of the relatively few reported fatigue failures of components in existing LWR plant. Consequently there is a perception that the rules are excessively conservative. There is a need to resolve current uncertainties and knowledge gaps to improve the understanding and treatment of environmentally assisted fatigue (EAF) for lifetime justification of LWR components.

In response to this need a knowledge gap analysis has been performed (EPRI Product ID 1023012 published in December 2011) which identified the specific technical areas where uncertainties exist. In that analysis the status of existing research and design code developments was reviewed to address EAF for ferritic steels, austenitic stainless steels and nickel based alloys in PWR and BWR environments. A critical review of design code developments was then undertaken and a statement given of the individual knowledge gaps identified therein.

Present Work

The purpose of the present report is to develop the data source and plant assessment procedure connectivity into a Roadmap which gives a suggested sequence by which knowledge gaps could be addressed, together with more detail of the work packages involved in resolving each knowledge gap. The intention is to prioritize the knowledge gaps to maximize the short term benefit to designers and in the longer term, lead to assessment procedures and fatigue management programs which avoid undue conservatism, are supported by mechanistic understanding and are fit-for-purpose.

Roadmap Development

Following the prioritization meetings, a more detailed scheme for knowledge evaluation has been developed which is described in this report. This scheme focuses on the need to propose and test hypotheses which aim ultimately to explain the anomalous position between the expectations from test data and plant experience, where knowledge gained is rationalized by the development of mechanistic understanding. The hypothesis based approach is intended to gain maximum understanding from testing, analysis or review work, rather than to simply add further data to an already considerable database.

Low level hypotheses may be associated with resolving individual knowledge gaps. High level hypotheses may be founded on a fundamental aspect related to stress-strain states, to conservatism inherent in design codes or mechanistically based.

The following seven high level hypotheses have been identified as worthy of further examination although additional hypotheses could be proposed:

Hypothesis 1. Cyclically variable parameters in a thermally-induced stress cycle reduce or negate the environmental influence on fatigue,

Hypothesis 2. Compressive stress does not contribute to the corrosion fatigue damage mechanism,

Hypothesis 3. Conservatism due to the use of bounding transients for design purposes is sufficient to accommodate environmental enhancement of fatigue damage,

Hypothesis 4. Conservatism in the current treatment of non-contiguous cycles for design purposes may partly account for environmental influences on fatigue,

Hypothesis 5. Conservatism is introduced in plant assessment through the use of available material data which is insufficiently comprehensive in terms of the parameters considered and the range of those parameters to adequately represent realistic plant conditions,

Hypothesis 6. Conservatism is introduced by the calculation methods recommended for the determination of F_{en} factor which are largely unsubstantiated and do not adequately consider the relevant parameters and their time dependent influences, Hypothesis 7. Improved mechanistic understanding would identify circumstances where the application of the F_{en} factor approach is not required.

Recommended Work Program

The various options have been considered and a recommendation made on the basis of perceived minimum cost, perceived shortest timescale and perceived maximum benefit (judged according to generic application). The following recommendations are subjective. The best option depends on actual funds available, actual timescale by which results are required and attitude to risk.

A work program has been considered on the basis of addressing all high priority knowledge gaps initially, and considering medium priority and low priority knowledge gaps subsequently as necessary. This approach would undoubtedly provide significant insight into the anomalous position between test data and plant operating experience. However, it will be very expensive and require a long time period to complete although short term benefits have been identified.

On the basis of high cost and long timescale, this option is not recommended.

An approach is advocated which considers high level hypotheses which are tested by addressing their associated high priority, medium priority and low priority knowledge gaps, as follows:

Hypothesis 1 (concerning the nature of thermal cycling) if true will be a generic issue since most fatigue damage occurs from plant thermal transients.

It is recommended that Hypothesis 1 should be tested in the first instance by resolving the associated knowledge gaps in the context of the knowledge evaluation scheme.

Hypothesis 6 (concerning the inadequacy of calculation procedures) if true will be a generic issue since the calculation of F_{en} factors in the F_{en} factor approach is the way in which knowledge is incorporated into design.

It is recommended that Hypothesis 6 should be tested in a parallel program with Hypothesis 1 in the first instance by resolving the associated knowledge gaps in the context of the knowledge evaluation scheme.

Hypothesis 3 (the use of bounding transients) is unlikely to be generic but may provide significant benefit through the development of screening rules for incorporation into design codes.

It is recommended that Hypothesis 3 should be tested in a parallel with Hypotheses 1 and 6 by resolving the associated knowledge gaps in the context of the knowledge evaluation scheme.

Hypothesis 5 (concerning inadequacy in material data) would require an extensive material testing program to resolve. The cost of fully addressing this issue is likely to be prohibitive.

The testing of Hypothesis 5 is not recommended in the first instance on the basis of high cost and long timescale. This should be considered over a longer timescale.

Hypothesis 7 (concerning inadequate mechanistic understanding) when resolved would accrue benefit to certain components under certain circumstances but the main benefit is that it enables judgments to be extrapolation outside the testing database.

The testing of Hypothesis 7, although important, is not recommended in the first instance because of limited immediate applicability. This should be considered over a longer timescale.

Hypothesis 4 (concerning conservatism in the treatment of non-contiguous cycles), if true would be a generic issue since most fatigue damage is from thermal transients. However, the hypothesis is difficult to consider in a short term test program due to the nature of non-contiguous cycles. It can only be tested sensibly on the basis of developments in mechanistic understanding of both crack initiation and crack growth.

The testing of hypothesis 4, although a generic issue is not recommended in the first instance since it can only be addressed sensibly on the basis of mechanistic understanding. This should be considered as mechanistic understanding improves.

Hypothesis 2 (concerning conservatism in the treatment of compressive stress), if true would influence certain components with certain transients but would not be a generic issue relating to all circumstances.

The testing of Hypothesis 2 is not recommended in the first instance because of limited applicability.

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INTRODUCTION

Background

Established fatigue initiation life curves that provide the design basis for nuclear power plant (NPP) components do not explicitly include allowance for the effects of high temperature water environments to which components of the reactor coolant system in light water reactors (LWRs) are typically exposed. Low cycle fatigue data, obtained by laboratory testing of small specimens, have demonstrated that substantial reductions in fatigue life may occur in LWR environments. These data may undermine the validity of current fatigue initiation life design curves for components exposed to such environments. Additionally, crack growth test data indicate that significant environmental enhancement of fatigue crack growth can occur under some conditions. The definition of in-service inspection (ISI) programs may be compromised if the assessment of fatigue crack growth is unrealistic.

The Nuclear Regulatory Commission (NRC), in Regulatory Guide 1.207 [1], has recently prescribed new assessment rules for fatigue initiation life of new NPP components exposed to LWR environments. These rules are based on statistical analysis by Argonne National Laboratory (ANL) of fatigue initiation life tests from a variety of sources [2]. Additionally, the American Society of Mechanical Engineers (ASME is developing Code Cases (CC) for assessing the effects of environmentally assisted fatigue (EAF), either using an approach similar to that prescribed by the NRC or using fatigue curves fitted to the experimental data in water environments. CCs to address environmental effects on fatigue crack growth are also under development. The new assessment rules predict substantially higher crack growth rates than the existing crack growth curves for inert environments. Application of the current NRC rules or either of the ASME CCs can result in high fatigue usage factors (FUFs) for some components of pressurized and boiling water reactors (PWRs and BWRs) which presents a significant challenge in justifying safe long term NPP operation. Similarly, use of the proposed crack growth rate CCs may have a significant impact on ISI intervals.

The more onerous rules for EAF lifetime assessments developed by NRC and ASME and/or the proposed environmentally-enhanced crack growth rate curves do not, however, appear consistent with experience of the relatively limited number of reported fatigue failures of components in existing plants, most of which have been attributed to transient loadings not anticipated at the design stage. Consequently there is a need to resolve current uncertainties concerning the understanding and treatment of EAF for LWR components.

Previous Work

In response to this need a knowledge gap analysis has previously been performed which identified the specific technical areas where uncertainties exist. In that analysis the status of existing research and design code developments were reviewed to address EAF for ferritic steels, austenitic stainless steels and nickel based alloys in PWR and BWR environments. A critical review of design code developments was then undertaken and a statement given of the individual knowledge gaps identified therein. A more general discussion followed which identified further knowledge gaps and drew together the interaction between the knowledge gaps.

The knowledge gaps fell into three categories:

1. the identification of an anomalous position with the current state of understanding which requires resolution,
2. the lack of application of existing knowledge which could prove instructive,
3. a knowledge gap which inhibits progress in the development of an acceptable position.

The knowledge gaps were collated into a table which included a summary of the research needs considered necessary to address them.

The gap analysis presented a high level diagram showing the connectivity between various data sources and practical plant assessment procedures. The connectivity shown there suggested a knowledge evaluation process which, given the resolution of the knowledge gaps, would lead to improved assessment procedures which are supported by mechanistic understanding. The results were presented in the Gap Analysis report (EPRI Product ID 1023012 published in December 2011 [3]) which forms the basis for development of the Roadmap for future EAF Research.

The Present Work

The purpose of the present work is to develop the data source and plant assessment procedure connectivity into a detailed Roadmap which gives a suggested sequence by which knowledge gaps could be addressed, together with more detail of the work packages involved in resolving each knowledge gap. The intention is to prioritize the knowledge gaps to maximize the short term benefit to designers and in the longer term, lead to assessment procedures and fatigue management programs which avoid undue conservatism, are supported by mechanistic understanding and are fit-for-purpose.

Approach

The results of the gap analysis were presented to two meetings of the EPRI EAF Expert Panel [4, 5] and to a separate Focus Group convened by EPRI [6], the objective being to bring together key stakeholders from both the research and practitioner arenas to prioritize the identified knowledge gaps, and define key project milestones.

The EPRI Expert Panel prioritized the gaps as High, Medium or Low using a ranking sheet distributed at the St Louis meeting [7] and circulated to non-attendees shortly afterwards. The second ranking was carried out at the meeting of the EPRI Environmentally Assisted Fatigue Focus Group in February 2012 [6]. At the Focus Group Meeting, priorities were attributed to the knowledge gaps as Priority 1, Priority 2 or Priority 3 using a voting system. The priorities accounted for the timescale to achieve results, the technical benefit to be expected, the probability of success and the range of applicability to BWRs, PWRs and the materials used in plants.

Following those meetings, a more detailed scheme for knowledge evaluation has been developed. This scheme focuses on the need to propose and test hypotheses to explain the anomalous position between the expectations from test data and plant experience, where knowledge gained is rationalized by the development of mechanistic understanding. The resolution of these issues is fundamental to international acceptance of new plant assessment procedures and fatigue management programs. The knowledge evaluation scheme is described here in Chapter 2.

A list of high priority gaps has been compiled as those which are scored either High (by the Expert Panel) or Priority 1 (by the Focus Group) from the two groups of experts and stakeholders. Similarly, a list of medium priority gaps has been compiled from those which are scored as either Medium or Priority 2 from those two meetings. The remaining gaps are listed as low priority. This analysis of priorities is also presented in Chapter 2.

During the knowledge gap analysis, various hypotheses were identified by which the apparent discrepancy between laboratory data and plant experience might be explained. These have been collected together and are presented here in Chapter 3. This list is by no means exhaustive; future work programs may suggest more.

The dependencies between the high priority gaps have been identified which suggests an optimum sequence by which the knowledge gaps could be resolved. This discussion, together with a more detailed evaluation of the knowledge gaps, is given in Chapter 4.

A similar exercise has been performed for the medium priority knowledge gaps and is reported in Chapter 5.

In Chapter 6, the low priority knowledge gaps are discussed. The prioritization process has identified these knowledge gaps as those which are more specific to a particular issue and less generic to the resolution of the anomalous position. Therefore, it is not appropriate here to suggest a sequence by which these could be resolved.

Conclusions are drawn together in Chapter 7 and a complete list of knowledge gaps together with their allocated priorities is given in Chapter 8.

2

DATA ACQUISITION AND KNOWLEDGE EVALUATION

The development process described below involves two aspects. Firstly, data are acquired. Secondly, data are processed and evaluated to acquire knowledge upon which action can be taken. Thus, two types of gap can be identified, data gaps and knowledge gaps.

A knowledge evaluation scheme is shown in Figure 2-1. Understanding of the influence of light water reactor environments on fatigue initiation and crack growth is developed from various sources of data including material test data, component test data and plant experience. Mechanistic understanding and supporting data together inform the development of assessment procedures. Figure 2-1 identifies connections between data sources and illustrates how practical assessment procedures and their plant application are informed and developed from the evaluation of various data.

The development of effective plant assessment procedures and fatigue management programs according to Figure 2-1 cannot be expedited at present because of a large number of significant gaps, both data gaps and knowledge gaps. To a limited extent, progress can be made by review and reassessment of existing data according to existing knowledge. These instances are discussed in Chapter 4.

Knowledge Evaluation Scheme

Foundational to the knowledge evaluation scheme is the requirement to propose and test hypotheses to resolve the anomalous position between material test data and current plant operating experience.

1. The scheme begins with the proposal of a hypothesis which may be suggested for a number of reasons. It may be founded on a fundamental aspect related to stress-strain states, to conservatism inherent in design codes or mechanistically based.
2. Experiments are designed by which phenomenological data are collected such that the hypothesis can be tested. These data may be material test data or component and plant focused test data.
3. The hypothesis is tested to identify whether or not both material test data and operating experience are consistent with the hypothesis.
4. If the hypothesis is not proved, the negative result can lead to improved mechanistic understanding by eliminating spurious mechanistic influences and suggest how the hypothesis could be revised.
5. The hypothesis is revised and the cycle of testing and evaluation repeated.
6. When a hypothesis is demonstrated to be true, an aspect of assessment procedures can be developed following the principle of similitude, i.e. the behavior of test data can be 'read-

across' to plant behavior. Also, fatigue management programs can developed based on, for example, inspection requirements or the control of water chemistry.

7. A number of true hypotheses will be required to develop codes and standards fit-for-purpose because of their wide ranging scope. Therefore, the knowledge acquisition and evaluation process is not once-through.
8. Whatever the state of development of assessment procedures, interpretation will always be required. This will be informed by developments in mechanistic understanding allowing sound judgments to be made.
9. New plants are designed, in the main, by extrapolating knowledge and experience gained from the operation of existing plant. The resolution of the current issues concerning corrosion fatigue will be instrumental in this.

Data Gaps and Knowledge Gaps

Figure 2-1 includes references to all data gaps and knowledge gaps identified in [2]. The gap numbers refer to the order in which they are listed in the gap analysis and have no other significance. The gaps are color coded to indicate the priority allocated to them here, which is described in Chapter 8. In Figure 2-1 the gaps are grouped together according to how they relate to the various aspects of the knowledge evaluation process. This grouping is subjective and is intended to illustrate which aspects of data acquisition and knowledge evaluation require most attention.

The following are noted for the twenty one Priority 1 knowledge gaps:

i) ten relate to the acquisition of data,

ii) two relate to the testing of hypotheses,

iii) seven relate to the development of assessment procedures,

iv) two relate to the development of mechanistic understanding.

The following are noted of the eighteen Priority 2 knowledge gaps (Gap 20 is split into two, making nineteen Priority 2 entries in Figure 2-1):

v) seven relate to the acquisition of data,

vi) nine relate to the development of assessment procedures,

vii) three relate to the development of mechanistic understanding.

The following are noted of the eight Priority 3 knowledge gaps:

viii) six relate to the acquisition of data,

ix) one relates to the development of assessment procedures,

x) one relates to the development of mechanistic understanding.

Therefore, nearly half (49%) of the gaps relate to the acquisition of data and the remainder (51%) relate to the development of knowledge upon which assessment procedures and fatigue management programs can be developed.

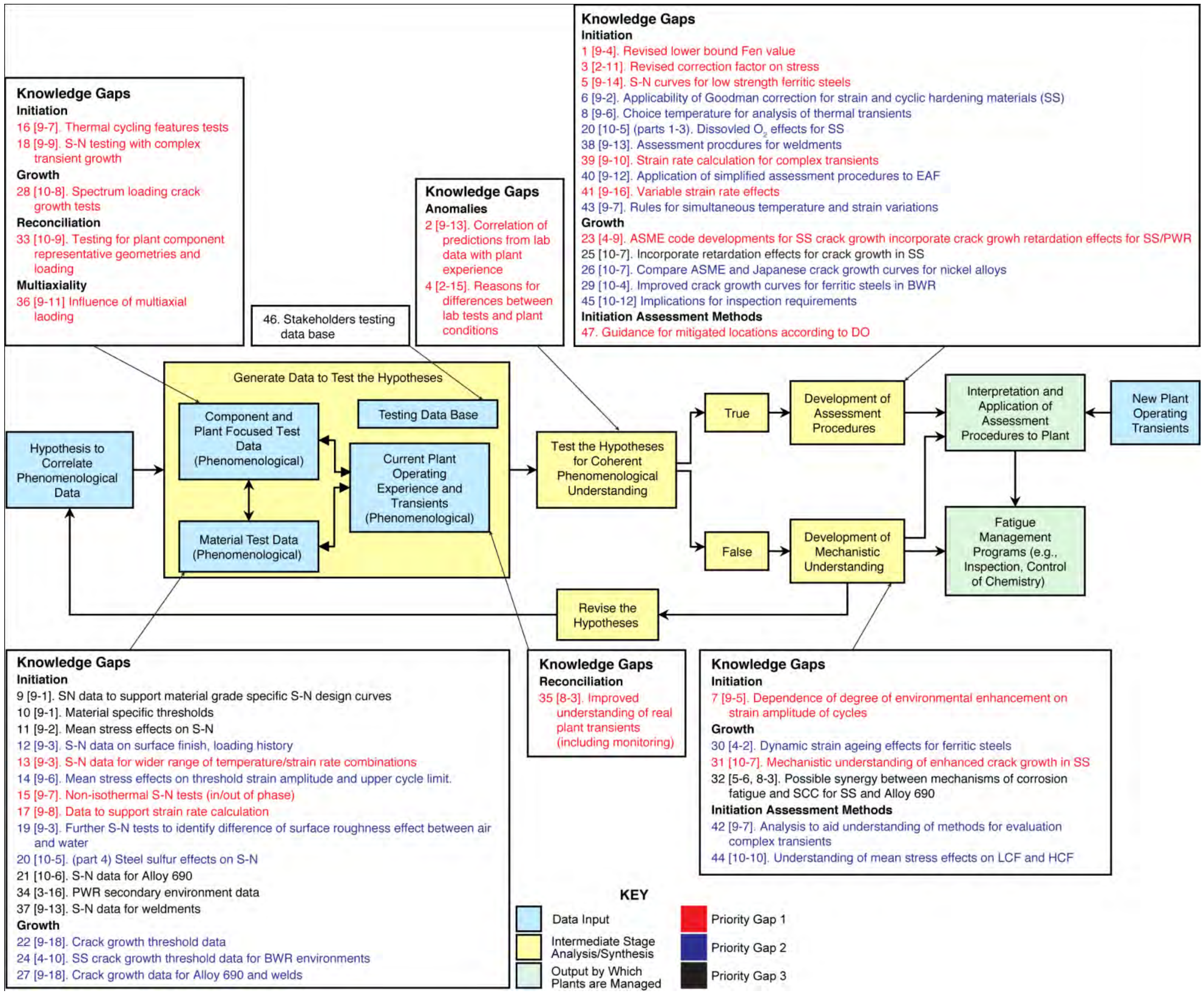

Figure 2-1
Knowledge Evaluation Scheme Showing the Context of All Data Gaps and Knowledge Gaps

3
SUMMARY OF HYPOTHESES

Background

As noted previously, the large degree of environmental enhancement of fatigue damage observed in laboratory tests appears inconsistent with the relatively small number of plant occurrences of fatigue, many of which appear explicable in terms of unforeseen transients. It is important to understand the reasons for this apparent discrepancy.

Given the large number of knowledge gaps identified, many reasons can be supposed for the anomalous position. The most likely outcome is that a combination of factors is involved, rather than a single overwhelming factor. Reasons which have been suggested fall into four main categories:

Category A. The loading conditions used in the laboratory testing may be different than the loading experienced in LWR components. For example, in almost all the environmental fatigue tests, the testing was done at constant temperature with strain controlled load cycling. In reality, fatigue cycling in power plant components is predominantly due to temperature transients.

Category B. There may be conservatisms in the current ASME Code fatigue analysis procedures that bound any adverse effect due to environment.

Category C. Conservatism is introduced through the use of inadequate material data and the calculation methods derived from them which do not fully represent relevant plant conditions.

Category D. Inadequate mechanistic understanding leads to conservative assessment procedures or inappropriate application of procedures to some components or plant conditions.

The following describes a number of proposed hypotheses to explain the apparent conflict between the test data and field experience. It is important to note that any proposed hypothesis should be tested and proved by focused experimentation and/or analysis, and underwritten by mechanistic understanding, before it is adopted (in part or in whole) as the explanation of the anomalous position between currently available EAF curves and equations (based on limited test data) and field experience. Many more such hypotheses could be proposed.

Hypothesis 1: Cyclically Variable Parameters in a Thermally Induced Stress Cycle Reduce or Negate the Environmental Influence on Fatigue (Category A)

Background

It is characteristic of all thermal transient stress cycles that the change of surface temperature and the change of surface strain are out-of-phase, i.e. as the temperature is reducing the strain is increasing, and vice versa. To date, the great majority of EAF initiation life test data have been obtained with strain controlled cycling under isothermal conditions. A reasonable hypothesis is that the nature of thermally induced out-of-phase cycling is fundamentally different to in-phase or isothermal cycling.

A number of thresholds or conditions have been identified whereby the corrosion enhancement to fatigue damage is reduced as the threshold or condition is approached and negated as the threshold or condition is passed. These relate to a minimum temperature, a minimum strain range and a maximum strain rate which is positive. Where negative strain rates are included in cycles, the negative strain rate appears have no additional influence compared to cycles with positive strain rate alone.

Consider as an example the following thermal transient cycle. A thermal down-ramp is suddenly applied to a surface. The strain rate is initially high (minimizing the corrosion influence), the strain rate is positive (maximizing the corrosion influence), and the temperature is reducing (minimizing the corrosion influence). The rapid thermal down-ramp is then followed by a gentle thermal up-ramp to complete the cycle. The strain rate is initially low (maximizing the corrosion influence), the strain rate is negative (minimizing the corrosion influence), and the temperature is increasing (maximizing the corrosion influence).

The cycle is complex and the various influencing parameters are changing up and down together in a non-linear relationship. An outcome of this hypothesis, if correct, is the possibility that the corrosion influence on fatigue damage is negated for a significant portion of the loading cycle, but for different reasons at different times.

Relevant Knowledge Gaps

The HIGH PRIORITY knowledge gaps which, if resolved, would contribute to the testing of this hypothesis are as follows:

- *Gap 15 which states that [only] limited data are available on the influence of variable temperature and variable strain rate within test cycles and of the influence of out-of-phase variations of temperature and strain rate.*
- *Gap 28 which states that very few data are available under plant representative loading conditions and the influence of complex loading conditions (including hold times and spectrum loading) waveforms and combined loading are not well quantified. Crack growth data are obtained under isothermal conditions whereas many plant transients involve simultaneous temperature and load cycling (either in- or out-of-phase).*
- *Gap 33 which states that more data using component like features with plant representative loading conditions are required to develop and validate methods for considering corrosion fatigue in LWR environments.*

The MEDIUM PRIORITY knowledge gaps which, if resolved, would contribute to the testing of this hypothesis are as follows:

- *Gap 8 which states that for non-isothermal cycles, the issue of temperature selection appropriate to the full calculation procedure of thermal analysis, elastic stress analysis, strain analysis and F_{en} factor calculation requires further consideration.*
- *Gap 42 states that the procedures for determining a cycle specific F_{en} factor are very important since they underpin the application of test data to plant assessment. Test data supporting averaging procedures for treatment of cyclically varying temperature, strain rate and stress (tension or compression) are sparse and this represents a significant uncertainty. There is a need to understand real behavior under temperature variable conditions.*
- *Gap 43 which states that NUREG/CR-6909 lacks guidance on the procedure to be followed for stainless steel when both strain rate and temperature vary during a cycle. Thus the NUREG/CR-6909 model does not consider the possibility that one or more of the influencing parameters may be outside its threshold value at all times during a cycle so that the combined influence may be reduced or negated.*

The LOW PRIORITY knowledge gaps which, if resolved, would contribute to the testing of this hypothesis are as follows:

- *None*

Hypothesis 2: Compressive Stress Does Not Contribute to the Corrosion Fatigue Damage Mechanism (Category A)

Background

A mechanistic basis for this hypothesis is as follows. The oxide film which forms on the surface of components is chemically inert so that once formed, it reduces the rate of further corrosion. If the film is mechanically damaged, more rapid corrosion can restart; enhanced corrosion would continue, with a rate that decreases with time until the surface is re-passivated, i.e. the surface oxide film is reformed. The surface oxide is a brittle layer so that it is mechanically weak in tension but mechanically strong in compression. Thus, mechanical damage to the oxide film is promoted by tensile stress but not by compressive stress.

All tests to date performed in the water environmental were either at an R ratio of -1 or at a positive R ratio and usually with a triangular waveform. For the R=-1 tests, the compressive and tensile part of each cycle were identical in terms of ramp rates and strain range. Therefore, it is not possible to differentiate between any supposed influences of tensile and compressive stress. For the positive R ratio tests, compressive stresses were not present. Thus the testing to date has not been able to demonstrate any beneficial influence of compressive stress which might exist.

Relevant Knowledge Gaps

The HIGH PRIORITY knowledge gaps which, if resolved, would contribute to the testing of this hypothesis are as follows:

- *None*

The MEDIUM PRIORITY knowledge gaps which, if resolved, would contribute to the testing of this hypothesis are as follows:

- *Gap 6 which states that stainless steels exhibit significant strain hardening and cyclic hardening so that a sharply defined yield stress does not exist. The Modified Goodman correction is used to adjust zero mean stress, fatigue endurance data to account for mean stress. The influence of using a higher yield stress in the Modified Goodman correction is to shift the influence of the mean stress correction towards low cycle fatigue. The extent to which this happens depends on the magnitude of the yield stress assumed.*
- *Gap 14 which states that the strain range and the associated number of cycles for which the consideration of environmental effects on fatigue is not required is based on zero mean stress test data only. The situation may be different for positive or negative mean stress. The lack of non-zero mean stress test data prevents this analysis being undertaken.*

The LOW PRIORITY knowledge gaps which, if resolved, would contribute to the testing of this hypothesis are as follows:

- *Gap 11 which states that there is likely to be a significant influence of mean stress on EAF which is not adequately quantified by existing test data.*

Hypothesis 3: Conservatism Due to the Use of Bounding Transients for Design Purposes is Sufficient to Accommodate Environmental Enhancement of Fatigue Damage (Category B)

Background

Fatigue analyses of pressure vessel and piping components are usually performed using design basis thermal cycle transients. Since the thermal cycles are defined well before plant construction and operation, they are often conservative and are intended to provide bounding fatigue usage values. One area of conservatism which commonly exists is the assumption of step change temperature transients (equivalent to thermal shock) which tends to overestimate the calculated thermal stress. It has been suggested on the basis of detailed thermal stress analyses with both bounding transients and realistic plant transients obtained from plant monitoring that the assumption of the temperature step change is very conservative. The conservatisms in stress analyses, using bounding transients, may more than compensate for the lack of an environmental enhancement factor in existing fatigue analyses.

An outcome of this hypothesis, if correct, is that no specific consideration of the influence of corrosion on fatigue damage may need to be made, provided that established design codes with bounding transients are used. However, such an approach would require validation for a range of transients and plant locations.

Relevant Knowledge Gaps

The HIGH PRIORITY knowledge gaps which, if resolved, would contribute to the testing of this hypothesis are as follows:

- *Gap 4 which states that the reasons for the apparent discrepancy between laboratory data and plant experience regarding the effects of environment on fatigue are not fully* *understood. Excessive conservatism in the current rules for design and/or the influence of complex loading may, at least in part, provide an explanation.*

- *Gap 35 which states that for many PWR and BWR plants, there is a lack of knowledge of actual plant transients which is important because of the sensitivity of EAF to temperature and strain rate variations.*

The MEDIUM PRIORITY knowledge gaps which, if resolved, would contribute to the testing of this hypothesis are as follows:

- *None*

The LOW PRIORITY knowledge gaps which, if resolved, would contribute to the testing of this hypothesis are as follows:

- *None*

Hypothesis 4: Conservatism in the Current Treatment of Non-Contiguous Cycles for Design Purposes May Partly Account for Environmental Influences on Fatigue (Category B)

Background

During plant design the precise order in which transients will occur is often unknown. Therefore, conservative assumptions are made. Pairs of cycles are identified which together constitute a larger strain range than the individual cycles treated separately. Such a cycle pair may be separated by a long period of time so that a number of less severe cycles will have occurred in between. It is generally accepted from fatigue test data that the application of high strain range cycles early in a cycle sequence is more damaging than random amplitude loading. Thus the design process does not account for the benefit of cycle sequencing which will be more random in practice. The observed benefit may be related to the negative mean stress which can occur for a large number of low strain range cycles and which may constitute a large proportion of the total fatigue damage. Negative mean stress has a different influence on the micro-cracking and macro-cracking phases of the crack initiation process. Moreover, the strain rate calculated for combined cycles may be lower than the true strain rate for individual cycles, leading to an overestimate of the environmental contribution to fatigue damage since the degree of environmental enhancement increases with decreasing strain rate. These conservatisms may be compounded by the Modified Goodman correction which is applied to the high cycle region of the design curve and which imposes the highest possible tensile mean stress correction to fatigue test data.

This hypothesis, if correct, suggests considerable conservatism in the design process which can partly account for the influence of corrosion on fatigue damage which is not specifically included. It may be unreasonable to apply corrosion fatigue influences to a non-contiguous cycle pair because of the time interval between them. Mechanistic substantiation for this statement would be required.

Relevant Knowledge Gaps

The HIGH PRIORITY knowledge gaps which, if resolved, would contribute to the testing of this hypothesis are as follows:

- *Gap 18 which states that there is no basis available for defining the treatment of non-contiguous cycle pairs with regard to both crack initiation and growth in LWR environments. This is because of a lack of mechanistic understanding on which to formulate rules and a lack of test data with which to validate them.*

The MEDIUM PRIORITY knowledge gaps which, if resolved, would contribute to the testing of this hypothesis are as follows:

- *None*

The LOW PRIORITY knowledge gaps which, if resolved, would contribute to the testing of this hypothesis are as follows:

- *None*

Hypothesis 5: Conservatism is Introduced in Plant Assessment Through the Use of Available Material Data which is Insufficiently Comprehensive in Terms of the Parameters Considered and the Range of those Parameters to Adequately Represent Realistic Plant Conditions (Category C)

Background

The large majority of the data which comprise the S-N database from which the NUREG/CR-6909 F_{en} factors were derived were obtained on wrought materials tested under fully reversed (R=-1) cyclic loading. The database does not cover the full range of materials and material grades used in plant worldwide, nor does it encompass metallurgical factors such as heat affected zones in welds[1]. Factors such as surface finish have only been studied in water environments to a limited extent. Corrosion fatigue must therefore be considered in the context of a wide range of materials and material conditions for which the material data base will be inadequate for the foreseeable future. Under such circumstances it is usual to make conservative assumptions concerning the application of materials data. Such assumptions may be compounded to arrive at an unduly conservative position. A large amount of material testing would be required to adequately account for all relevant circumstances.

Relevant Knowledge Gaps

The HIGH PRIORITY knowledge gaps which, if resolved, would contribute to the testing of this hypothesis are as follows:

- *Gap 3 which states that no comment is given in NUREG/CR-6909 on how the factor of 2 on stress was derived or why it is retained for both air and water environments. This issue requires resolution since the technical basis for design codes should be clearly understood.*
- *Gap 5 which states that the proposed new fatigue life curves for carbon and low alloy steels in water environments cover only high strength materials, whereas the current ASME curves cover also lower strength materials.*

[1] The recent reanalysis by ANL (presented at ASME Sub-group on Fatigue Strength, Nashville, May 2012) includes additional data and a wider range of material heats. It has not been possible to evaluate these additional data but it is judged that the statement made here still stands.

- *Gap 13 which states that comprehensive test data to define the environmental enhancement factor and encompassing the full range of relevant parameters as independent variables are not available.*
- *New Gap 46 which states that a universal, stakeholders' testing database should be established to provide a consistent basis for developments around the world.*

The MEDIUM PRIORITY knowledge gaps which, if resolved, would contribute to the testing of this hypothesis are as follows:

- *Gap 12 which states that conservatism is included in NUREG/CR-6909 concerning the derivation of the adjustment factor of 12, which is used to relate test endurance data in air to component endurance data. Insufficient data exist concerning the values for the individual factors which are combined and the means by which they should be combined.*
- *Gap 19 which states that further S-N tests are warranted to confirm the apparently differing influence of surface roughness between air and water environments. This may justify a reduction in the design margin applicable for components in water environments.*
- *Gap 20 which states in three parts as follows; (Part 1) - NUREG/CR-6909 acknowledges conservatism in its model regarding the influence of DO level. This particularly applies to some grades of stainless steel in high-DO water. Further refinement of the model to recognize an effect of DO (i.e. a difference between PWR and BWR/NWC) may be warranted; (Part 2) - There are no data on the influence of DO in PWR water containing boric acid and lithium hydroxide (i.e. under transient conditions); (Part 4) - Only limited data are available for BWR HWC. Whilst PWR data may be bounding, this remains to be established.*
- *Gap 20 (Part 3) states that the effect of steel sulfur content on fatigue initiation life of stainless steel has not been established – it has a substantial influence on fatigue crack growth rate.*
- *Gap 22 which states that the lack of relevant environmental crack growth data for some materials (e.g. Alloy 690 and its weld metals) or grades of material (e.g. Types 316L(N) or 347 stainless steel) represents a knowledge gap. Heat to heat variability also appears to be important, especially the influence of sulfur for stainless steel but is not adequately understood. There is also a lack of threshold ΔK data for many materials.*
- *Gap 24 which states that ASME XI does not include a fatigue crack growth law for wetted flaws in austenitic stainless steels. Fewer relevant data are available for BWR environment than for PWR although recent data suggest environmental effects are somewhat greater in BWR NWC than HWC or PWR (this is in contrast to S-N data).*
- *Gap 26 which states that some data are available for Alloy 600 and its weld metals which have enabled an assessment curve to be incorporated in ASME XI. Alternative curves have also been published which appear more conservative.*
- *Gap 27 which states that [only] very limited data are available for Alloy 690 [and its weld metals] (Alloy 52, 152 and variants).*
- *Gap 29 which states that reference crack growth curves are available covering both BWR and PWR environments for ferritic steels but do not explicitly represent the influence of all*

significant factors on the degree of enhancement such as DO concentration and transient rise time. For BWR HWC, ASME XI reference curves may be excessively conservative, but may be non-conservative for some BWR NWC conditions.

- *Gap 38 which states that whilst there are some data concerning the behavior of welded features, there is a lack of data to account for aspects such as geometric stress concentration factor, weld defects, residual stress and multiaxiality, all of which may be influential.*

The LOW PRIORITY knowledge gaps which, if resolved, would contribute to the testing of this hypothesis are as follows:

- *Gap 9 which states that the generic stainless steel inert fatigue design curve for stainless steels may prove difficult to apply since it appears to be too conservative in the high cycle fatigue regime for some materials. Material specific, high cycle Design Fatigue Curves may be preferred in some cases.*
- *Gap 10 which states that there is a lack of data concerning the definition of material specific thresholds for the occurrence of EAF. This is likely to contribute importantly to the identification of components for which consideration of environmental effects is not required. This is particularly so for stainless steel.*
- *Gap 21 which states that the existing data for nickel based alloys (Alloy 600, 182 and 82) are limited. NUREG/CR-6909 provides* F_{en} *factors for nickel based alloys based on these limited data and Regulatory Guide 1.207 recommends that these factors be applied to the new austenitic stainless steel air curve. Data on Alloy 690 and its weld metals are very limited.*
- *Gap 25 which states that the effects of parameters influencing when retardation of enhanced crack growth occurs are not adequately understood. The possibility of crack growth rate retardation is not evident in the available data for BWR environments.*
- *Gap 32 which states that existing uncertainties concerning SCC propagation behavior in Alloy 690 may have any implications for EAF, for which the available database is very limited.*
- *Gap 34 which states that very few data are available to establish the influence of PWR secondary water on EAF.*
- *Gap 37which states that data on weld metal are more limited than on parent materials but, where studied, appear to be bounded by parent data.*

Hypothesis 6: Conservatism is Introduced by the Calculation Methods Recommended for the Determination of F_{en} Factor which are Largely Unsubstantiated and Do Not Adequately Consider the Relevant Parameters and their Time Dependent Influences (Category C)

Background

The calculation methods necessary for corrosion fatigue assessments are more complicated than for non-corrosive environments because of the requirement to consider strain rate. It is conventional to introduce conservatism into assessments by over-estimating strain. However, this leads to an over-estimate of strain rate which is non-conservative in a PWR/BWR environment.

Several methods have been proposed for evaluation of strain rate for complex transients but validation of an appropriate approach is limited. As a result, simplistic methods are most commonly used. Undue conservatism may be introduced into corrosion fatigue calculation procedures where the definition of a conservative assessment approach is not necessarily obvious.

Relevant Knowledge Gaps

The HIGH PRIORITY knowledge gaps which, if resolved, would contribute to the testing of this hypothesis are as follows:

- *Gap 1 which states that there is a disparity between the lower bound values of F_{en} derived by NUREG/CR-6909 and the Japanese Environmental Fatigue Evaluation Method for Nuclear Power Plants (JSME S NF1-2009).*
- *Gap 7 which states that mechanistic understanding leads to the expectation that the degree of environmental enhancement of fatigue damage should depend on strain range. This is not consistent with the F_{en} factor approach.*
- *Gap 16 which states that test data supporting averaging procedures for complex non-isothermal transients are very sparse and this represents a significant uncertainty. Therefore, the averaging procedures are based largely on assumptions. Mechanistic understanding is required as a basis for identifying those parts of the cycle for which water environment is damaging. This understanding can then be used as the basis for developing averaging procedures, which should then be validated with test data involving cyclically variable parameters.*
- *Gap 17 which states that NUREG/CR-6909 recommends a 'modified rate approach' for which a unique F_{en} factor is determined for each cycle. Only very limited test data are available to substantiate the modified rate approach or the use of partial FUFs.*
- *Gap 23 which states that ASME XI does not include a fatigue crack growth law for wetted flaws. A Code Case has been proposed based on an extensive database but is not currently incorporated in the Code.*
- *Gap 36 which states that the basis for the selection of effective stress parameters for biaxial stress conditions is not established. Test data are required under conditions of biaxial loading for the treatment of plant thermal transients and non-proportional loading for combined thermal and mechanical transients. The most appropriate parameter may be different for the crack nucleation and subsequent propagation of microstructurally small cracks.*
- *Gap 39 which states that while methods for the determination of cycle effective strain rate can be proposed for conformance to ASME Code analysis, there are very few experimental data or plant data that can be used to validate the methods for use in corrosion fatigue assessments. Methods need to be consistent with mechanisms which operate under plant conditions.*
- *Gap 41 which states that interpreting a plant transient with variable strain rate in terms of the single strain rate curves is problematic, and no relevant guidance is available.*

- *New Gap 47 which states that the need exists to provide guidance on circumstances where the approach of NUREG/CR-6909 is not appropriate because of DO levels.*

The MEDIUM PRIORITY knowledge gaps which, if resolved, would contribute to the testing of this hypothesis are as follows:

- *Gap 40 which states that the method of stress indices commonly used for simplified piping analysis requires further development for corrosion fatigue assessments.*
- *Gap 44 which states that the extent to which mean stress influences both low cycle fatigue and high cycle fatigue of stainless steel in air, and an appropriate means by which is should be accounted for, are considered to be significant knowledge gaps.*
- *Gap 45 which states that there is a lack of understanding of the extent to which the inclusion of environmental effects on fatigue will influence inspection programs with regard to how to inspect, when to inspect and where to inspect.*

The LOW PRIORITY knowledge gaps which, if resolved, would contribute to the testing of this hypothesis are as follows:

- *None*

Hypothesis 7: Improved Mechanistic Understanding Would Identify Circumstances Where the Application of the F_{en} Factor Approach is Not Required (Category D)

Background

There is a general lack of mechanistic understanding for both fatigue initiation and fatigue crack growth in PWR/BWR environments. It is unrealistic to test all relevant conditions for all components to identify those circumstances in which corrosion fatigue does not occur or can be managed within existing design margins. Mechanistic understanding is required to extrapolate test data beyond the testing envelope within which the data was obtained.

Relevant Knowledge Gaps

The HIGH PRIORITY knowledge gaps which, if resolved, would contribute to the testing of this hypothesis are as follows:

- *Gap 31 which identifies several issues related to mechanistic understanding, as follows:*

  The mechanism of environmental enhancement is not well understood. Why does enhancement occur and why does crack growth rate sometimes retard?

  Several possible mechanisms for crack growth retardation have been proposed but it is unclear which are operative under specific conditions.

  There is a lack of understanding regarding the reasons for effect of sulfur content on crack growth. Does this also affect S-N behavior?

  Effects of flow rate appear to differ between S-N and crack growth testing.

  Reasons for different influence of DO/corrosion potential on S-N and crack growth behavior are not known.

The MEDIUM PRIORITY knowledge gaps which, if resolved, would contribute to the testing of this hypothesis are as follows:

- *Gap 30 which states that the mechanistic understanding [of crack growth for ferritic steels] is better than for austenitic SS but some uncertainties remain, e.g. influence of time dependent material deformation behavior, e.g. dynamic strain aging.*

The LOW PRIORITY knowledge gaps which, if resolved, would contribute to the testing of this hypothesis are as follows:

- *None*

4
PRIORITY 1 ROADMAP

Structure of the Priority 1 Road Map

A Priority 1 work program is identified from the Priority 1 gaps identified at the Focus Group Meeting [6]. The gaps are set into the context of the knowledge evaluation scheme in Figure 4-1.

The effort and timescale required to resolve each gap and complete the knowledge evaluation process is different. Some gaps require re-evaluation of existing data on the basis of new knowledge, some require extensive testing programs to acquire new data and others require evaluation of new data. There are also dependencies between gaps. These factors indicate the order in which work programs are ideally undertaken. Figure 4-2 gives a suggested sequence which accounts for the dependencies between them and the possibility of benefit being derived in the short term. The gap numbers relate to the order in which they were listed in the gap analysis report [1] and do not have any other significance.

The following gives a discussion of each individual gap to identify the context in which it arises, the research and development needs to be addressed, an outline of the test or evaluation program, the sequence in which the gap should be addressed and an anticipated outcome from closing the gap. A summary is given below of the possible final position from completion of the Priority 1 work program and knowledge evaluation.

Figure 4-1 (the knowledge evaluation process), Figure 4-2 (the suggested sequence) and the discussion below of each individual Priority 1 gap, together comprise the Priority 1 Road Map.

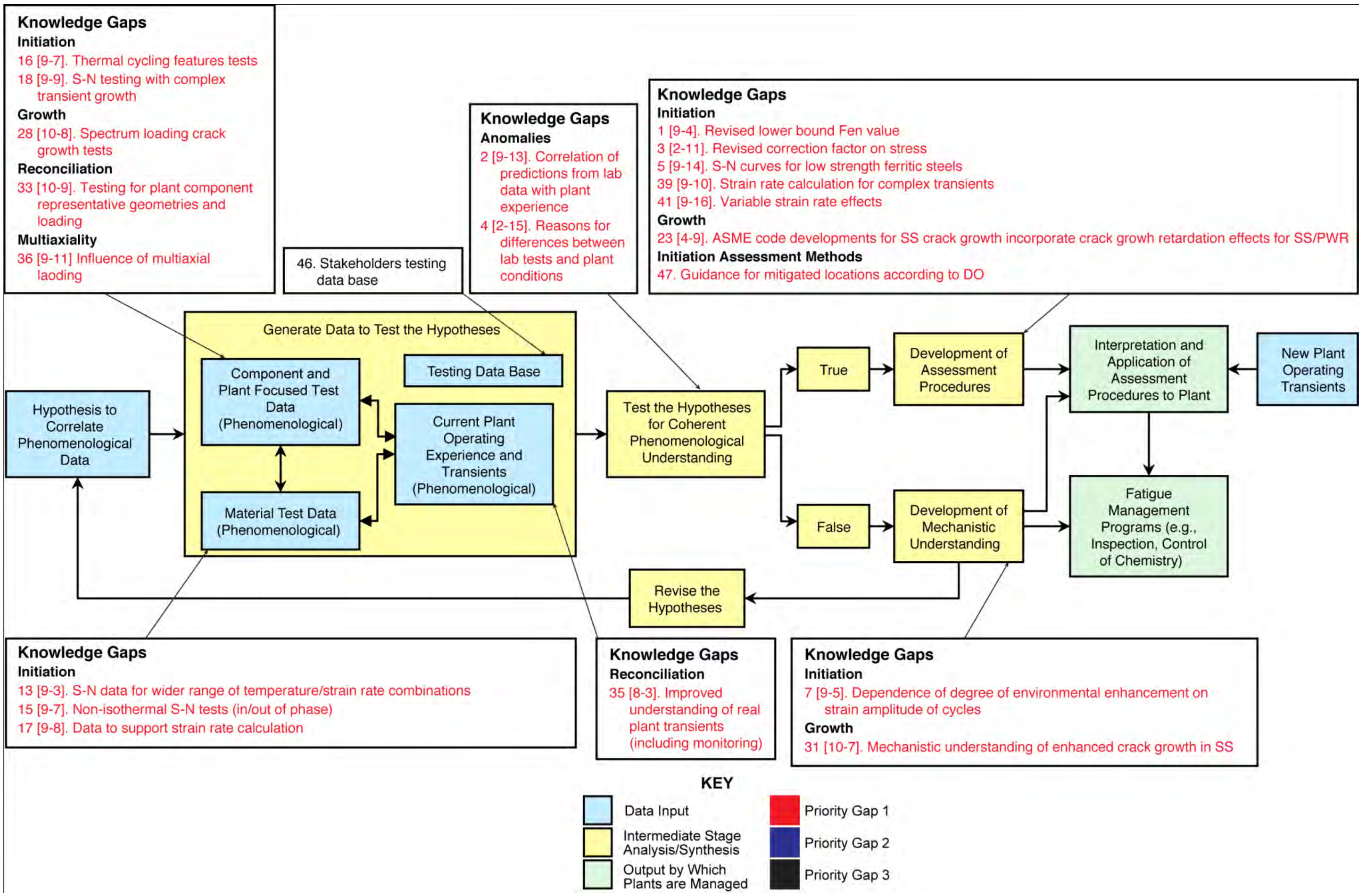

Figure 4-1
Knowledge Evaluation Scheme with Priority 1 Gaps Indicated

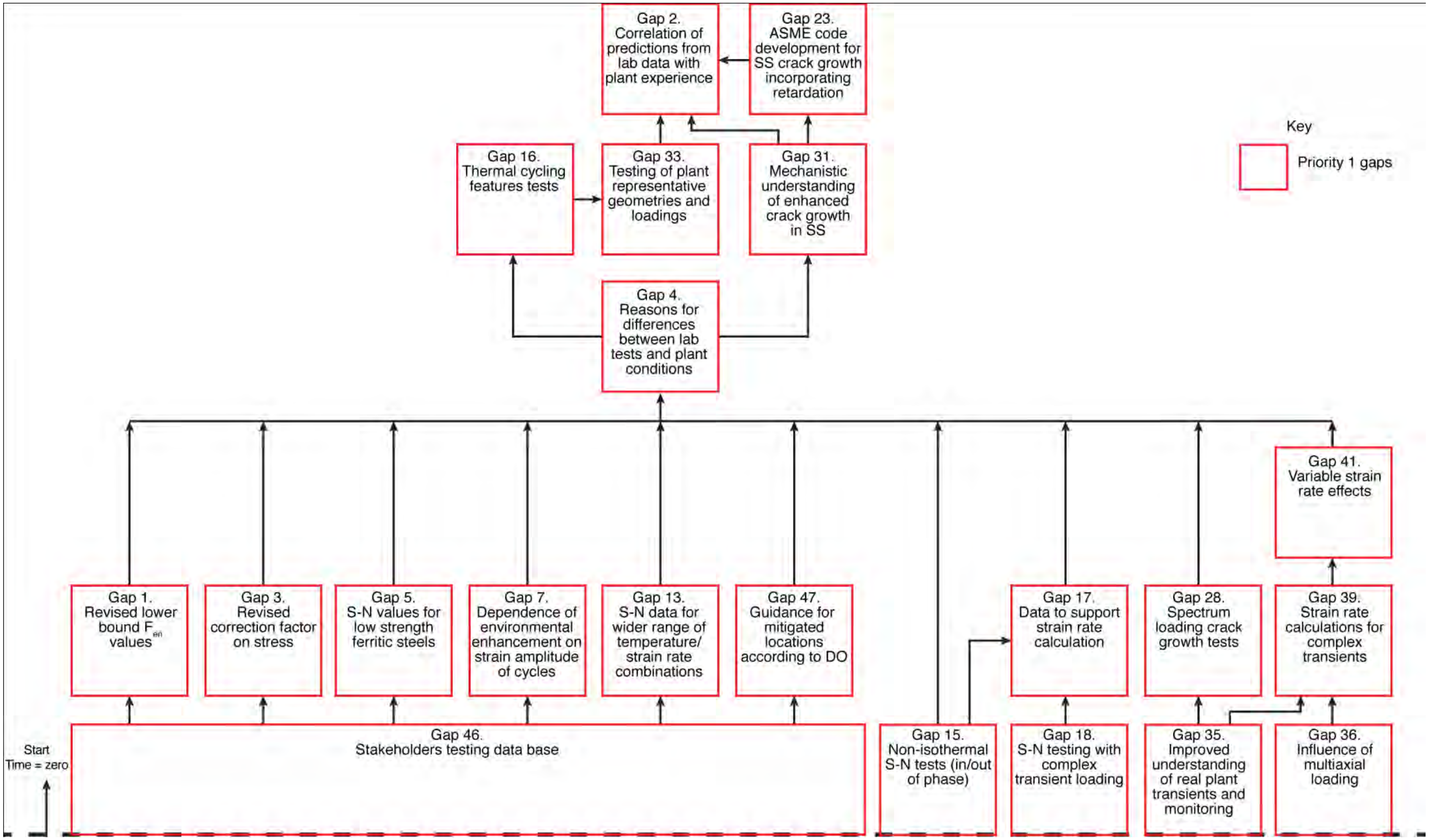

Figure 4-2
Priority 1 Gap Dependencies by Time Sequence

Summary of the Expected Outcomes

The outcome from the Priority 1 work program can be separated into three categories relating to short term benefits, intermediate term benefits and longer term benefits.

Short term benefits

Data may be identified which benefit designers, including circumstances where the influence of corrosion on fatigue damage is less marked or not relevant. Such benefits accrue from the re-evaluation of existing data and relate to:

1. correlations identified from the availability of a complete testing data base;
2. revision to the high cycle air fatigue design curve;
3. reduced environmental influence for low strain ranges;
4. possible mitigation due to close control of dissolved oxygen where NUREG/CR-6909 does not specify a threshold DO below which corrosion fatigue need not be considered[2].

Intermediate term benefits

Certain test programs can begin in the short term since they have no dependencies on other programs. These tests may identify circumstances by which the rules for the treatment of corrosion fatigue can be mitigated to reduce conservatism. These aspects relate to:

1. comparison of in-phase and out-of-phase S-N test data;
2. treatment of non-contiguous cycles;
3. evaluation of crack growth with more representative cycles.

Longer term benefits

The designs of certain test programs are dependent on the outcome of other work. Also, some evaluation tasks require input from the resolution of knowledge gaps. Benefits from these aspects will accrue over a longer term and relate to:

1. S-N data for a wider range of temperature and strain rate conditions;
2. test data to validate the ‘modified rate’ approach or alternative approaches;
3. evaluation of differences between test data and plant conditions;
4. thermal cycling features tests;
5. improved and substantiated assessment procedures, consistent with mechanistic understanding and plant operating experience.

[2] The expression for the F_{en} factor in NUREG/CR-6909 uses a transformed value of DO (O*). In an earlier NUREG report, O* was dependent on DO. In the current issue, DO is a constant value and therefore independent of DO.

Gap 1: Revised Lower Bound F_{en} Value

Gap 1 states that there is a disparity between the lower bound values of F_{en} derived by NUREG/CR-6909 and the Japanese Environmental Fatigue Evaluation Method for Nuclear Power Plants (JSME S NF1-2009)[3].

Hypothesis

This gap relates to Hypothesis 6 (Category C) and is allocated a HIGH PRIORITY

Context from the Gap Analysis [Page 9-4]

In NUREG/CR-6909, the F_{en} factor is determined quantitatively from transformed values of S*, T*, O* and $\dot{\varepsilon}*$ for ferritic steels and T', O' and $\dot{\varepsilon}'$ for stainless steels. These transformed values are subject to threshold values (except for S* and O') such that the transformed parameter is zero if its threshold value is not satisfied. NUREG/CR-6909 states that:

"For all steels, environmental effects on fatigue life are significant only when critical parameters (temperature, strain rate, DO level and strain amplitude[4]) meet certain threshold values. Environmental effects are moderate, e.g. less than a factor of 2 decrease in life, when any one of the threshold conditions is not satisfied."

The proposed rules adequately represent the above statement since when any one of T*, O* or $\dot{\varepsilon}*$ for ferritic steels or when either T' or $\dot{\varepsilon}'$ for stainless steels are set to zero, then the limiting F_{en} factor is close to 2.0. However, no alternative guidance is provided where none of the transformed parameters meet their threshold values. If none of the parameters which reduce fatigue life are operative, it may be appropriate that the fatigue life should not be reduced due to environmental effects, i.e. the F_{en} factor should be unity. The F_{en} factor formulation returns a F_{en} factor which is never less than ≈ 2.0, irrespective of the number of transformed parameters which do not meet their threshold values. It is noted that the Japanese procedure for calculating F_{en} (EFEM) returns a lower bound value which approaches unity as any one of the influencing parameters approach their bounding values.

Research and Development Need

Further analysis of available test data is required.

Outline Work Program

NRC has recently commissioned further work in this area and it is expected that changes may be proposed to address the current assumption of a minimum environmental enhancement factor of approximately 2 in NUREG/CR-6909.

Sequence

This work is in hand.

Outcome

[3] Referred to here and in the gap analysis report as EFEM.

[4] Note that strain amplitude is half the strain range for an R= -1 transient. The term 'strain range' is usually used in the current report.

Resolution of the anomalous position between the lower bound values of F_{en} derived by NUREG/CR-6909 and EFEM.

Gap 2: Correlation of Predictions from Laboratory Data with Plant Experience

Gap 2 states that there is a lack of correlation between expectations from laboratory test data and plant operating experience which does not give confidence in the methods which are being developed for the treatment of corrosion fatigue in LWR environments.

Hypothesis

This gap relates to all Hypotheses

Context from the Gap Analysis [Page 9-14]

Design and assessment procedures are based on the principle of similitude which states that observations of phenomena are transferable between components of different size and shape provided that differences in influences such as loading, boundary conditions, material properties, environment, etc are accounted for. Thus, the phenomenological observations of the behavior of test specimens, when sufficiently comprehensive, can be used to predict the behavior of plant components.

Field experience has been reviewed where a number of authors have reported failures of reactor components in LWR environments. There is no evidence available to specifically identify the mechanism of corrosion fatigue with plant failures. Failures have been attributed to related mechanisms [e.g. thermal fatigue, stress corrosion cracking, strain-induced corrosion cracking] or to the identification of cycles not identified and accounted for at the design stage. [This statement should not be taken to mean that corrosion fatigue has never occurred in plant, rather that the attribution of failure to this cause has not been made. The main point remains that substantially fewer fatigue related failures have occurred than would be expected based on predictions from laboratory data on small test specimens.]

Research and Development Need

A wide ranging investigation into the basis of the F_{en} factor, or similar, approaches, and their application to plant transient analysis is required.

Outline Work Program

Gap 2 is an anomalous position which may be resolved by addressing other gaps, and does not require a work program in itself. Gap 2 is resolved when observed outcomes and expected outcomes are consistent and in-line with mechanistic understanding.

Sequence

The resolution of Gap 2 follows from a knowledge evaluation process in line with the roadmap shown in Figure 4-1. Therefore, it is on-going throughout the Priority 1 work program. However, the final resolution depends on the evaluation of all knowledge including the evolution of Priority 1 work program and so is shown at the end of the dependencies sequence in Figure 4-2.

Outcome

The outcome will be improved assessment procedures which avoid undue conservatism, substantiated by test data and mechanistic understanding and correlating with plant operating experience.

Gap 3: Revised Correction Factor on Stress in the Design Fatigue Curve

Gap 3 states that no comment is given in NUREG/CR-6909 on how the factor of 2 on stress was derived or why it is retained for both air and water environments. This issue requires resolution since the technical basis for design codes should be clearly understood.

Hypothesis

This gap relates to Hypothesis 5 (Category C) and is allocated a HIGH PRIORITY

Context from the Gap Analysis [Page 2-12]

NUREG/CR-6909 identified conservatism in the adjustment factor on cycles which is used to adjust laboratory data to an industrial environment. This applies to both ferritic and austenitic materials. In NUREG/CR-6909, ANL evaluated the margins in the ASME design curves by examining factors that give rise to uncertainties and differences between real components and laboratory test specimens. Monte Carlo statistical analyses were conducted to develop fatigue design curves having a 95% confidence that the fatigue life of 95% of the population will be greater than that predicted by the design curves. These results indicated that, for carbon, low alloy steels and austenitic stainless steels, the current ASME requirement for a factor of 20 on cycles to account for the effects of material variability, data scatter, size, surface finish, and loading history, contain at least a factor of 1.7 conservatism. The modified design air fatigue curves presented in NUREG/CR-6909 incorporate a less conservative factor of 12 on cycles, rather than the factor of 20 prescribed by ASME. The factor of 2 on strain is retained unaltered. The factors of 20 or 12 on cycles predominantly influence the low cycle fatigue regime. The factor of 2 on strain predominantly influences the high cycle fatigue regime. Thus the ANL margin of 12 on cycles better reflects the ASME intent of predicting component failure without undue conservatism. However, this only applies to the low cycle fatigue regime since the factor of 2 on strain is unchanged.

Research and Development Need

Further review of the data underlying this methodology is warranted.

Outline Work Program

A review and analysis of existing data is required to identify whether or not a stress adjustment factor 2 is appropriate for stainless steel in an air environment. This links to New Gap 46, *the establishment of a stakeholders' testing data base,* and follows from it.

Sequence

The revised design curve for austenitic stainless steel is more restrictive for high cycle fatigue and is expected to be problematic for designers, even without the incorporation of corrosion influences. This gap should be addressed as soon as possible. This links to New Gap 46, *the establishment of a stakeholders' testing data base,* and follows from it.

Outcome

The outcome is a firmer basis for high cycle fatigue assessment, perhaps with a revised approach applied. The basis may demonstrate that corrosion influences are less marked or not relevant for high cycle fatigue. The revised approach could set limits on where Fen approach is applied and/or provide an alternative to the existing S-N curves.

Gap 4: Reasons for Differences Between Laboratory Tests and Plant Conditions

Gap 4 states that the reasons for the apparent discrepancy between laboratory data and plant experience regarding the effects of environment on fatigue are not fully understood. Excessive conservatism in the current rules for design and/or the influence of complex loading may, at least in part, provide an explanation.

Hypothesis

This gap relates to Hypothesis 3 (Category B) and is allocated a HIGH PRIORITY

Context from the Gap Analysis [Page 2-15]

An apparent reduction in fatigue initiation life is indicated by data from laboratory testing of small specimens in simulated LWR environments. These data undermine the validity of current fatigue design curves but, it has been asserted, this phenomenon is not reflected in reported nuclear plant component operating experience. The review of laboratory and component/structural fatigue test data establishes the need to reconcile laboratory data with real operating conditions. Data obtained from laboratory fatigue tests of component-like specimens has been cited in support of this position. Comparison of the observed number of cycles for crack initiation with the predicted number using the appropriate ASME design fatigue curve indicates that predicted CUFs are conservative, usually by a large margin.

Research and Development Need

The reasons for this apparent discrepancy require to be understood. Many of the research needs identified in the gap analysis are ultimately aimed at resolution of this issue.

Outline Work Program

This gap will be resolved by invoking the knowledge evaluation scheme with the outcomes from the work programs from other gaps, and does not represent a work package in itself.

Sequence

The sequence is shown in Figure 4-2.

Outcome

The outcome is a progressive understanding of the reasons for discrepancies between test data and plant behavior. This is an intermediate step towards providing rules for fatigue evaluation.

Gap 5: S-N Curves for Low Strength Ferritic Steels

Gap 5 states that the proposed new fatigue life curves for carbon and low alloy steels in water environments cover only high strength materials, whereas the current ASME curves cover also lower strength materials

Hypothesis

This gap relates to Hypothesis 5 (Category C) and is allocated a HIGH PRIORITY

Context from the Gap Analysis [Page 9-15]

Deliberations continue within ASME regarding how the fatigue design curves may be amended to account for EAF in LWR environments. A draft ASME CC N-792 has been developed to calculate an environmental enhancement factor (F_{en}) method which is used to modify existing design curves. The method proposed in the draft code case is very similar, but not identical to that in NUREG/CR-6909. The only difference is the omission of the threshold upper strain range criterion.

There is also an alternative proposal (ASME CC N-761) to redraw the current ASME Section III S-N curves to account for corrosion influences by bounding all relevant EAF laboratory data at given values of strain rate. A lower bounding design curve applicable for all strain rates is also proposed. This differs from the F_{en} approach in that the environmental correction factor is not necessarily the same at all values of strain range or cycles, which may provide more accurate description of behavior.

For stainless steel, a new air curve has been proposed which is also applicable to reactor water under restricted conditions of temperature and strain rate. This curve differs slightly from the 2010 ASME air curve and it is generally considered that it is unlikely to be adopted in the Code Case. A family of strain rate dependent water environment curves is provided for use where the restrictions are not met. The most restrictive of these curves, corresponding to the lowest quoted strain rate, can also be used as a bounding curve for all cases where the strain rate is not known.

Similarly, an equivalent set of curves are proposed for carbon and low-alloy steels. Carbon and low-alloy steel reactor water curves, in part based on differences observed in crack growth data, are provided for both low-strength and high-strength steels up to 10^6 cycles. Design curves, identical in air and water, are also suggested for carbon and low alloy steels in the high-cycle regime. The new curves are only provided for a UTS that has been defined in the range of 115-139 ksi whereas the current curves also address UTS<80 ksi and provide for interpolation between 80 and 115 ksi.

Research and Development Need

Additional assessment curves for low strength ferritic steels needs to be developed.

Outline Work Program

S-N curves for low strength (UTS <80 ksi) carbon and low-alloy steels in LWR water are required at temperatures appropriate to reactor operation.

Sequence

This links to New Gap 46, the *establishment of a stakeholders' testing data base,* and follows from it.

Outcome

The necessary S-N curves for low strength carbon and low-alloy steels in LWR environments will become available.

Gap 7: Dependence of the Degree of Environmental Enhancement on Cyclic Strain Range

Gap 7 states that mechanistic understanding leads to the expectation that the degree of environmental enhancement of fatigue damage should depend on strain amplitude. This is not consistent with the F_{en} *factor approach.*

Hypothesis

This gap relates to Hypothesis 6 (Category C) and is allocated a HIGH PRIORITY

Context from the Gap Analysis [Page 9-5]

In NUREG/CR-6909, a factor, F_{en}, is used to correct S-N curves obtained in air for the effect of an LWR environment. F_{en} is a function of several factors as described previously but does not depend on strain range. Fatigue failure of smooth test specimens can be considered to comprise two stages. Stage I, crack initiation, occurs to a crack depth of say 150 μm to 250 μm. Stage II crack propagation occurs up to specimen failure; say a crack depth of 3 mm. The two stages involve different mechanisms. In terms of the relative number of cycles for each stage, low cycle fatigue is dominated by Stage II (growth) and high cycle fatigue is dominated by Stage I (initiation). Since the dominant mechanisms for low cycle fatigue and high cycle fatigue in air are different, it may be expected that the mechanistic influence of a water environment would also be different. Therefore, the F_{en} factor is expected to be different for low cycle fatigue and high cycle fatigue, even where tests are performed at the same strain rate and temperature. Thus, mechanistic understanding suggests that the F_{en} factor should also depend on strain range.

Research and Development Need

Further analysis of available test data is required to determine the extent to which the environmental enhancement factor is a function of strain rate. If significant, an alternative to the F_{en} approach may be warranted. Note that the alternative ASME CC N-761 does not assume a constant environmental factor or all strain ranges.

Outline Work Program

A review and analysis of existing data is required to identify whether or not a strain range dependency of the F_{en} factor can be identified. There may also be a need to generate additional data at medium to high strain range. This links to New Gap 46, *the establishment of a stakeholders' testing data base,* and follows from it.

Sequence

This is a very important issue since it relates to the fundamental form of the environmental fatigue curves. This issue should be resolved as soon as possible. This links to New Gap 46, *the establishment of a stakeholders' testing data base*, and follows from it.

Outcome

The outcome will be F_{en} factor algorithms which are more representative of test data. A strain range has been identified, below which the F_{en} factor approach need not be applied. This represents a step change threshold on the influence of strain range. The identification of a more progressive influence would be of immediate benefit to the assessment of low strain range cycles which are above the currently strain range threshold. Mechanistic understanding will be enhanced if a link between strain range and F_{en} factor is established.

Gap 13: S-N Data for a Wider Range of Temperature/Strain Rate Combinations

Gap 13 states that comprehensive test data to define the environmental enhancement factor and encompassing the full range of relevant parameters as independent variables are not available.

Hypothesis

This gap relates to Hypothesis 5 (Category C) and is allocated a HIGH PRIORITY

Context from the Gap Analysis [Page 9-3]

The F_{en} factor formulations in NUREG/CR-6909 assume that where test conditions would simultaneously invoke a number of factors that each influence fatigue degradation, their combined effect is compounded from their individual effects. Evidence in support of this is not presented. Two examples follow:

For stainless steel in a LWR environment, data are presented in NUREG/CR-6909 which show the increasing degradation in fatigue life as temperature increases between 150°C and 325°C (*T'*), at a particular strain rate of 0.01%/s ($\dot{\varepsilon}'$). Also, data are presented which show the increasing degradation in fatigue life for strain rates reducing from 0.4%/s to 0.0004%/s ($\dot{\varepsilon}'$), for temperatures in the range of 288°C to 325°C (*T'*). Data accommodating this full range of temperature (*T'*) with this full range of strain rate ($\dot{\varepsilon}'$) are not believed to exist. This represents a significant knowledge gap. A similar situation exists for ferritic steels.

Research and Development Need

Further test data are required to cover a wider range of the independent variables of temperature and strain rate, which are relevant to the F_{en} factor definition.

Outline Work Program

The potential scope of work relates to crack initiation life data for carbon and low alloy steels, austenitic stainless steels and nickel-based alloys in BWR and PWR water environments. The exact range of strain rate and temperature conditions for which data are required depends on evaluation of the scope of data compiled in support of New Gap 46.

Sequence

This links to New Gap 46, *the establishment of a stakeholders' testing data base*, and follows from it.

Outcome

The completion of this test program will allow comprehensive and valid F_{en} factor algorithms to be derived which adequately account for the required range of influencing parameters.

Also, Hypothesis 3 may be tested relating to the conservatism inherent in the use of bounding transients with very high strain rates.

Gap 15: Non-Isothermal Test Data, In-Phase and Out-of-Phase are Required

Gap 15 states that limited data are available on the influence of variable temperature and variable strain rate within test cycles and of the influence of out-of-phase variations of temperature and strain rate.

Hypothesis

This gap relates to Hypothesis 1 (Category A) and is allocated a HIGH PRIORITY

Context from the Gap Analysis [Page 9-7]

The majority of fatigue damage to a LWR plant is attributable to thermal cycling so that individual fatigue cycles experience variable temperature, variable strain rate and variable stress which can alternate between tension and compression. Guidance is provided in NUREG/CR-6909 on procedures which may be adopted when parameters vary around a cycle. It is noted that the procedure requires determination of a cycle specific F_{en} factor based on the average or weighted average of the influencing parameters around the cycle. Test data supporting averaging procedures for treatment of cyclically varying temperature, strain rate and stress (tension or compression) are sparse and this represents a significant uncertainty. There is a need to understand real behavior under temperature variable conditions.

Consider as an example the following thermal transient cycle. A thermal down-ramp is suddenly applied to a surface. The strain rate is initially high (minimizing the corrosion influence), the strain rate is positive (maximizing the corrosion influence) and the temperature is reducing (minimizing the corrosion influence). The rapid thermal down-ramp is then followed by a gentle thermal up-ramp to complete the cycle. The strain rate is initially low (maximizing the corrosion influence), the strain rate is negative (minimizing the corrosion influence) and the temperature is increasing (maximizing the corrosion influence).The cycle is complex and the various influencing parameters are changing up and down together in a non-linear relationship. The specific details of the averaging procedure used can have a profound effect on the predicted outcome. It can easily be envisaged that two such cycles with different parametric rates can have the same calculated F_{en} factor, but be behaving quite differently with regard to corrosion fatigue damage.

Research and Development Need

Testing with mixed thermal/mechanical loading both in and out of phase is required. Resolution of this issue is likely to prove difficult, but there is the potential to realize significant benefit.

Outline Work Program

Tests are required which focus specifically on the influence on fatigue initiation of in-phase and out-of-phase, temperature and strain variations without introducing other factors. A suggested test program is as follows: Using uniaxial test specimens in a water environment, isothermal, constant strain range tests are required at two temperatures, a low temperature and a high temperature. Also, tests at the same strain range are required where the temperature varies between the low temperature and the high temperature, in-phase with the strain variation or out-of-phase with the strain variation. In this test matrix, the influence of in-phase and out-of-phase temperature and strain variations is uniquely identified by comparison with the isothermal tests. The test matrix should be repeated at different strain ranges to check the generality of the outcome.

The knowledge gap relates to crack initiation in PWR and BWR water environments, in carbon and low alloy steels, austenitic stainless steel and nickel based alloys. However, the issue is fundamental to the effects of temperature/strain phasing so that progress could be made in the first instance by concentrating on one particular material and one particular water environment. Austenitic stainless steels in PWR coolant chemistry are judged the highest priority. Subsequently, validation tests would be required with other materials and environments to confirm the general applicability of knowledge gained or to modify it as appropriate.

Sequence

These tests do not depend on the outcome from closing other knowledge gaps and so can begin independently.

Outcome

The completion of this work program will test Hypothesis 1 which states that the nature of thermally induced out-of-phase cycling is fundamentally different to in-phase or isothermal cycling which has been the basis of test data to date.

If this hypothesis is demonstrated to be true, a significant development in mechanistic understanding will result. It may be possible to identify much more clearly those parts of a strain-time history which contribute to corrosion fatigue damage, and those parts which do not. This may lead to screening rules which identify those parts of strain-time histories which need not be considered or cycle types which need not be considered.

The outcome will inform the design of thermal cycle features testing (Gap16), which should be performed subsequently. Also the outcome will inform the design of tests to support strain rate calculations (the modified rate approach, Gap 17), which should be performed subsequently.

Gap 16: Thermal Cycling Features Tests

Gap 16 states that test data supporting averaging procedures for complex non-isothermal transients are very sparse and this represents a significant uncertainty. Therefore, the averaging procedures are based largely on assumptions. Mechanistic understanding is required as a basis for identifying those parts of the cycle for which water environment is damaging. This understanding can then be used as the basis for developing averaging procedures, which should then be validated with test data involving cyclically variable parameters.

Hypothesis

This gap relates to Hypothesis 6 (Category C) and is allocated a HIGH PRIORITY

Context from the Gap Analysis [Page 9-7]

The majority of fatigue damage to a LWR plant is attributable to thermal cycling so that individual fatigue cycles experience variable temperature, variable strain rate and variable stress which can alternate between tension and compression. Guidance is provided in NUREG/CR-6909 on procedures which may be adopted when parameters vary around a cycle. It is noted that the procedure requires determination of a cycle specific F_{en} factor based on the average or weighted average of the influencing parameters around the cycle.

Research and Development Need

Features tests can involve a number of aspects not included in standard S-N material tests such as geometric stress concentrating features, weldments, material mismatch, biaxial stress states, residual stress, non proportional loading, etc. Some of these aspects could be addressed using mechanical loading without the complication of thermal cycling features tests. Smaller scale features testing with control of temperature cycling would support further mechanistic understanding and enable the refinement of averaging rules for complex cycles. They would be complimentary to the non-isothermal small specimen tests identified as Gap 15.

Outline Work Program

Detailed consideration needs to be given to the requirements and scope of a features test program. The objective may be to perform more complex tests to consider the combined effects of individual issues considered in other gaps, e.g. the correction factor on stress (Gap 3), the influence of strain range (Gap 7), mitigation according to DO (gap 47), in-phase and out-of-phase loading (Gap 15), non-contiguous cycling (Gap 18) or spectrum loading (Gap 28). Alternatively, the objective may be to consider the influence of other aspects which relate to plant components such as such as stress concentrating features, material miss-match and stress state. Further tests similar to the Bettis testing with welded pipe fittings and thermal cycling would be helpful in simulating more realistic plant conditions and validating averaging procedures for practical cases.

The knowledge gap relates to crack initiation in PWR and BWR water environments, in carbon and low alloy steels, austenitic stainless steel and nickel based alloys. However, the issue is fundamental to the application of assessment procedures to practical cases so that progress could be made in the first instance by concentrating on one particular material and one particular water environment. Subsequently, validation tests would be required with other materials and environments to confirm the general applicability of knowledge gained or to modify it as appropriate.

Sequence

The first activity should be a detailed evaluation of requirements to define the scope of the proposed testing program. The design of the testing equipment will be challenging, especially when thermal cycling is required, and should begin as soon as the objectives of the study have been adequately defined. Where the objective of the work program is to consider the combined influence of individual issues considered in other gaps, then the work program follows from addressing those gaps, i.e. Gaps 46, 3, 7, 47, 13, 15, 18, 28, 17 and 4 where the objective is to consider aspects relating to plant components not addressed in those gaps, then the work can begin earlier.

Outcome

Validated and less conservative averaging procedures for complex cycles could result.

Improved mechanistic understanding may suggest alternative methods for assessing corrosion fatigue damage. For example, fatigue damage and corrosion damage may be determined independently from a strain-time history. The fatigue damage is determined by partitioning the strain-time history into cycles in the normal way. The corrosion damage is determined by identifying those time intervals in the strain-time history when corrosion damage can occur, and performing a time fraction damage summation. Total damage is the sum of fatigue damage plus corrosion damage plus an additional damage fraction from fatigue/corrosion interaction. By analogy with creep-fatigue assessment, ASME III-NH may provide a better basis than ASME III-NB for the incorporating such a methodology into plant design.

An early indication would be gained of the applicability of improved assessment methods to components with more realistic features relating to geometry, material combinations and stress states.

Gap 17: Data to Support Strain Rate Calculations

Gap 17 states that NUREG/CR-6909 recommends a 'modified rate approach' for which a unique F_{en} factor is determined for each cycle. Only very limited test data are available to substantiate the modified rate approach or the use of partial FUFs.

Hypothesis

This gap relates to Hypothesis 6 (Category C) and is allocated a HIGH PRIORITY

Context from the Gap Analysis [Page 9-8]

The aim of the 'modified rate approach' described in NUREG/CR-6909 is to determine a unique F_{en} factor for each cycle. The total strain range for the cycle is divided into a number of strain range increments and the incremental F_{en} factor for each strain increment is determined according to the instantaneous strain rate and temperature associated with the increment and weighted by the ratio of the increment strain range to the total strain range. The F_{en} factor for the cycle is then determined as the sum of the F_{en} increments.

In Appendix A of NUREG/CR-6909 the use of partial FUFs is also specified. A partial FUF is calculated for each type of stress cycle and multiplied by a F_{en} factor specific to that type of stress cycle. Guidance is given on the determination of the cycle specific F_{en} factors. The understood intent is that environmental effects occur during up-ramp with increasing strain, irrespective of whether the stress is tension or compression. However, the wording in NUREG/CR-6909 is ambiguous. The following points are noted:

1. An average strain rate for the transient yields a conservative result.
2. For the case of a constant strain rate and linear temperature response, an average temperature (i.e. the average of the maximum and minimum temperatures for the transients) may be used.

Research and Development Need

Test data to validate the 'modified rate approach' or an alternative procedure are required.

Outline Work Program

The detailed design of these tests depends on the outcome of in-phase and out-of-phase tests (Gap 15), and cycle sequencing tests (Gap 18) and follow from them. Specific rules for the treatment of cyclically variable temperature and strain may be proposed and tested here using complex temperature controlled and strain controlled tests with uniaxial specimens. The data should include compressive mean stress and positive R ratios. Significant effort will be required to design the equipment to perform such tests.

The knowledge gap relates to crack initiation in PWR and BWR water environments, in carbon and low alloy steels, austenitic stainless steel and nickel based alloys. However, the issue is fundamental to the effects of temperature/strain phasing so that progress could be made in the first instance by concentrating on one particular material and one particular water environment. Subsequently, validation tests would be required with other materials and environments to confirm the general applicability of knowledge gained or to modify it as appropriate.

Sequence

Testing cannot sensibly start until the outcome from addressing Gap 15 and Gap 18 are known, since these will inform the type of cycle which needs to be considered. However, the design of the test equipment can begin earlier than this, and is not dependent on the closure of any other knowledge gap.

Outcome

For those plant cycles where a corrosion fatigue damage enhancement factor is required, these tests will enable the validation of the ‘modified rate approach’, or the development of alternative procedures.

This work program will also contribute to the testing of Hypothesis 2, relating to the influence of compressive mean stress.

Gap 18: S-N Data for a Wider Range of Temperature/Strain Rate Combinations

Gap 18 states that there is no basis available for defining the treatment of non-contiguous cycle pairs with regard to both crack initiation and growth in LWR environments. This is because of a lack of mechanistic understanding on which to formulate rules and a lack of test data with which to validate them.

Hypothesis

This gap relates to Hypothesis 4 (Category B) and is allocated a HIGH PRIORITY

Context from the Gap Analysis [Page 9-9]

For plant design purposes, individual transients can be defined but the order of transients may be unknown. Consequently it is common practice to combine cycles by identifying transient pairs which represent a thermal up-ramp and a thermal down-ramp and which taken together, represent the most severe stress range cycles which could possibly occur. Such transient pairs can be separated in time by a number of years. The application of the F_{en} model to such a transient pair would require that the F_{en} factor is derived for each part of the combined cycle separately, having accounted for the appropriate parameter averaging for each part cycle, and then the maximum F_{en} factor applied to the fatigue damage based on the total strain range of the entire combined cycle.

The application of a single F_{en} factor to transient pairs which are not contiguous may be unrealistic. It is also unclear how to define the strain rate for such a cycle. The approach leads to practical problems for plant analysis. Without the environmental influence, the up-ramp having the maximum tensile stress range is combined with the down-ramp having the maximum compressive stress range to determine the maximum total stress range, and hence identify the cycle with the maximum fatigue damage. Such a transient pair may not produce the maximum damage with F_{en} factors included since other transient pairs with lower stress ranges may have higher F_{en} factors. Therefore, it appears to be necessary to compare every possible up-ramp transient with its F_{en} factor to every possible down-ramp with its F_{en} factor, in order to identify the pair with the maximum possible damage. This is not a practicable approach for plant assessment purposes where ≈ 100,000 transients may need to be considered.

Research and Development Need

Mechanistic understanding is required as a basis for formulating rules for the treatment of non-contiguous cycles or for developing an alternative approach. Validation testing with complex transient loading should be performed compared with predictions of current assessment methods for EAF.

Outline Work Program

Water environment material tests are required in which high strain range cycles are separated by long hold times and alternatively, separated by long hold times and interjected with a number of low strain range cycles. Such cycle sequences provide an idealized representation of actual plant transient combinations sequences. By comparison to continuous cycling tests, such hold time and mixed cycle tests will identify whether hold time add or subtract from cycle interaction and the influence of cycle sequencing. The knowledge gap relates to crack initiation in PWR and BWR water environments, in carbon and low alloy steels, austenitic stainless steel and nickel based alloys. However, the issue is fundamental to the effects of cycle sequencing so that progress could be made in the first instance by concentrating on one particular material and one particular water environment. Subsequently, validation tests would be required with other materials and environments to confirm the general applicability of knowledge gained or modify it as appropriate.

Sequence

These tests do not depend on the outcome from closing other knowledge gaps and so can begin independently.

Outcome

The completion of this work program will test Hypothesis 4 which states that the current treatment of non-contiguous cycles for design purposes is conservative and partly accounts for corrosion fatigue influences. The outcome will contribute to mechanistic understanding and may lead to much less conservative assessment procedures for incorporating corrosion fatigue influences. The outcome will also inform the design of thermal cycling features tests which should be performed subsequently.

Gap 23: ASME Code Developments for Stainless Steel Crack Growth in PWR Environments

Gap 23 states that ASME XI does not include a fatigue crack growth law for wetted flaws. A Code Case has been proposed based on an extensive database but is not currently incorporated in the Code.

Hypothesis

This gap relates to Hypothesis 6 (Category C) and is allocated a HIGH PRIORITY

Context from the Gap Analysis [Page 2-13, 2-15, 4-2, 9-17, 10-4]

An analysis has recently been performed of corrosion fatigue crack growth data of type 304 and 316 stainless steel in high temperature deaerated water, including power generation PWR and other environments. The majority of the data included were from the UK, USA and Japan and covered a range of ΔK values, stress ratios (R>1), rise times and temperatures. Several deficiencies with the testing database were identified as follows:

- The data sets are unbalanced where the test parameters were not systematically varied. This is an inherent problem in corrosion fatigue testing as excessive test times preclude the systematic evaluation of critical parameters.
- The data sets were generated over narrow and non-overlapping ranges of ΔK. This means that regression analysis must be performed with a common ΔK exponent so that the influence of R ratio, rise time and temperature can be evaluated, even though the fatigue crack growth rates were evaluated in different ΔK regimes.
- There is considerable data scatter as fatigue crack growth rate varies by orders of magnitude. Much of this scatter is due to the fact that, whilst cyclic growth rates generally increased with increasing rise time, in some cases retardation of the enhanced rates was observed as the rise time was increased further. To handle data scatter in the regression analysis, data showing "severe" crack growth rate retardation were not included. Consequently, for lower ΔK values and/or very long rise times, the predicted crack growth rate may be excessively conservative.

An ASME Code Case N-809 for PWR environments has been proposed and is based on the above analysis, although some minor changes are being incorporated following Code Committee discussions. One suggestion being considered is to include a maximum rise time threshold above which no further increase in environmental enhancement occurs. The basis for this threshold is unclear.

Research and Development Need

There is a need to follow ASME CC developments and consider the need for further data to support development of the draft CC. It should be noted that there is currently no plan to include retardation effects in the ASME Code Case; this issue is identified under Gap 25 (uniform cyclic loading) and Gap 28 (spectrum loading). The suggested inclusion of a maximum rise time threshold may have a similar effect, although may not be conservative under all conditions.

Outline Work Program

This gap will be resolved over a period of time by evaluating and re-evaluating data and information as it becomes available from the resolution of other gaps.

Sequence

The resolution of this gap is an ongoing task, primarily dependent on the rate at which Gap 31 is resolved, *mechanistic understanding of enhanced crack growth in SS* and the rate at which Gap 4 is resolved, *reasons for differences between laboratory tests and plant conditions*. These gaps follow from the resolution of all or some of Gaps, 46, 15, 18, 35, 36, 3, 7, 47, 13, 1, 5, 17, 28, 39 and 41, as shown in Figure 4-2.

Outcome

Improved and validated methods, incorporating mechanistic understanding, for the treatment of crack growth in stainless steel with PWR environments.

Gap 28: Spectrum Loading Crack Growth Tests

Gap 28 states that very few data are available under plant representative loading conditions and the influence of complex loading conditions (including hold times and spectrum loading) waveforms and combined loading are not well quantified.

Crack growth data are obtained under isothermal conditions whereas many plant transients involve simultaneous temperature and load cycling (either in- or out-of-phase).

Hypothesis

This gap relates to Hypothesis 1 (Category A) and is allocated a HIGH PRIORITY

Context from the Gap Analysis [Page 10-8]

For all materials, very limited data are available on the effects of complex loading conditions more representative of plant transients. There are some indications that spectrum loading behavior may not always be as severe as predicted from simple cyclic data. Beneficial effects of hold time on retardation have been observed in some crack growth studies on stainless steel under PWR conditions and ferritic steels under BWR conditions. However, there appear to be inconsistencies between data in different laboratories and these warrant further quantification. Some plant transients involve negative R loading and data to cover this regime are required. The influence of transient waveforms (triangular, sine, exponential etc.) is also not well quantified.

Crack growth data are obtained under isothermal conditions whereas many facility plant transients involve simultaneous temperature and load cycling (either in- or out-of-phase). Some testing to identify the significance of this difference is recommended.

There is no clear reported evidence from plant operation that enhanced crack growth rates in water environments have been observed. However, crack growth arguments are sometimes used when fatigue usage factors exceed unity. The need for crack growth arguments will become more acute where the consideration of environmental influences increases the rate of fatigue initiation damage. The enhanced crack growth data for stainless steel being codified into ASME

XI will prove very restrictive. Therefore, the need exists to clearly understand the circumstances under which crack growth rate retardation occurs.

Research and Development Need

Further crack growth tests are required to investigate the influence of different loading waveforms and better represent the temperature and loading conditions experienced in real plant.

Outline Work Program

Crack growth tests using simplified waveforms such as triangular are required to investigate behavior under non-isothermal conditions with load and temperature in-phase and out-of-phase. Hold times at the high temperature regime or low temperature regime should be included. Isothermal testing using cycle combinations should also be carried out, e.g. sequences of one or more low R cycles followed by hold periods or multiple high R cycles. The results should be compared with predictions from single frequency, constant cycle amplitude tests for each of the components of the complex cycle.

The knowledge gap relates to crack initiation in PWR and BWR water environments, in carbon and low alloy steels, austenitic stainless steel and nickel based alloys. However, the issue is fundamental to the effects of temperature/strain phasing so that progress could be made in the first instance by concentrating on one particular material and one particular water environment.

Subsequently, further tests are required with other materials and environments and with plant realistic load cycles to confirm the general applicability of knowledge gained and to obtain the necessary crack growth data.

Sequence

This links to Gap 35, *improved understanding of real plant transients through monitoring,* and follows from it.

Outcome

The outcome may be more representative rules for considering the influences on crack growth in a water environment of representative waveforms, cycle sequencing, negative R ratio and hold times. On the basis of limited present understanding, these rules will be less conservative.

Gap 31: Mechanistic Understanding of Enhanced Crack Growth in Stainless Steel

Gap 31 identifies several issues related to mechanistic understanding, as follows:

> *The mechanism of environmental enhancement is not well understood. Why does enhancement occur and why does crack growth rate sometimes retard?*
>
> *Several possible mechanisms for crack growth retardation have been proposed but it is unclear which are operative under specific conditions.*
>
> *There is a lack of understanding regarding the reasons for effect of sulfur content on crack growth. Does this also affect S-N behavior since a significant proportion of the cycles to fail in S-N tests involve fatigue crack growth, particularly for low cycle fatigue?*
>
> *Effects of flow rate appear to differ between S-N and crack growth testing.*

Reasons for different influence of DO/corrosion potential on S-N and crack growth behavior are not known.

These observations relate specifically to PWR data; there are insufficient data under BWR conditions to determine their relevance; the knowledge gap can therefore be considered to apply to both PWR and BWR.

Hypothesis

This gap relates to Hypothesis 7 (Category D) and is allocated a HIGH PRIORITY

Context from the Gap Analysis [Page 10-7]

For stainless steels, no curves are available in ASME Section XI for water wetted defects. However, the available fully enhanced data in PWR environments are fairly well described and form the basis for the ASME Code Case N-809 now being developed. Data in BWR environments are somewhat more limited but appear to follow similar trends with regard to rise time dependency; recent data suggest that growth rates are slightly higher than in PWR environments; this observation differs from the observed effects on fatigue initiation life. In some instances, the fully enhanced crack growth rates in PWR environments are not observed, with retardation of crack growth to rates quite close to the ASME air line occurring with an increase in rise time. The factors influencing retardation are not sufficiently well characterized to allow benefit to be claimed in assessment procedures, but there are indications of an influence due to variations in R ratio, temperature, coolant flow rate and material composition. High sulfur content steels have been shown to be particularly prone to retarded crack growth, although the reasons are not adequately understood. More data and improved understanding are required if benefit is to be demonstrated from retarded rates, although material composition effects may make it difficult to provide generalized substantiation of retardation. No sources of data have been identified that show similar retardation under BWR normal water chemistry conditions.

Research and Development Need

Mechanistic understanding is necessary to explain the apparent discrepancy between field and laboratory data. Specific areas to be addressed could include:

- Mechanisms of retardation of enhanced crack growth.
- Is hydrogen generated by corrosion implicated in enhancement?
- Reasons for influences of material composition, e.g. sulfur content on crack growth enhancement/retardation.
- Relevance of low and high flow rate laboratory data to plant conditions.

Outline Work Program

Although some insight into the factors influencing corrosion fatigue will arise from ongoing data generation activities in support of other gaps, it is considered that some specific mechanistically focused work is necessary to understand the reasons for some of the observed dependencies. The detailed scope of the work requires further definition. However, studies aimed at characterization of crack tip oxides for high and low sulfur steels, measurements of the influence of material composition on creep in air and high temperature water, and further work on flow rate effects may be considered.

Sequence

Mechanistically focused tests are not dependent on studies in support of other gaps. Additional insight will arise from work in support of other gaps. The resolution of this gap is therefore an on-going task, primarily dependent on the rate at which Gap 4 is resolved, *reasons for differences between laboratory tests and plant conditions*. Gap 4 itself follows from the resolution of all or some of Gaps, 46, 15, 18, 35, 36, 3, 7, 47, 13, 1, 5, 17, 28 , 39 and 41, as shown in Figure 4-2.

Outcome

Improved mechanistic understanding will result, giving confidence in the basis for design code developments and giving means by which design codes can be interpreted for specific situations.

Gap 33: Testing for Geometries and Loading Representative of Plant Components

Gap 33 states that more data using component like features with plant representative loading conditions are required to develop and validate methods for considering corrosion fatigue in LWR environments.

Hypothesis

This gap relates to Hypothesis 1 (Category A) and is allocated a HIGH PRIORITY

Context from the Gap Analysis [Section 7 and Page 9-14]

Despite the apparent mismatch between laboratory data and operating experience, there have been relatively few experimental studies performed to understand the disparity. Available test data obtained with test specimens having geometric and loading features similar to plant components are limited. Some correlations with plant operating experience have been noted, although the tests are complex to perform, limited in number and in some cases difficult to interpret. For example, the Bettis stepped pipe tests using thermal transients resulted in substantially greater numbers of cycles to failure than predicted by the NUREG/CR-6909 F_{en} procedures. In contrast, the Areva mechanically loaded U-bend tests showed a substantial environmental effect, with both crack location and orientation differing in air and high temperature water. Nevertheless, the outcome from these tests, taken together, indicates that a significant benefit would be obtained from further component or features type testing.

Research and Development Need

Analysis is required to identify conditions needed for testing to simulate plant conditions. This will involve focused testing on geometries representative of components. This should include conventional constant amplitude cyclic loading as well as more plant relevant transient conditions, simulated by mechanical cycling. Testing should accurately simulate plant water chemistry, including transient chemistry where appropriate. Testing under thermal cyclic loading is considered separately under Gap 16. Testing of standard specimens under plant relevant spectrum loading (Gap 28) also supports this need.

Outline Work Program

These tests to address Gap 33 compliment those to address Gap 16. Whereas Gap 16 addresses the influence of local features such as geometric stress concentration factors, weldments and material mismatch, Gap 33 concentrates more on component representative geometries, loadings, and environments. The tests here could consider geometries such as a U bend with complex, thermomechanical, non-proportional loading, with transient water chemistry.

These tests are essentially proving tests to consolidate and verify knowledge gained in the resolution of other gaps. Therefore, more specific proposals for an outline work program are not appropriate at the present time.

Sequence

The interpretation of these tests relies extensively on the knowledge gained from the resolution of the Priority 1 Gaps and Priority 2 Gaps 12, 19 and is dependent on them. Therefore, these tests are sensibly performed as the last in the sequence following Priority 1 and Priority 2 issues.

Outcome

Confidence will be gained in the validity of plant assessment procedures and fatigue management programs.

Gap 35: Improved Understanding of Real Plant Transients Including Monitoring

Gap 35 states that for many PWR and BWR plants, there is a lack of knowledge of actual plant transients which is important because of the sensitivity of EAF to temperature and strain rate variations.

Hypothesis

This gap relates to Hypothesis 3 (Category B) and is allocated a HIGH PRIORITY

Context from the Gap Analysis [Page 8-2 to 8-3]

It is common practice to use bounding thermal transients for reactor design purposes, which in some instances could lead to the conservative assumption of step changes, rather than ramp changes, in fluid temperature. It has been claimed by some that there is sufficient compounded conservatism in the ASME design fatigue curves, the ASME design by analysis calculation procedure and the use of bounding transients, such that no additional measures to account for EAF are necessary.

Plant monitoring to determine actual plant thermal transients is not widespread. The most extensive use of plant transient monitoring is in existing German LWR plants where long term thermal transient monitoring has been carried out and may provide justification against the punitive effects of introducing large environmental enhancement factors.

Research and Development Need

Conservatism is introduced into the assessment of thermal transient cycles by the use of bounding transients involving step changes in temperature. However, this maximizes strain rate which is non-conservative for the evaluation of F_{en} factors. Therefore, the concept of conservatism is difficult to define for fatigue assessments in a water environment. The problem is compounded by the lack of knowledge of actual plant transients.

Plant monitoring may be required and/or detailed thermodynamic modeling.

Outline Work Program

The establishment of a stakeholder data base of thermal plant transients would be valuable for the development of assessment procedures, the validation of thermodynamic plant modeling and would inform the testing of plant component representative geometries and loadings.

Life assessment without a F_{en} factor correction can be performed for the two cases of an actual transient and its bounding transient equivalent. The ratio of the actual transient allowable cycles to the bounding transient allowable cycles can be compared to the maximum possible F_{en} factor. In certain cases it may be possible to demonstrate that conservatism introduced by the use of a bounding transient with air data is greater than that from the use of the actual transient with the maximum possible F_{en} factor. This calculation may provide confidence that for certain components with certain transients, the current practice of using a bounding transient with air data is sufficiently conservative that the additional inclusion of a F_{en} factor is not required.

Sequence

Some data are available and could be used to populate a database initially. This is not dependent on the resolution of other gaps and could be resolved quickly. The database could be enhanced as more information becomes available.

Gap 35 was allocated Priority 2 at the Focus Group Meeting [6] but has been re-assessed here as Priority 1. This is because of the dependence of Gap 28 which is Priority 1 on Gap 35 where Gap 28 requires crack growth testing with waveforms more representative of real plant conditions.

Outcome

Knowledge of real plant transients would enable methods development to be appropriate to realistic applications.

The demonstration will need to be made on a case-by-case basis and the costs will be significant. Given an acceptable outcome for a wide range of cases, it is unlikely that the generic case can be made that F_{en} factors are not required. Some cases may exist which are not bounded by the cases considered.

It may be possible to define screening rules which identify circumstances involving component geometries and transient characteristics, for which the use of a bounding transient with air data is adequately conservative and the use of an additional F_{en} factor is not required.

Gap 36: Influence of Multiaxial Loading

Gap 36 states that the basis for the selection of effective stress parameters for biaxial stress conditions is not established. Test data are required under conditions of biaxial loading for the *treatment of plant thermal transients and non-proportional loading for combined thermal and mechanical transients. The most appropriate parameter may be different for the crack nucleation and subsequent propagation of microstructurally small cracks.*

Hypothesis

This gap relates to Hypothesis 6 (Category C) and is allocated a HIGH PRIORITY

Context from the Gap Analysis [Page 9-11]

ASME III uses the Tresca yield criterion to define an effective stress for biaxial loading. NUREG/CR-6909 assumes the same. No evidence is given that the Tresca criterion is appropriate for environmental fatigue conditions. One possible mechanism for environmentally assisted fatigue crack initiation is as follows: During cyclic loading, the chemically inert oxide film is ruptured at strains greater than the fracture strain of surface oxides to produce microstructurally small cracks. The microstructurally small cracks grow by anodic dissolution of the freshly exposed metal surface to produce mechanically small cracks. The appropriate effective stress parameter for these two mechanisms may be different. For example, the Rankine maximum principal stress parameter may be most appropriate for fracture of the brittle oxide and the Tresca or von Mises parameters may be most appropriate for mechanically small ductile crack growth. It should be noted, however, that the mechanism of EAF may differ between austenitic and ferritic steels or between PWR and BWR environments so that other stress parameters may need to be considered.

Research and Development Need

Test data are required to identify the appropriate multiaxial stress parameter for the treatment of biaxial condition in corrosion fatigue assessments.

Outline Work Program

A convenient means of controlling stress biaxiality is by the use of axially loaded pressure tubes. Pressure cycling alone will give a fixed biaxiality ratio of 2:1. Simultaneous axial loading with pressure loading can give non-proportional loading. Such tests can be compared to uniaxial data to determine which effective stress parameter gives the closest correlation. The knowledge gap relates to crack initiation in PWR and BWR water environments, in carbon and low alloy steels, austenitic stainless steel and nickel based alloys. However, the issue is fundamental to the effects of cycle sequencing so that progress could be made in the first instance by concentrating on one particular material and one particular water environment. Subsequently, validation tests would be required with other materials and environments to confirm the general applicability of knowledge gained or to modify it as appropriate.

Sequence

These tests do not depend on the outcome from closing other knowledge gaps and so can begin independently.

Outcome

An appropriate stress parameter for the assessment of corrosion fatigue crack initiation will be established. Alternatively, the need for different criteria for the two stages of crack nucleation and growth to mechanically small cracks may be indicated.

Gap 39: Strain Rate Calculation for Complex Transients

Gap 39 states that the calculation of strain rate is required to evaluate EAF initiation life. While methods for the determination of cycle effective strain rate can be proposed for conformance to ASME Code analysis, there are very few experimental data or plant data that can be used to validate the methods for use in corrosion fatigue assessments. Methods need to be consistent with mechanisms which operate under plant conditions.

Hypothesis

This gap relates to Hypothesis 6 (Category C) and is allocated a HIGH PRIORITY

Context from the Gap Analysis [Page 9-10]

Unlike ASME Section III, the calculation of strain rate is required to evaluate the F_{en} factor, and definition of appropriate strain rates is amongst the most challenging issues in NPP component environmental fatigue analysis. NUREG/CR-6909 does not provide a method or criterion for quantification of the strain rate to be input to the F_{en} calculation. There are issues associated with the calculation of strain rate which require clarification.

It is necessary to determine whether the strain rate is positive or negative, but guidance regarding how this is to be established is not provided in NUREG/CR-6909. Whilst strain may be derived by dividing stress intensity by Young's modulus, the stress intensity has no sign assigned to it.

Research and Development Need

Further work is required to establish a clear approach for calculation of strain rate. This is likely to include testing under complex loading conditions combined with analytical work to assess the suitability of different evaluation approaches for effective strain rate. Work to develop improved mechanistic understanding may also be required.

Outline Work Program

Assessment procedures such as ASME NH and R5 [8] consider the application of a strain based approach to the assessment of fatigue initiation damage and creep damage. These procedures and others should be reviewed to consider the necessary factors to be involved in more accurately assessing strain changes and hence strain rate. Features within stress-strain hysteresis loops such as ramp rates, hold times, and differences in behavior of mechanical strain and thermal strain need to be accounted for, together with the treatment of stress/strain concentrating features. These methods may be adopted or adapted for use in corrosion fatigue assessment. From an understating of robust and realistic means of calculating strain rate, a means of calculating an effective strain rate for variable conditions should be developed and verified against test data.

The knowledge gap relates to the assessment of strain rate in PWR and BWR water environments, in carbon and low alloy steels, austenitic stainless steel and nickel based alloys. Experiments simulating realistic transients in LWR water environments will be required for verification and may consider one material and one environment in the first instance. Subsequently, further verification tests may be required for other materials and environments.

Sequence

This links to Gap 35, *improved understanding of real plant transients through monitoring*, and follows from it. It also links to Gap 36, *influence of multiaxial* loading, and follows from it.

Outcome

Verified means of determining realistic, effective strain rates for complex cycles will result. Undue conservatism may be avoided.

Gap 41: Variable Strain Rate Effects

Gap 41 states that interpreting a plant transient with variable strain rate in terms of the single strain rate curves is problematic, and no relevant guidance is available.

Hypothesis

This gap relates to Hypothesis 6 (Category C) and is allocated a HIGH PRIORITY

Context from the Gap Analysis [Page 9-17]

The bounding fatigue curve approach proposed in ASME Code Case N-761 as an alternative to the F_{en} approach in NUREG/CR-6909 and Code Case N-792 is simple to apply, but may be excessively conservative. For stainless steels, the maximum environmental effect using the bounding water curve is approximately one tenth to one fifteenth the cycles of the air curve; beyond 10^6 cycles on the air curve there is no difference between the air and the water curves. For carbon and low-alloy steel, the bounding water curve results in a fatigue life reduction up to approximately one twentieth the cycles of the air curve (up to 10^6 cycles on the air curve). The less conservative, strain rate dependent curves are also relatively easy to apply but will often necessitate interpolation on the basis of transient strain rates. This approach does, however, avoid the possibly incorrect assumption of a constant environmental enhancement factor irrespective of strain rate as used in the F_{en} approach (see Gap 7).

Research and Development Need

Further consideration is required to develop a methodology which is not unduly conservative. Threshold values for the lack of, or saturation of an environmental effect need to be included, e.g. strain rate, strain range and temperature.

Outline Work Program

Further review of bounding water curves is required to consider any undue conservatism which may be removed. An effective means of assessing an equivalent strain rate for complex cycles is required but would result from the resolution of other gaps.

Sequence

This links to Gap 35, *improved understanding of real plant transients*, Gap 36, *influence of multiaxial* loading and Gap 39, *strain rate calculations for complex transients*, and follows from them.

Outcome

A bounding fatigue curve is easy to use but is likely to be unduly conservative. Strain rate dependent curves are less conservative but introduce the same issues of strain rate calculations for complex transients as the F_{en} approach. Reduced conservatism should result.

New Gap 46: Development of a Stakeholders' Testing Database

New Gap 46 can be stated as a universal, stakeholders' testing database should be established to provide a consistent basis for developments around the world.

Hypothesis

This gap relates to Hypothesis 5 (Category C) and is allocated a HIGH PRIORITY

Context for identifying the gap

This gap was not identified in the gap analysis. It was identified at the 'Environmentally Assisted Fatigue Focus Group Meeting [6].

Research and Development Need

Some gaps identify the need for further analysis of existing data. Other gaps identify the need to add to existing data. In both cases, a comprehensive and up-to-date database is required. This will identify specifically where material data gaps exist and provide a basis for coherent International collaboration. The data base should be continually updated as new data become available.

Outline Work Program

A database of all published test data should be compiled relating to: crack incubation and crack growth, BWR and PWR water environments, carbon and low alloy steels, austenitic stainless steels and nickel based alloys. For ease of access, the data base should be arranged so that keyword searches can be performed.

Sequence

The testing data base is a fundamental input into the design of material testing programs and the re-evaluation tasks identified in Gaps 3, 7 and 47 and tasks relating to the extension of the data base in Gaps 13 and 18. This gap should be addressed in the first instance.

Outcome

The outcome will be the avoidance of duplication in obtaining test data, the clear identification of specific data gaps and the availability of a broad database by which concepts can be evaluated and mechanistic understanding developed.

A complete database may draw attention to aspects previously overlooked and be of immediate benefit in the re-evaluation of methods.

The comparison of load-controlled and displacement-controlled S-N data may provide a test of Hypothesis 5 which relates to a fundamental difference in behavior between primary stress and secondary stress.

New Gap 47: Guidance for Mitigated Locations According to Dissolved Oxygen Content (DO)

New Gap 47 can be stated as the need exists to provide guidance on circumstances where the approach of NUREG/CR-6909 is not appropriate because of DO levels.

Hypothesis

This gap relates to Hypothesis 6 (Category C) and is allocated a HIGH PRIORITY

Context for identifying the Gap

The gap analysis identified unresolved issues relating to effects of dissolved oxygen content on S-N behavior (Parts 1-3 of Gap 20: see Section 6). However, at the Environmentally Assisted Fatigue Focus Group Meeting [6] a need was identified to provide more specific guidance for BWR plant operators on possible benefits to be gained from the use of specific water chemistry regimes.

The gap analysis report comments on the treatment of dissolved oxygen content in the F_{en} factor algorithms as follows. The influence of DO is included in the carbon and low alloy steel F_{en} factor algorithms using the factor O* which is a function of DO with discontinuous influences at certain threshold values; high DO levels increase F_{en}. A variable O* is also included in the F_{en} factor algorithm for stainless steel. Although laboratory data show a beneficial effect of high DO in this case, O* is set to a constant irrespective of DO in the NUREG/CR-6909 expressions for F_{en} of stainless steel. This may be excessively conservative for BWR plants operating normal (high oxygen) water chemistry.

Research and Development Need

Some BWR plants operate a strict control of DO, minimizing concentrations using hydrogen water chemistry (HWC) and noble metal chemical additions (NMCA). The discontinuous influence of DO in the NUREG/CR-6909 F_{en} algorithms for carbon and low alloy steels is insufficiently refined to take advantage of closely controlled DO levels in reducing F_{en} values. F_{en} factors defined as continuous functions of DO without thresholds are required. For austenitic stainless steels, the environmental effect is reduced in high oxygen conditions. The inclusion of a DO dependent expression for O* in this case would be of benefit to those BWRs operating normal water chemistry (NWC).

Outline Work Program

The issue of DO dependence of F_{en} for austenitic stainless steels is being revisited in ongoing NRC work and there may be sufficient data to revise the model for the benefit of BWRs operating NWC. If insufficient data are available to justify a change, further tests are warranted to better establish the influence of DO level on the fatigue life of austenitic stainless steels. A review of existing data may be warranted to determine whether or not more refined functions of F_{en} factor versus DO can be derived. The review should consider the influences of BWR (NWC, HWC, NMCA) and PWR water environments, for carbon and low alloy steels and for austenitic stainless steels. Based on the review, reformulation of the F_{en} algorithms would be required. It is possible that more test data may be required.

It is noted that the DO level a wetted surfaces is likely to be different to that of the bulk chemistry. The influence of this should be considered in redefining the sensitivity of F_{en} factor to DO.

Sequence

Since there may be an immediate benefit to some plant operators from resolving this gap, this gap should be addressed as soon as possible. This links to New Gap 46, *the establishment of a stakeholders' testing data base*, and follows from it.

Outcome

Reduced F_{en} factors may result in some circumstances from more refined definitions of DO versus F_{en} factor. Also, regions of plants where corrosion influences are not appropriate may be identified.

5
PRIORITY 2 ROADMAP

Structure of the Priority 2 Road Map

The Priority 2 Road Map is structured as for the Priority 1 Road Map. Figure 5-1 gives the Priority 2 Gaps in the context of the knowledge evaluation process. Figure 5-2 gives a suggested sequencing. Some of the Priority 2 Gaps have dependencies on Priority 1 Gaps and should sensibly follow from them. Similarly, they provide further information to Priority 1 Gaps 4, 31 and 23 which are knowledge evaluation gaps to further aid their resolution. The dependencies between Priority 3 Gaps and Priority 1 Gaps are shown in Figure 5-2.

Figure 5-1 (the knowledge evaluation process), Figure 5-2 (the suggested sequence) and the discussion below of each individual Priority 2 Gap, together comprise the Priority 2 Road Map.

A discussion of the individual gaps follows.

Certain pairs of gaps are quite closely related and work to address them could sensibly be combined into a single work package. Where this is the case, a commentary is given in the discussion of the individual gaps. These pairs of gaps are:

Gap 12 with Gap 19

Gap 42 with Gap 43

Gap 6 with Gap 44

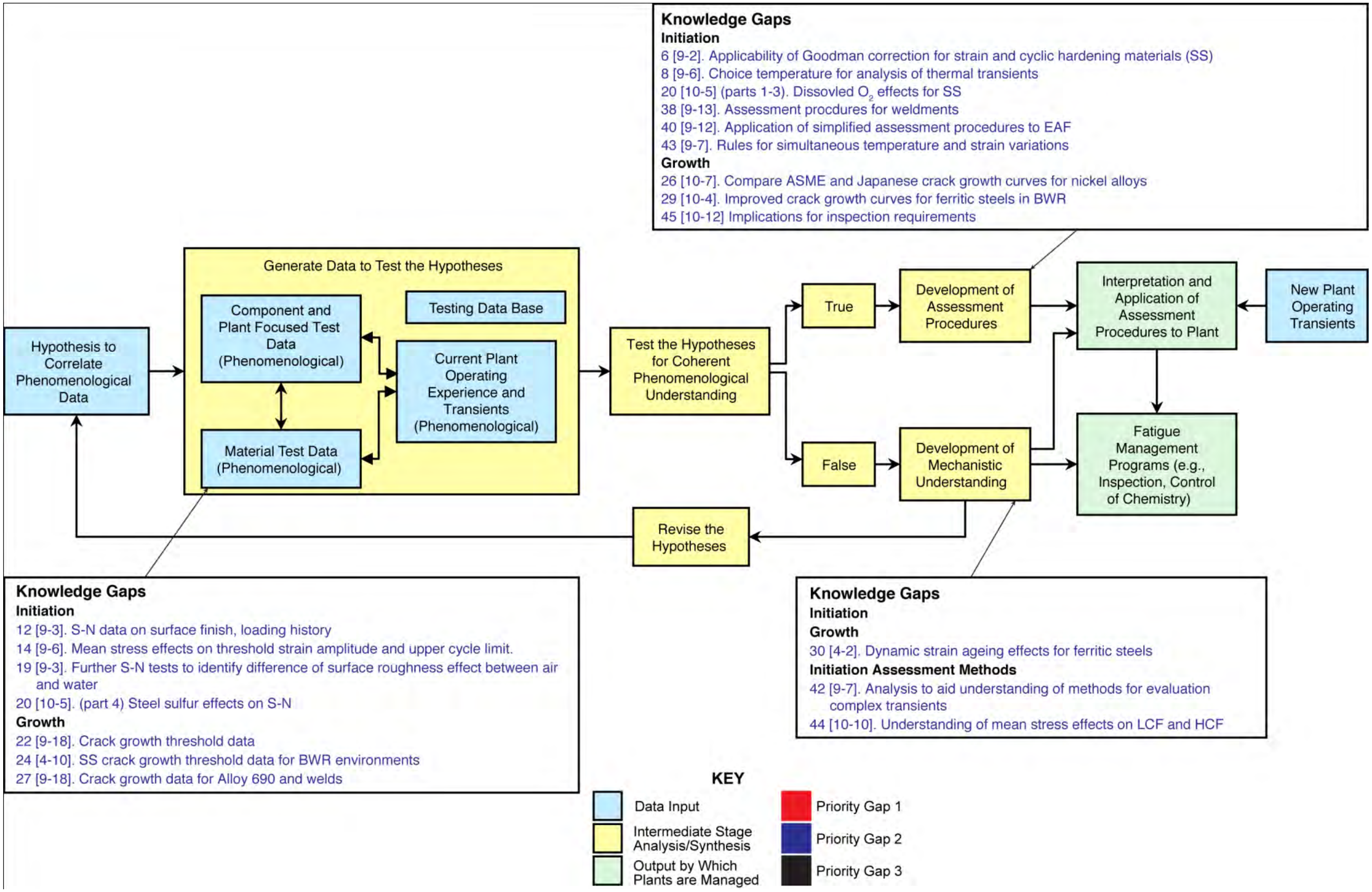

Figure 5-1
Knowledge Evaluation Scheme with Priority 2 Gaps Indicated

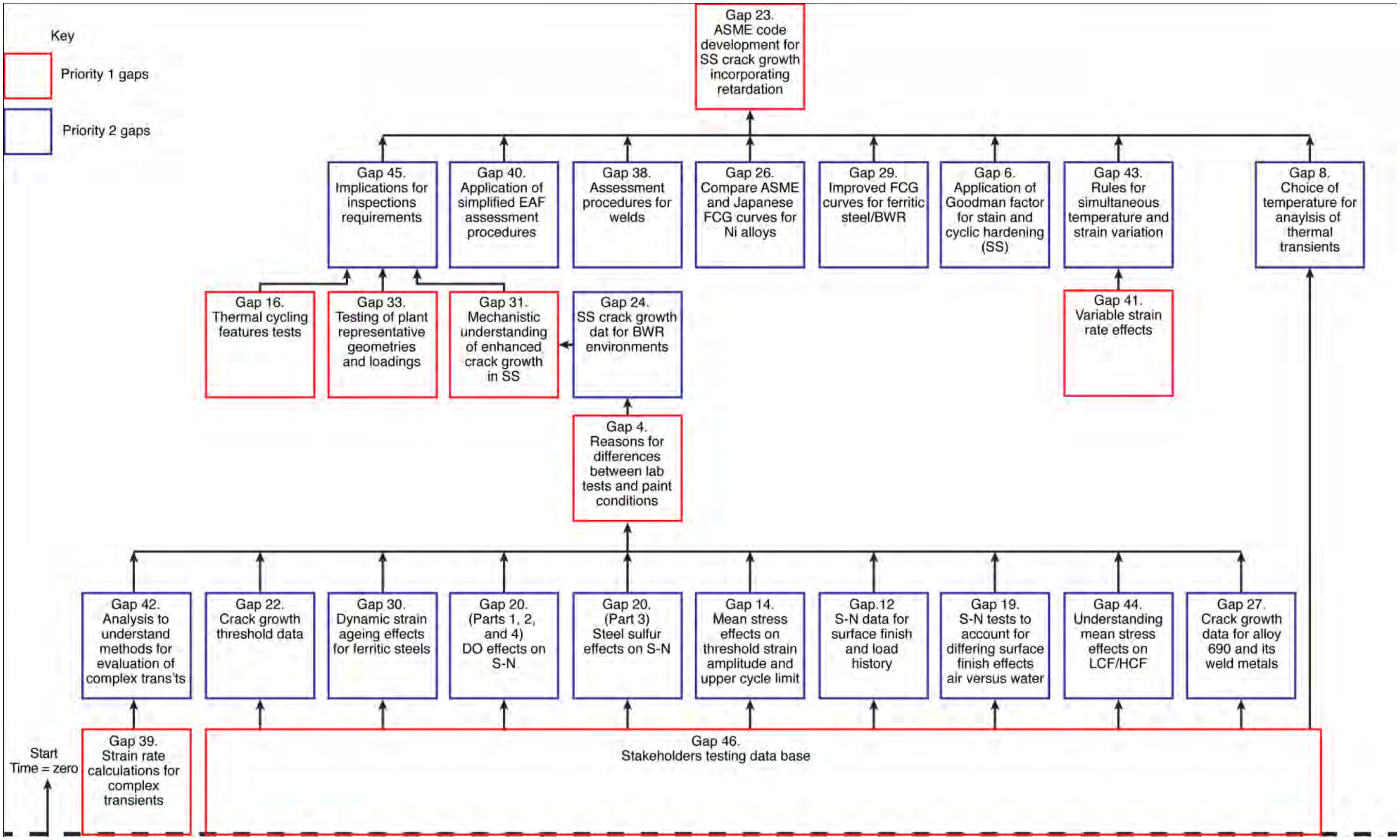

Figure 5-2
Priority 2 Gap Dependencies by Time Sequence & Connectivity

Summary of the Expected Outcomes

The resolution of the Priority 2 Gaps will provide data and information to further resolve three key aspects of the Knowledge Evaluation Scheme, Figure 5-1, these being:

1. testing of hypotheses for coherent phenomenological understanding,
2. development of mechanistic understanding,
3. development of assessment procedures.

Gap 6: Applicability of Goodman Correction for Strain and Cyclic Hardening Materials (SS)

Gap 6 states that stainless steels exhibit significant strain hardening and cyclic hardening so that a sharply defined yield stress does not exist. The Modified Goodman correction is used to adjust zero mean stress, fatigue endurance data to account for mean stress. The influence of using a higher yield stress in the Modified Goodman correction is to shift the influence of the mean stress correction towards low cycle fatigue. The extent to which this happens depends on the magnitude of the yield stress assumed.

Hypothesis

This gap relates to Hypothesis 2 (Category A) and is allocated a MEDIUM PRIORITY

Context from the Gap Analysis [Page 9-2]

The Criteria of the ASME Boiler and Pressure Vessel Code document specifies that a modified Goodman approach should be used to adjust the high cycle laboratory fatigue data for the most conservative effect of mean stress. For low cycle fatigue, the mean stress in S-N testing is always zero. This is because plastic strain occurs at both the positive stress/strain quadrant and the negative stress/strain quadrant of the hysteresis loop so that the cycle will become symmetrical at zero mean stress. Therefore, a mean stress correction is not appropriate for low cycle fatigue. For high cycle fatigue and for materials where the yield stress is greater than the endurance limit, it is possible for the stress cycle to be from tensile yield downwards, so that a positive mean stress can exist. Thus the Criteria document specifies that the most conservative mean stress correction be applied to high cycle fatigue data on this basis, where applicable. The adjustment is applied to carbon and low alloy steels since the endurance limit is less than the yield stress but is not normally applied to stainless steel since the endurance limit is stated to be greater than the yield stress.

NUREG/CR-6909 states that the modified Goodman mean stress correction has been applied to stainless steel in deriving the revised Design curves. However, no details are given as to how this was done.

Research and Development Need

Further analysis is required to consider how the Modified Goodman correction should be applied to stainless steel fatigue endurance data.

Outline Work Program

This gap is very closely related to Gap 44, *understanding of mean stress effects on LCF and HCF*, and could be subsumed with it into a single work package.

The knowledge gap relates to PWR and BWR water environments, in carbon and low alloy steels, austenitic stainless steel and nickel based alloys.

Sequence

This gap and Gap 44 link to Gap 14, *mean stress effects on threshold strain range and upper cycle limit*, since a mean stress correction will be influential in the threshold regime. Work on Gaps should be performed in a coordinated work program, with work extended to address Gap 14.

Outcome

The mean stress correction to stainless steel S-N data will be more robustly quantified.

Gap 8: Choice of Temperature for Analysis of Thermal Transients

Gap 8 states that for non-isothermal cycles, the issue of temperature selection appropriate to the full calculation procedure of thermal analysis, elastic stress analysis, strain analysis and F_{en} factor calculation requires further consideration.

Hypothesis

This gap relates to Hypothesis 1 (Category A) and is allocated a MEDIUM PRIORITY

Context from the Gap Analysis [Page 9-6]

For the case of thermal transient cycling, Section III of the ASME Code does not give clear guidance on whether the cycle maximum temperature, cycle minimum temperature or cycle mean temperature should be used to perform a fatigue assessment. Indeed, the ASME Section III fatigue assessment for stainless steel is insensitive to the assumed temperature, since the design fatigue curve and strain range enhancement factor do not require a temperature to be specified. Temperature is only used to factor the design fatigue curve according to the ratio of Young's modulus to the reference Young's modulus used to construct the stress based Design curves. This is a minor adjustment.

Notwithstanding the ASME Code position, the temperature selection for fatigue damage assessment of thermal cycling is not straightforward. For simplicity, it may be required to select all material data at a single temperature. Should this temperature be the maximum temperature or minimum temperature during the cycle? The calculation involves heat conduction analysis using the material properties of thermal conductivity, specific heat and density. Following this, thermal stress analysis is required involving the mechanical properties of expansion coefficient and Young's modulus. All of these properties are temperature dependent. Using typical materials properties data, simple calculations show that, for stainless steel, the maximum elastic stress range occurs by selecting properties at the minimum cycle temperature whereas, for ferritic steel, the maximum stress range occurs by selecting properties at the maximum cycle temperature.

This influence of property selection according to temperature dependence has been noted in thermal cycle fatigue testing. A thermal fatigue test program for a stainless steel piping component performed in laboratory air (not in a water environment) investigated the temperature that should be used to select all material properties necessary to perform a fatigue assessment. It was concluded that the use of the cycle minimum temperature rather than the cycle maximum temperature resulted in a better correlation between the calculated initiation life and the observed initiation life. The rationale for this was that since fatigue initiation was defined as a defect 3 mm deep, a considerable amount of fatigue crack growth was included in the crack initiation definition. Crack growth occurs when the crack is at its maximum opening position which, for a thermal down ramp is at the cycle minimum temperature corresponding to the maximum surface tensile stress. Therefore the cycle minimum temperature should be used to define the material properties for thermal down-ramp fatigue assessment.

The differences in elastically calculated stress range due to temperature selection of properties may be typically 3% for stainless steel and 10% for ferritic steel. These differences are magnified when strain range and hence strain rate are required for subsequent F_{en} factor evaluation. To date, the selection of an appropriate temperature for the analysis of thermal cycles has been limited to the F_{en} factor formulation only. The full calculation process has not been considered.

Research and Development Need

Further analysis of available test data is required to assess the most appropriate temperature to use for analysis for non-isothermal cycles.

Outline Work Program

The calculation of F_{en} factor for cycles with temperature variations is required to consider various assumptions about the appropriate temperature to select for simplified analysis. The full calculation concerning stress analysis, strain analysis and F_{en} factor calculation should be considered by setting material properties for the cycle minimum temperature or cycle maximum temperature. The difference in F_{en} factor for these two assumptions may be significant. Other assumptions concerning forms of temperature averaging should be considered. Guidance should be formulated on the appropriate single temperature to select for a simplified analysis where the cycle is a thermal up-shock or thermal down-shock.

The knowledge gap relates to PWR and BWR water environments, in carbon and low alloy steels, austenitic stainless steel and nickel based alloys.

Sequence

The resolution of this gap would benefit from the resolution of Gap 46 (Priority 1), *stakeholder testing data base*, by the provision of suitable temperature dependent material properties. Information from the test program in support of Priority 1 Gap 13, *S-N data for a wider range of temperature and strain rate combinations*, would provide support to this analysis but it is not considered that work in this area awaits completion of that program.

Outcome

Improved guidance for the simplified treatment of temperature variable cycles would result.

Gap 12: S-N Data to Support Surface Finish, Loading History

Gap 12 states that conservatism is included in NUREG/CR-6909 concerning the derivation of the adjustment factor of 12, which is used to relate test endurance data in air to component *endurance data. Insufficient data exist concerning the values for the individual factors which are combined and the means by which they should be combined.*

Hypothesis

This gap relates to Hypothesis 5 (Category C) and is allocated a MEDIUM PRIORITY

Context from the Gap Analysis [Page 9-3]

NUREG/CR-6909 has modified the factor of 20 to allow for component conditions relative to test data conditions to a factor of 12. This has been obtained by compounding a number of individual factors relating to material variability and data scatter, size effects, surface finish and loading history. A conservative factor of 1.55 for cycle sequence effect has been included. Arguably, this is not appropriate for nuclear power plants which do not experience all high cycle fatigue at the beginning of their life and low cycle fatigue later on, or vice-versa. Also, NUREG/CR-6909 stated that the specimen size effect of 1.2 to 1.4 is not required for rough surfaces. Nevertheless, a factor of 1.2 -1.4 has been conservatively included.

Research and Development Need

Further test data are likely to be required to relate smooth specimen fatigue initiation life in air to engineering component fatigue initiation life by accounting for material variability, size effects, surface finish and loading history.

Outline Work Program

Displacement controlled, S-N tests are required to consider, in particular, the influence of cycle sequencing and surface roughness. The detailed work program would benefit from resolution of Gap 46, *the establishment of a stakeholders' testing data base*, since this will identify specific data gaps which should be addressed.

The knowledge gap relates to S-N data in air for carbon and low alloy steels, austenitic stainless steel and nickel based alloys. However, the issue is fundamental to the application of assessment procedures to practical cases so that progress could be made in the first instance by concentrating on one particular material and one particular water environment. Subsequently, validation tests would be required with other materials and environments to confirm the general applicability of knowledge gained or to modify it as appropriate.

Sequence

This links to New Gap 46, *the establishment of a stakeholders' testing data base*, and follows from it. It also links to Gap 19, *further S-N tests to identify difference of surface roughness effects between air and water*. Some adjustment factors used to define the ASME reference air curve may not be applicable in water. For example, the ASME air code includes an "environment" factor to account for differences between industrial environments and an air conditioned laboratory which is clearly not appropriate for wetted defects if a water environment factor (F_{en}) is also applied. Also, some published data appear to suggest that roughness effects are smaller in water than in air. It is proposed that work in support of Gap 12 is combined with work to address differences between air and water environments (Gap 19) in a joint work program.

Outcome

The factor of 12 relates to low cycle fatigue assessment which is appropriate to the treatment of thermal transients. Reduced conservatism for air environments could result if the influence of cycle sequencing and surface roughness can be better quantified and accounted for.

Gap 14: Mean Stress Effects on Threshold Strain Range and Upper Cycle Limit

Gap 14 states that the strain range and the associated number of cycles for which the consideration of environmental effects on fatigue is not required is based on zero mean stress test data only. The situation may be different for positive or negative mean stress. The lack of non-zero mean stress test data prevents this analysis being undertaken.

Hypothesis

This gap relates to Hypothesis 2 (Category A) and is allocated a MEDIUM PRIORITY

Context from the Gap Analysis [Page 9-7]

In NUREG/CR-6909, both the ferritic steel and stainless steel F_{en} models are recommended for use for predicted fatigue lives $\leq 10^6$ cycles. The precise reason for the stated limit on cycles is not explicitly specified in NUREG/CR-6909. However, examination of the data trends for both ferritic and austenitic materials indicates that environmental effects are small above 10^6 cycles, although only limited high cycle test data are available.

The limit on cycles is generally adequate for low frequency, high strain range operational transients over a reactor lifetime. However, many more high frequency, low strain range cycles can occur due to phenomena such as thermal striping, turbulent mixing and flow stratification. It may be supposed that the limit of 10^6 cycles is intended to imply that high frequency cycles are not susceptible to corrosion fatigue influences since their strain rates would be very high and their strain ranges very low. This interpretation is consistent with strain ranges below which the F_{en} factor is not applicable (i.e. 0.07% for carbon and low alloy steels and 0.1% for stainless steels) since these strain ranges correspond approximately to 10^6 cycles. If this interpretation is correct, it has been demonstrated only for zero mean stress cycling since that is the basis of the test data considered in NUREG/CR-6909. A discussion on circumstances for which non-zero mean stress can occur during plant cycling is given in Section 10 of the gap analysis report.

Research and Development Need

Further test data are required to identify the strain range threshold for non-zero mean stress, both tensile and compressive.

Outline Work Program

Fatigue initiation S-N tests are required with non-zero mean stress to investigate the strain range below which, or the number of cycles above which, a F_{en} factor need not be applied. These tests should be isothermal at various temperatures, include various strain rates and various levels of DO. For stainless steels, various levels of sulfur content may also be important. Algorithms which define the F_{en} factor in terms of temperature, DO and strain rate may require modification to include mean stress.

The knowledge gap relates to crack initiation in PWR and BWR water environments, in carbon and low alloy steels, austenitic stainless steel and nickel based alloys.

Sequence

This links to New Gap 46 (Priority 1), *the establishment of a stakeholders' testing data base*, and follows from it. It also links to Gap 20, *steel sulfur effect on S-N (for stainless steels)*.

Outcome

An understanding of the influence of mean stress on F_{en} factor will result.

Gap 19: Further S-N Tests to Identify the Differences of Surface Roughness Effect Between Air and Water

Gap 19 states that further S-N tests are warranted to confirm the apparently differing influence of surface roughness between air and water environments. This may justify a reduction in the design margin applicable for components in water environments.

Hypothesis

This gap relates to Hypothesis 5 (Category C) and is allocated a MEDIUM PRIORITY

Context from the Gap Analysis [Page 9-3]

Limited mechanistic understanding suggests that Stage I crack nucleation may be shortened or eliminated in a water environment compared to an air environment. The persistent slip bands which form short surface notches at an angle of 45^o to a free surface, in evidence in an air environment, appear less obvious in a PWR water environment. The action of persistent slip bands in an air environment act as a surface roughening effect.

Limited experimental data (ANL on LAS for BWRs, Areva on SS for PWRs) suggest that the effect of surface roughness in high temperature water is less than that in a high temperature air environment. This suggests that there may be an excessive conservatism in multiplying the surface roughness factor (2-3.5 in NUREG/CR-6909) by the F_{en} factor. Also, the ASME air code includes an "environment" factor to account for differences between industrial environments and an air conditioned laboratory which is clearly not appropriate for wetted defects if a water environment factor (F_{en}) is also applied.

Research and Development Need

Further S-N tests in air (see Gap 12) and water (this gap) are warranted to consider possible differences in the influence of surface roughness on fatigue initiation life between air and water environments.

Outline Work Program

Displacement controlled S-N tests in water are required to consider specifically the influence of surface roughness. Strain ranges the same as those considered in Gap 12 should be used so that a direct comparison of air data and water data can be made. Low strain range and high strain range should both be considered.

The knowledge gap relates to S-N data in water for carbon and low alloy steels, austenitic stainless steel and nickel based alloys. However, the issue is fundamental to the application of assessment procedures to practical cases so that progress could be made in the first instance by concentrating on one particular material and one particular water environment. Subsequently, validation tests would be required with other materials and environments to confirm the general applicability of knowledge gained or to modify it as appropriate.

Sequence

This links to New Gap 46, *the establishment of a stakeholders' testing data base*, and follows from it. It also links to Gap 12, *S-N data on surface finish, loading history*, and could be combined with it in a joint work program.

Outcome

Factors to account for surface roughness are not necessarily the same in an air environment and a water environment. Limited data suggests that the factor can be reduced for water environments, leading to reduced conservatism in assessment procedures.

Gap 20 (Parts 1, 2 and 4): Dissolved Oxygen Effects on S-N Data

Gap 20 states that:

Part 1 - NUREG/CR-6909 acknowledges conservatism in its model regarding the influence of DO level. This particularly applies to some grades of stainless steel in high-DO water. Further refinement of the model to recognize an effect of DO (i.e. a difference between PWR and BWR/NWC) may be warranted.

Part 2 - There are no data on the influence of DO in PWR water containing boric acid and lithium hydroxide (i.e. under transient conditions).

Part 4 - Only limited data are available for BWR HWC. Whilst PWR data may be bounding, this remains to be established.

Hypothesis

This gap relates to Hypothesis 5 (Category C) and is allocated a MEDIUM PRIORITY

Context from the Gap Analysis [Page 10-5 & 10-6]

From S-N test data on fatigue initiation life specimens taken alone, it is established that corrosion fatigue life of low alloy and stainless steels in light water reactor environments is influenced by strain range, strain rate, temperature and corrosion potential. The latter parameter is a function of the dissolved oxygen concentration in reactor water, although other species such as hydrogen peroxide or copper may also increase the corrosion potential. Maximum environmental effects are observed for ferritic and austenitic materials at slow strain rates and high temperatures (>200-250°C). For ferritic steels, fatigue lives are reduced in high oxygen (BWR) environments compared to low oxygen (PWR) conditions. The reverse appears to be true for austenitic stainless steels, with reduced fatigue life being observed in deaerated or hydrogenated (PWR) chemistry than in oxygenated water as in BWR normal water chemistry. Data in BWR hydrogen water chemistry, for which corrosion potential is somewhat higher than in PWRs, are more limited, but appear to be adequately described by PWR data.

Research and Development Need

Issue (1) is currently being revisited in ongoing NRC work and there may be sufficient data to revise the model for BWR NWC. If insufficient data are available to justify a change, further tests are warranted to better establish the influence of DO level on the fatigue life of austenitic stainless steels. Both Issues (1) and (3) are covered by the work identified under New Gap 47 (Priority 1).

It is judged that there is unlikely to be significant benefit from additional data regarding issue (2).

Outline Work Program

See work identified under New Gap 47.

Sequence

See New Gap 47.

Outcome

See New Gap 47.

Gap 20 (Part 3): Steel Sulfur Effects on S-N Data

Gap 20 (Part 3) states that the effect of steel sulfur content on fatigue initiation life of stainless steel has not been established – it has a substantial influence on fatigue crack growth rate.

Hypothesis

This gap relates to Hypothesis 5 (Category C) and is allocated a MEDIUM PRIORITY

Context from the Gap Analysis [Page 10-6]

For ferritic steels, the fatigue life is reduced for high sulfur content steels, especially in oxidizing conditions. No data are available on the effects of steel sulfur content in austenitic stainless steels. Recent data indicate that retarded corrosion fatigue growth rates more readily for high sulfur content steels than their low sulfur counterparts. This is in contrast to ferritic steels where high sulfur enhances crack growth; however, it is not known if a similar beneficial effect of sulfur for stainless steels applies to fatigue initiation life.

Research and Development Need

Gap 20 (Part 3) warrants study since this effect may be significant.

Outline Work Program

Fatigue initiation life tests are required in stainless steels in PWR and BWR environments to investigate the influence of sulfur content. Algorithms which define the F_{en} factor in terms of temperature, DO and strain rate may require modification to include sulfur content.

Sequence

This links to New Gap 46 (Priority 1), *the establishment of a stakeholders' testing data base*, and follows from it. It also links to Gap 14, *mean stress effects on threshold strain range and upper cycle limit*.

Outcome

It is possible that reduced F_{en} factors for some heats of stainless steel will result where sulfur content is accounted for. An effect of sulfur on fatigue initiation life has not been demonstrated so the probability of success is unknown.

Gap 22: Near-Threshold Crack Growth Data etc.

Gap 22 states that the lack of relevant environmental crack growth data for some materials (e.g. Alloy 690 and its weld metals) or grades of material (e.g. Types 316L(N) or 347 stainless steel) represents a knowledge gap. Heat to heat variability also appears to be important, especially the influence of sulfur for stainless steel but is not adequately understood. There is also a lack of threshold ΔK data for many materials. Gap 22 is concerned with austenitic stainless steel only. The emphasis here is on near threshold effects, possible differences between different grades of austenitic stainless steels, and the requirement for data for cast grades at low frequencies. Sulfur effects are considered in Gap 25 and data for Alloy 690 are covered by Gap 27.

Hypothesis

This gap relates to Hypothesis 5 (Category C) and is allocated a MEDIUM PRIORITY

Context from the Gap Analysis [Page 9-19]

Section XI of the ASME BPVC provides dry fatigue crack growth curves for austenitic stainless steels but does not currently include curves for wetted flaws. The ASME has recently proposed draft Code Case N-809 to address this shortfall. This provides advice on the fatigue crack growth curve to be used for austenitic stainless steels exposed to PWR environments.

It can be seen that the proposed ASME XI wet curves provide fatigue crack growth rates that are between 10x and 1000x the dry curve, and the enhancement factor is dependent on the rise time. No threshold value of ΔK is included in the proposed approach, hence the unrealistically large predicted environmental enhancement at very low values of ΔK. Experimental data indicate a maximum environmental enhancement factor of approximately 80x ASME air rates, with this occurring only at extremely long rise times (>20h). Similar equations apply to other wrought stainless steels except for the value of C: 1.30×10^{-5} for Type 304L and 7.28×10^{-6} for Type 316. It is further noted that, for some grades of stainless steel, the quantity of data used to derive the proposed curves is rather limited.

Research and Development Need

Further corrosion fatigue crack growth data are required under near threshold conditions to provide an upper bound to the proposed ASME XI curves for austenitic stainless steels in water environments. The current proposal includes a rise time threshold (nominally 1000s) which is aimed at providing an upper bound but this is not supported by experimental data. There may also be a need for additional data on specific grades of stainless steel to determine any possible differences between, for example, 304 and 316, between low (L) and standard grades of the materials and possible difference in the behavior of stabilized grades such as 321 and 347. Data for cast austenitic stainless steels at low frequencies are also required.

Outline Work Program

Fatigue crack growth tests for specific heats of wrought stainless steel is required in the near threshold region. Sufficient data are required for wet fatigue crack growth curves to be defined including threshold values. Low frequency data are required for cast grades,

This applies to stainless steels in both PWR and BWR water environments.

Sequence

This links to New Gap 46 (Priority 1), *the establishment of a stakeholders' testing data base,* and follows from it.

Outcome

Significantly reduced conservatism in wet fatigue crack growth curves at low ΔK values may result from near-threshold testing. Data for cast grades will support development of a specific assessment curve for these materials. The benefit for grades specific data for wrought material is more difficult to define.

Gap 24: Crack Growth Data and Reference Curves for Stainless Steels in BWR Environments

Gap 24 states that ASME XI does not include a fatigue crack growth law for wetted flaws in austenitic stainless steels. Fewer relevant data are available for BWR environment than for PWR although recent data suggest environmental effects are somewhat greater in BWR NWC than HWC or PWR (this is in contrast to S-N data).

Hypothesis

This gap relates to Hypothesis 5 (Category C) and is allocated a MEDIUM PRIORITY

Context from the Gap Analysis [Pages 10-4 and 4-11 to 10-13]

Section XI of the ASME Code provides dry fatigue crack growth curves for austenitic stainless steels but does not currently include fatigue crack growth curves for wetted flaws for austenitic steels despite evidence that fatigue crack growth rates in stainless steels can be enhanced appreciably in PWR and BWR coolant. A model has developed describing environmentally enhanced fatigue crack growth in PWR environments only which includes expressions for the effects of rise time, R ratio, temperature, and stress intensity factor range. The crack growth model has been proposed as the basis of ASME draft Code Case N-809.

Corrosion fatigue crack growth data available in the mid 1990s for BWR environments indicated higher crack growth rates with increasing oxygen content and equations were developed corresponding to two different oxygen levels, 0.2ppm and 8ppm. These data extend to air crack velocity ($\dot{a}_{air}$) values approximately two orders of magnitude lower than for the PWR data and show environmental enhancement more than 20 times those in air.

More recent data for austenitic stainless have been generated where crack growth rates are up to a factor of 5 higher in BWR normal water chemistry, NWC (ECP≈+150mV SHE) compared to hydrogen water chemistry, HWC (ECP≈-500 to -300mV SHE) or PWR environments. For sensitized stainless steels, higher rates were observed at very low frequencies due to a contribution from stress corrosion cracking. These observations are generally consistent with the earlier data, but extend to somewhat lower values of $\dot{a}_{air}$. It should be noted that enhancement of crack growth rates under more oxidizing conditions is in contrast to fatigue initiation testing, for which shorter fatigue lives, i.e. a larger effect of the environment, is observed under more reducing (lower oxygen) conditions.

Behavior under BWR (HWC) and PWR conditions has been compared where it was concluded that neither the presence of pH control additives, such as LiOH and boric acid, nor sulfate and chloride at levels up to 100ppb, have any major effect at these relatively low potentials. Unsurprisingly, impurity additions did increase crack growth rates for sensitized stainless steel under more oxidizing (BWR NWC) conditions at low loading frequencies, where SCC can enhance crack growth. In HWC, crack growth rates increase with temperature between 150 and 300°C, with an activation energy of about 20kJ/mol.

Research and Development Need

There is a need to evaluate the significance of recent BWR NWC and HWC data with a view to developing crack growth relationships for wetted flaws in austenitic stainless steels in BWRs, covering both MWC and HWC conditions. It is also necessary to ascertain whether further test data are required.

Outline Work Program

A review is required of recent data on crack growth of stainless steels in BWR NWC and HWC conditions. It is considered likely that sufficient data are now available to formulate assessment curves using a similar, rise time dependent, approach to the draft ASME code case for PWR conditions, although the constants in the equations are likely to be different. Draft crack growth relationships should be prepared and submitted to the ASME Section XI Task Group on Crack Growth Reference Curves for review.

Sequence

This gap has no dependencies on other gaps and so work could start as soon as convenient.

Outcome

Definitive reference crack growth relationships would be developed for austenitic stainless steels exposed to BWR normal and hydrogen water chemistry environments. It is possible that the expressions currently being developed for PWR environments as an ASME Code Case may be appropriate for BWR hydrogen water chemistry also.

Gap 26: Compare ASME & Japanese Crack Growth Curves for Nickel Alloys

Gap 26 states that some data are available for Alloy 600 and its weld metals which have enabled an assessment curve to be incorporated in ASME XI. Alternative curves have also been published which appear more conservative.

Hypothesis

This gap relates to Hypothesis 5 (Category C) and is allocated a MEDIUM PRIORITY

Context from the Gap Analysis [Page 10-13 to 10-17]

In the case of nickel based alloys, ASME Section XI provides a crack growth rate reference curve for Alloy 600 base metal for both PWR and BWR environments. Japanese workers have proposed different, more conservative curves for Alloy 600 and its weld metals.

Research and Development Need

There is a need to understand basis of the alternative assessment curves.

Outline Work Program

A review is required of the two alternative fatigue crack growth assessment curves for Alloy 600 (ASME XI and JSME) in order to establish the basis on which they were derived. Reasons for inconsistencies between data from different laboratories should be established by reviewing factors such as R ratio and waveform. A view will be required on the significance of the differences identified in the testing procedures. The review should also consider available data on nickel-based weld metals such as Alloys 182, 132 and 82 (Alloys 52, 152 and variants are covered by Gap 27).

Following guidance from the review, some crack growth rate testing may be required to establish a definitive crack growth law.

This gap relates to Alloy 600 in PWR and BWR water environments.

Sequence

This links to New Gap 46 (Priority 1), *the establishment of a stakeholders' testing data base,* and follows from it.

Outcome

A definitive crack growth law for Alloy 600, without undue conservatism or inconsistencies will be established.

Gap 27: Crack Growth Data for Alloy 690 and its Weld Metals

Gap 27 states that [only] very limited data are available for Alloy 690 [and its weld metals] (Alloy 52, 152 and variants).

Hypothesis

This gap relates to Hypothesis 5 (Category C) and is allocated a MEDIUM PRIORITY

Context from the Gap Analysis [Page 9-19, 10-6 and 10-7]

In the case of nickel based alloys, ASME Section XI provides a crack growth rate reference curve for Alloy 600 base metal for both PWR and BWR environments, but no reference curve is available for Alloy 690 or its weld metals.

Research and Development Need

There is a need to review available data for Alloys 690, 52, 152 (and weld metal variants) and determine whether additional data generation are required to develop crack growth reference curves.

Outline Work Program

A review is required of the available crack growth data on Alloy 690 and its weld metals. If necessary, some crack growth rate testing may be required to establish a definitive crack growth law.

This gap relates to Alloy 690 and its weld metals in PWR water environments. BWRs do not currently use this material.

Sequence

This gap follows from Gap 46 (Priority 1), *stakeholder testing data base*. This gap also has a link to Gap 32 which is dependent on it.

Outcome

A definitive crack growth law for Alloy 690 and its weld metals will be established.

Gap 29: Improved Crack Growth Curves for Ferritic Steels in BWR

Gap 29 states that reference crack growth curves are available covering both BWR and PWR environments but do not explicitly represent the influence of all significant factors on the degree of enhancement such as DO concentration and transient rise time. For BWR HWC, ASME XI reference curves may be excessively conservative, but may be non-conservative for some BWR NWC conditions.

Hypothesis

This gap relates to Hypothesis 5 (Category C) and is allocated a MEDIUM PRIORITY

Context from the Gap Analysis [Page 10-4]

Laboratory data from fatigue crack growth testing of pre-cracked specimens indicates the potential for considerable environmental enhancement of fatigue crack growth in reactor water conditions. There are significant gaps in current guidance to account for environmental effects on fatigue crack growth, and the influence of many key influencing parameters remains to be established. Reference curves for carbon and low alloy steels in high temperature LWR environments are available but do not represent the influence of all significant factors on the degree of enhancement such as steel sulfur content, dissolved oxygen concentration and transient rise time. ASME CC N-643-2 provides alternative crack growth curves according to sulfur content and also recognizes transient rise time dependence, but is applicable to PWR environments only. Methods to incorporate other important environmental influences on fatigue crack growth into design codes have yet to be established.

Research and Development Need

For BWR HWC it would be advantageous to develop new crack growth reference curves since the current ASME XI wet curves are pessimistic under these conditions. It is possible that ASME Code Case N-643-2, which defines criteria which determine whether or not time dependent fatigue crack growth occurs may be directly applicable to BWR HWC conditions, although there may be a need for redefinition of the threshold criteria. For BWR NWC, time dependent EAC is expected to occur over a wider range of conditions.

Outline Work Program

Recent data on corrosion fatigue crack growth requires analysis using an approach similar to ASME Code Case N-643-2 in order to determine appropriate reference crack growth curves for BWR normal and hydrogen water chemistry conditions which recognize the significant influence of transient rise time, steel sulfur content and water chemistry. Separate curves are expected to be appropriate to HWC and NWC. There is a possible need for some additional data generation.

This gap relates to carbon and low alloy steels in BWR HWC and NWC environments.

Sequence

This gap has no dependencies on other gaps.

Outcome

Improved reference crack growth relationships for carbon and low alloy steels exposed to BWR normal and hydrogen water chemistry environments would be developed which recognize the influence of several important parameters such as transient rise time, steel sulfur content and water chemistry (HWC, NWC) . It is possible that the expressions in ASME Code Case N-643-2 for PWR conditions may be appropriate for BWR hydrogen water chemistry also.

Gap 30: Dynamic Strain Aging Effects for Ferritic Steels

Gap 30 states that the mechanistic understanding [of crack growth for ferritic steels] is better than for austenitic SS but some uncertainties remain, e.g. influence of time dependent material deformation behavior, e.g. dynamic strain aging.

Hypothesis

This gap relates to Hypothesis 7 (Category D) and is allocated a MEDIUM PRIORITY

Context from the Gap Analysis [Page 4-2, 4-7, 5-5, 5-6 and 6-3]

Fatigue crack growth rates in carbon and low alloy steels are enhanced under oxidizing conditions, which is consistent with a slip oxidation/dissolution mechanism of crack advance. An important influencing factor for EAF in ferritic steels is the sulfur content of the steel, with greater environmental influences on both fatigue life and crack growth being observed for higher sulfur content steels, This can be rationalized using a slip dissolution mechanism since an increased sulfur content in the crack enclave arising from dissolution of MnS inclusions in the steel increases the dissolution rate of bare metal following local rupture of the passive film and hence increases crack advance. Support for this hypothesis is provided by the fact that additions of sulfur-bearing anions to the bulk environment have a similar effect to sulfur in the steel. High water flow rates have been shown to reduce the environmental enhancement, especially in PWR environments, which has been rationalized in terms of flushing of the local crack tip environment. The hypothesis is also consistent with the observed larger environmental effect in oxidizing environments since the potential gradient between the crack mouth and crack enclave serves to retain the aggressive environment close to the crack tip, as well as reducing the local pH. In PWR environments, where there is no potential gradient to maintain the crack tip environment, it has been shown that a critical crack velocity is required to maintain the aggressive crack tip environment. If this condition is not achieved, environmentally enhanced crack growth is not sustained. This crack velocity criterion is incorporated into ASME Code Case N-643. In the case of crack initiation, local dissolution of outcropping inclusions or, under oxidizing conditions, pitting, may provide the initial crevice in which the aggressive environment is produced.

Some published corrosion fatigue data appear inconsistent with the above mechanistic description, in that high crack growth rates have been reported for specific low sulfur, low alloy steels in PWR environments at temperatures somewhat below normal PWR operation. Some heats of low alloy steel show significant dependency of tensile deformation behavior on both temperature and strain rate due to dynamic strain aging and it has been hypothesized that this may be the cause of the anomalous crack growth behavior.

Research and Development Need

Further research is warranted to develop understanding of the possible influence of dynamic strain aging on corrosion fatigue as an aid to understanding some anomalous published data.

Outline Work Program

The nature of this research requires further consideration. A combination of crack growth testing, measurements of tensile properties as a function of strain rate and temperature for different heats of material, and more fundamental materials characterization may be required.

Sequence

This study is not directly dependent on other identified knowledge gaps.

Outcome

The work would inform understanding of factors influencing corrosion fatigue of ferritic steels and may ultimately assisted the development of material specific crack growth curves.

Gap 38: Assessment Procedures for Weldments

Gap 38 states that whilst there are some data concerning the behavior of welded features, there is a lack of data to account for aspects such as geometric stress concentration factor, weld defects, residual stress and multiaxiality, all of which may be influential.

Hypothesis

This gap relates to Hypothesis 5 (Category C) and is allocated a MEDIUM PRIORITY

Context from the Gap Analysis [Page 9-13]

ASME III-NB specifies the use of fatigue strength reduction factors for weldments which multiply the stress range used to calculate the fatigue life. Fatigue strength reduction factors are considered to be a geometrical influence related to local structural discontinuities and are therefore equated to stress concentration factors. ASME Section III-NB gives fatigue strength reduction factors for some common weldment geometries. Some designers consider that for dressed weldments, the fatigue strength reduction factor is unity. Alternatively, for non-dressed weldments where stress analysis has accounted for the shape of the weld, then the fatigue strength reduction factor is accounted for in the stress analysis and no further factor is necessary.

The UK R5 procedure recognizes that a weldment fatigue strength reduction factor can comprise both a geometrical component and a metallurgical component. The metallurgical aspect relates to the presence of a hard weld metal in a softer parent material which therefore acts as an additional stress concentrating feature. Fatigue strength reduction factors for various weldments are specified, the lowest for a fully dressed weldment being 1.5.

Other procedures such as KTA specify different values to those given in ASME III-NB or R5 so that there is no common agreement on the treatment of weldments. Since corrosion fatigue is a mechanism which enhances the rate at which fatigue cracks initiate but the nature of this mechanism is not fully understood, then it should not be presumed that the existing code methods for the treatment of weldments are adequate. The lack of data in this context represents a significant knowledge gap in the treatment of plant components.

Very few experimental data have been presented concerning the treatment of weld metal or weldments in a corrosion fatigue environment. Some Japanese experimental data are available which suggest that corrosion fatigue behavior of weld metal is bounded by wrought material. Similarly, UK data suggest that environmental fatigue crack growth rates in Type 308L weld metal are bounded by those for Type 304/304L stainless steel.

NUREG/CR-6909 makes no mention of weld metal or weldments for carbon steels, low alloy steels and stainless steels. For nickel based alloys, the same F_{en} factors are specified for parent metal and welds. The Japanese EFEM procedure specifies the same F_{en} factors for each of these three material types and their corresponding welds.

Research and Development Need

There is a general need to understand whether weld related features can lead to differences in EAF behavior compared to parent materials. Two specific issues are relevant; differences in the intrinsic behavior (both S-N and crack growth) of wrought materials and weld metal, and possible effects of geometry and stress concentrators in weldments. The work outlined here is focused on the second of these issues. Material specific differences are covered under Gap 37.

Outline Work Program

S-N testing of welded features in reactor water environments is required to establish whether or not the behavior of welded features can be bounded by smooth specimen S-N data or where correction factors are needed. Nothing should be presumed about the fatigue behavior of welded joints in reactor water since tests have not been performed.

Potentially this could be a very extensive testing program involving many variables. All the parameters used to establish F_{en} factors for various materials and various environments are relevant. In additions, aspects specific to the fatigue of welded joints such as inclusions, weld toe undercut, surface dressing, material mismatch, residual stress and joint type (geometry and loading type) also need to be considered.

Welded features in a laboratory air environment contain inherent defects which shorten their fatigue life compared to smooth specimen parent material data. The expectation is that the fatigue life of welded features in reactor water will also be reduced compared to smooth specimen data. It is noted however, that corrosion fatigue issues with welded features in reactor environments have not been confirmed in the literature.

Some specific features in water environments should be tested in the first instance, and compared to smooth specimen S-N data under the same conditions. These tests are exploratory, to establish whether or not an issue exists. A view on the behavior of welded features should be established, together with a view on the need for a more extensive test program to quantify the differences.

The knowledge gap relates to PWR and BWR water environments, in carbon and low alloy steels, austenitic stainless steel and nickel based alloys.

Sequence

This gap does not depend in the resolution of any other gaps. Given the potential long term nature of the program, some testing of welded features should begin as soon as reasonable practicable.

The interpretation of fatigue tests on welded features is dependent on progress with the resolution of Gap 4 (Priority 1), *reasons for differences between laboratory tests and plant conditions*.

Outcome

It will be established whether or not an issue exists with the fatigue life of welded features in reactor water environments. The extent of necessary testing work will become clear.

Gap 40: Application of Simplified Assessment Procedures to EAF

Gap 40 states that the method of stress indices commonly used for simplified piping analysis requires further development for corrosion fatigue assessments.

Hypothesis

This gap relates to Hypothesis 6 (Category C) and is allocated a MEDIUM PRIORITY

Context from the Gap Analysis [Page 9-12]

In addition to the full assessment methodology (ASME NB-3200), simplified rules can be used for certain components such as piping. The Japanese EFEM approach gives further guidance for incorporating the F_{en} approach into these component specific rules. For all components, any of the three methods to calculate the F_{en} factor can be used, singly or in any suitable combination. Also, for all components, the vessel rules for determining the sign of the strain rate can be used. Additionally for some component types, specific rules relate to the way the strain rate may be calculated and signed (as positive or negative) using component specific simplifications. Both the vessel rules and component specific rules represent an increase in calculation complexity when consideration of corrosion fatigue is required.

For piping, both JSME simplified rules and the ASME NB-3600 procedure use the simplified method of stress indices which generally does not require time histories of stress or strain. Stress indices can be thought of as component specific stress concentration factors. For example, the bending of a hollow pipe is different from the bending of a solid beam since pipe ovalization occurs. The stress index is a multiplication factor accounting for the additional stress due to ovalization so that simplified beam calculations can be used for a piping system.

In the EFEM procedure, the method of stress indices is retained with the addition that the strain rate for the transient with the largest temperature difference, among the combination of transients being evaluated, can be used as the strain rate for the relevant combination of transients. Hence, an analysis of strain history is now required, which is an additional complication. Alternatively, the method for vessels can be used which introduces a significant calculation complexity compared to the method of stress indices.

A further complication occurs due to the method of stress indices itself. The specified stress index is appropriate to the position of maximum stress in a pipe cross section which therefore corresponds to the position of maximum strain rate. However, the F_{en} factor is maximized at the position of minimum stress concentration factor corresponding to the minimum strain rate so that it is not self-evident at which position the maximum corrosion fatigue damage occurs. It is noted in Section 7 of the gap analysis report that pipe elbow fatigue tests failed at a different location with an air environment and a simulated PWR environment.

Research and Development Need

Further testing and analysis work is required to develop and validate simplified assessment methods for specific components.

Outline Work Program

The method of stress indices for piping should be developed for corrosion fatigue damage, accounting for the possible changes to the failure location compared to fatigue in a non-corrosive environment. The effects of both strain range and strain rate need to be considered. Development of piping codes will be required against which the revised method of stress indices can be validated in the first instance. Some validation tests may be required in the longer term.

The knowledge gap relates to PWR and BWR water environments, in carbon and low alloy steels, austenitic stainless steel and nickel based alloys.

Sequence

This gap has no dependencies on other gaps.

Outcome

Revised short cut methods for piping analysis will result.

Gap 42: Analysis to Aid Understanding of Methods for Evaluation of Complex Transients

Gap 42 states that the procedures for determining a cycle specific F_{en} factor are very important since they underpin the application of test data to plant assessment. Test data supporting averaging procedures for treatment of cyclically varying temperature, strain rate and stress (tension or compression) are sparse and this represents a significant uncertainty. There is a need to understand real behavior under temperature variable conditions.

Hypothesis

This gap relates to Hypothesis 1 (Category A) and is allocated a MEDIUM PRIORITY

Context from the Gap Analysis [Page 9-7]

The majority of fatigue damage to a LWR plant is attributable to thermal cycling so that individual fatigue cycles experience variable temperature, variable strain rate and variable stress which can alternate between tension and compression. Guidance is provided in NUREG/CR-6909 on procedures which may be adopted when parameters vary around a cycle. It is noted that the procedure requires determination of a cycle specific F_{en} factor based on the average or weighted average of the influencing parameters around the cycle.

Consider as an example the following thermal transient cycle. A thermal down-ramp is suddenly applied to a surface. The strain rate is initially high (minimizing the corrosion influence), the strain rate is positive (maximizing the corrosion influence) and the temperature is reducing (minimizing the corrosion influence). The rapid thermal down-ramp is then followed by a gentle thermal up-ramp to complete the cycle. The strain rate is initially low (maximizing the corrosion influence), the strain rate is negative (minimizing the corrosion influence) and the temperature is increasing (maximizing the corrosion influence).

The cycle is complex and the various influencing parameters are changing up and down together in a non-linear relationship. The specific details of the averaging procedure used can have a profound effect on the calculated outcome. It can easily be envisaged that two such cycles with different parametric rates can have the same calculated F_{en} factor, but behave quite differently with regard to corrosion fatigue damage.

Research and Development Need

Analysis is required to understand how the necessary simple representation of complex plant transients results in conservatism.

Outline Work Program

Stress-strain hysteresis loops appropriate to plant thermal transients involve continuously variable strain rates, both positive and negative. This is as a result of continuously variable load and continuously variable temperature, resulting in continuously variable material properties. Analysis is required to consider how a definition of instantaneous corrosion fatigue damage rate based on instantaneous strain rate can be integrated to give a cycle specific F_{en} factor, without making simplifying and conservative assumptions. To do this, means for accurately constructing hysteresis loops are required accounting for cyclic hardening (or softening) behavior and continuously varying temperature and material properties. Such methods are available and should be considered here. Calculations using these more sophisticated procedures should be compared to simple averaging rules to consider the conservatism of the latter.

The knowledge gap relates to PWR and BWR water environments, in carbon and low alloy steels, austenitic stainless steel and nickel based alloys.

Sequence

This links to Gap 39 (Priority 1), *strain rate calculations for complex transients*, and follows from it. It also links to Gap 14, *mean stress effects on threshold strain range and upper cycle limit*, and follows from it.

This gap also relates closely to Gap 43, *rules for simultaneous temperature and strain variations*, and could be combined with it into a joint work program.

Outcome

More realistic and less conservative means of calculating cycle specific F_{en} factors will result.

Gap 43: Rules for Simultaneous Temperature and Strain Variations

Gap 43 states that NUREG/CR-6909 lacks guidance on the procedure to be followed for stainless steel when both strain rate and temperature vary during a cycle. Thus the NUREG/CR-6909 model does not consider the possibility that one or more of the influencing parameters may be outside its threshold value at all times during a cycle so that the combined influence may be reduced or negated.

Hypothesis

This gap relates to Hypothesis 1 (Category A) and is allocated a MEDIUM PRIORITY

Context from the Gap Analysis [Page 9-4 and 9-7]

The majority of fatigue damage to a LWR plant is attributable to thermal cycling so that individual fatigue cycles experience variable temperature, variable strain rate and variable stress which can alternate between tension and compression. Guidance is provided in NUREG/CR-6909 on procedures which may be adopted when parameters vary around a cycle. It is noted that the procedure requires determination of a cycle specific F_{en} factor based on the average or weighted average of the influencing parameters around the cycle.

Consider as an example the following thermal transient cycle. A thermal down-ramp is suddenly applied to a surface. The strain rate is initially high (minimizing the corrosion influence), the strain rate is positive (maximizing the corrosion influence) and the temperature is reducing (minimizing the corrosion influence). The rapid thermal down-ramp is then followed by a gentle thermal up-ramp to complete the cycle. The strain rate is initially low (maximizing the corrosion influence), the strain rate is negative (minimizing the corrosion influence) and the temperature is increasing (maximizing the corrosion influence).

The cycle is complex and the various influencing parameters are changing up and down together in a non-linear relationship. The specific details of the averaging procedure used can have a profound effect on the calculated outcome. It can easily be envisaged that two such cycles with different parametric rates can have the same calculated F_{en} factor, but be behaving quite differently with regard to corrosion fatigue damage.

Research and Development Need

The concept of the ‘modified rate approach’ could reasonably be applied as the weighted average of the combined F_{en} factor around the cycle. Work is required to develop and validate a suitable method for treatment of variations in both temperature and strain rate, and also to provide a realistic treatment of variable temperature transients.

Outline Work Program

Analysis is required to develop methods for the treatment of cycles where both temperature and strain rate vary simultaneously.

This gap relates very closely to Gap 42, *analysis to aid understanding of methods for evaluation of complex transients*, and could be combined with it into a joint work program.

The knowledge gap relates to PWR and BWR water environments, in carbon and low alloy steels, austenitic stainless steel and nickel based alloys.

Sequence

This gap is related to Gap 41 (Priority 1), *variable strain rate effects*, and follows from it.

Outcome

More realistic and less conservative means of calculating cycle specific F_{en} factors will result.

Gap 44: Understanding of Mean Stress Effects on LCF and HCF

Gap 44 states that the extent to which mean stress influences both low cycle fatigue and high cycle fatigue of stainless steel in air, and an appropriate means by which is should be accounted for, are considered to be significant knowledge gaps.

Hypothesis

This gap relates to Hypothesis 6 (Category C) and is allocated a MEDIUM PRIORITY

Context from the Gap Analysis [Page 10-10]

The issue of mean stress is an important consideration in the treatment of high cycle fatigue as follows. Operational thermal transients are high strain range and low frequency events. Superimposed on these can be high frequency, low amplitude events from mechanical vibrations or local thermal instabilities. These high frequency transients can occur under tensile mean stress or compressive mean stress depending on when they occur within the operational transient, i.e. during an up-ramp or a down-ramp. Thus the influence of positive or negative mean stress is important in the consideration of high cycle fatigue.

The influence of mean stress is included in the ASME Section III-NB fatigue design curve by an adjustment using a Goodman relationship to the test data (see Gap 6). The means by which the adjustment is applied results in the adjustment being sensitive to yield stress so that the adjustment is only important at the high cycle part of the fatigue curve. In the ASME criteria document, the mean stress correction was not applied to stainless steel fatigue data. NUREG/CR-6909 specifies that in deriving the revised air design curve for stainless steel, the Goodman mean stress correction has been applied. Because of strain hardening and cyclic hardening, stainless steel does not exhibit a sharply defined yield stress. NUREG/CR-6909 does not specify the magnitude of stainless steel yield stress used to apply the correction. Higher values will result in the Goodman correction influencing low cycle fatigue. Thus, both high cycle fatigue and low cycle fatigue of stainless steel may be sensitive to mean stress.

Research and Development Need

Further analysis may be required to address this issue which is important to prevent undue conservatism.

Outline Work Program

Analysis is required to investigate the application of S-N curve mean stress correction factors to stainless steel. A number of different methods of doing this, in addition to the modified Goodman correction are available and should be considered. Both positive and negative mean stress should be addressed. The influence of cyclic hardening or softening in the temperature range of interest for PWR and BWR applications should be included.

Sequence

This gap links to Gap 14, *mean stress effects on threshold strain range and upper cycle limit*, since a mean stress correction will be influential in the threshold regime.

It also relates closely to Gap 6, *application of Goodman correction for strain and cyclic hardening materials*, and could be combined with it into a joint work program.

Outcome

The mean stress correction to stainless steel S-N data will be more robustly quantified.

Gap 45: Implications for Inspection Requirements

Gap 45 states that there is a lack of understanding of the extent to which the inclusion of environmental effects on fatigue will influence inspection programs with regard to how to inspect, when to inspect and where to inspect.

Hypothesis

This gap relates to Hypothesis 6 (Category C) and is allocated a MEDIUM PRIORITY

Context from the Gap Analysis [Page 10-12]

Inspection requirements are often informed by design code assessment of fatigue damage since this provides information on when to inspect, where to inspect and, from the anticipated crack morphology, how to inspect. These three aspects are likely to vary between fatigue cracking in air and corrosive environments. A more comprehensive understanding of the implications of corrosion fatigue to determine appropriate inspection requirements is required. It is unclear that the component rankings for CUF based on inert fatigue assessments are correct if EAF is occurring; moreover, cracking locations may differ in these two cases.

Risk based inspection programs may be implemented. The probability that a component can fail from all known failure mechanisms and the consequence of that component failing are compounded to identify a risk ranking. The risk ranking then informs an inspection program to mitigate against the risks.

Research and Development Need

A review of the implications of environmentally assisted fatigue to inspection requirements is required.

Outline Work Program

A review of inspection requirements is required to consider when to inspect (according to anticipated crack growth rates), where to inspect (according to anticipated failure locations) and how to inspect (according to anticipated crack morphology). Detailed understanding of these three aspects of corrosion fatigue behavior will be required for the review to be definitive.

Sequence

This gap is dependent on the resolution of many other gaps related to procedures for assessment of crack initiation and growth, observations of cracking and mechanistic understanding. In particular, this gap is dependent on Gap 31 (Priority 1), *mechanistic understanding of enhanced* *crack growth in SS*, Gap 16, *thermal cycling features tests* and Gap 33, *testing for plant component representative geometries and loading*, and follows from them.

This gap is also dependent on Gap 4 (Priority 1), *reasons for differences between laboratory tests and plant conditions*. If corrosion fatigue is not established as a relevant damaging mechanism for plant conditions then revised inspection requirements will not be required.

Outcome

Revised guidance on inspection requirements will result.

6
PRIORITY 3 ROADMAP

Structure of the Priority 3 Road Map

The Priority 3 Road Map is structured as for the Priority 1 and 2 Road Maps. Figure 6-1 gives the Priority 3 Gaps in the context of the knowledge evaluation process. Figure 6-2 gives a suggested sequencing. Some of the Priority 3 Gaps have dependencies on Priority 1 Gaps and should sensibly follow from them. Similarly, they provide further information to the Priority 1 Gap 4 which is a knowledge evaluation gap to further aid its resolution. The dependencies between Priority 3 Gaps and Priority 1 Gaps are shown in Figure 6-2.

Figure 6-1 (the knowledge evaluation process), Figure 6-2 (the suggested sequence) and the discussion below of each individual Priority 3 Gap, together comprise the Priority 3 Road Map.

A discussion of the individual gaps follows.

Summary of the Expected Outcomes

The resolution of the Priority 3 Gaps will provide data and information to further resolve three key aspects of the Knowledge Evaluation Scheme, Figure 6-1, these being:

1. test of hypotheses for coherent phenomenological understanding,
2. development of mechanistic understanding,
3. development of assessment procedures.

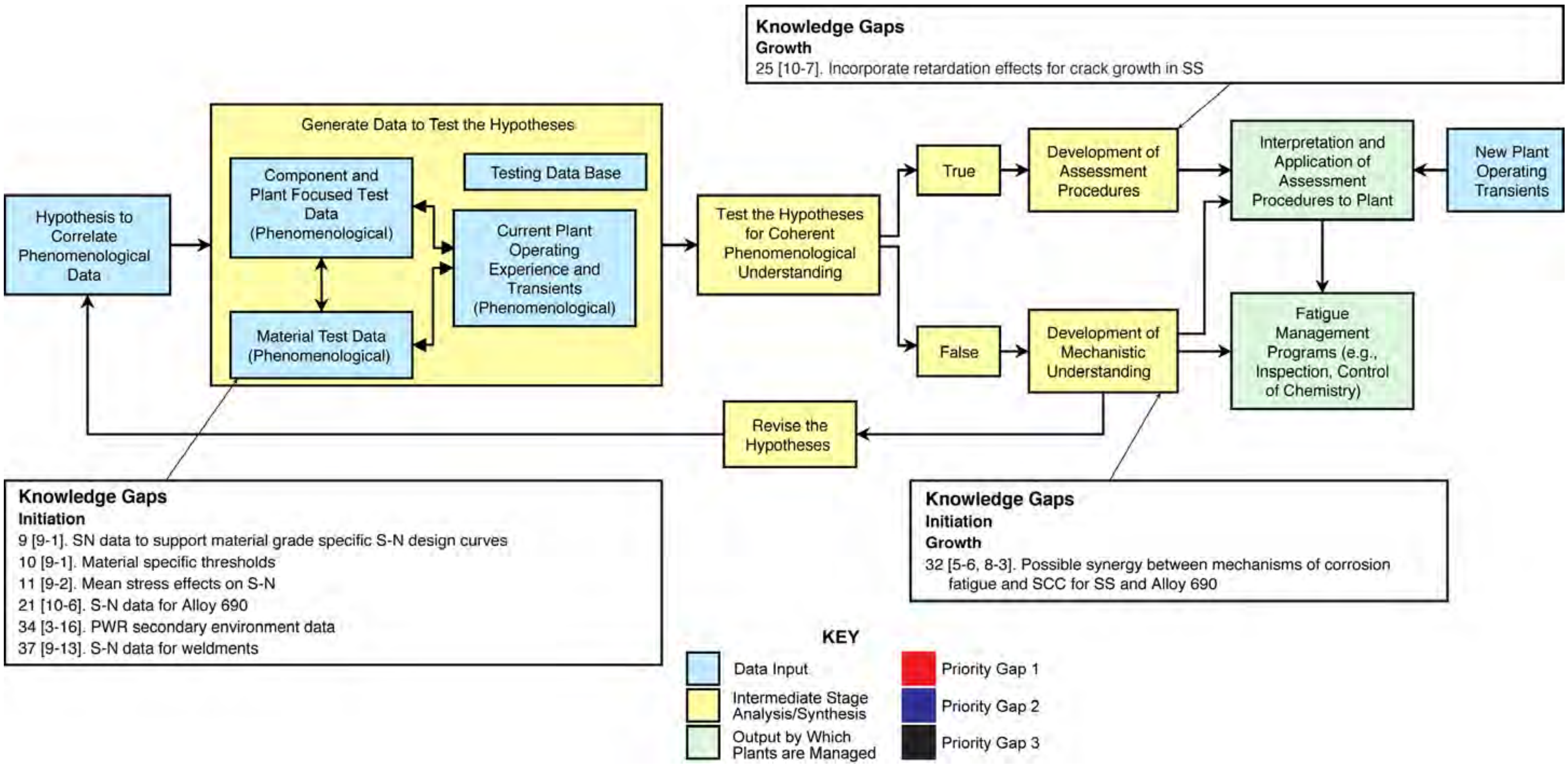

Figure 6-1
Knowledge Evaluation Scheme with Priority 3 Gaps Indicated

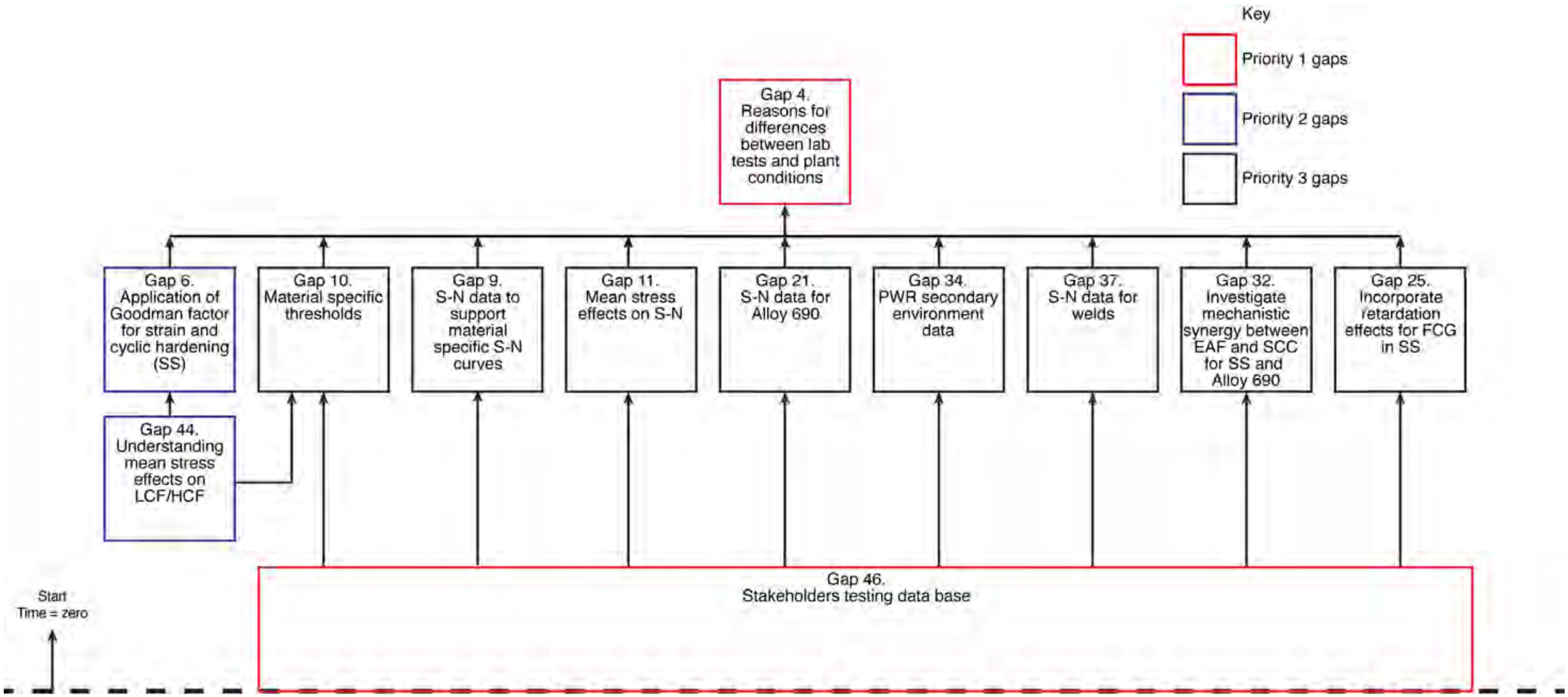

Figure 6-2
Priority 3 Gap Dependencies by Time Sequence & Connectivity

Gap 9: S-N Data to Support Material Grade Specific S-N Inert Design Curves

Gap 9 states that the generic stainless steel inert fatigue design curve for stainless steels may prove difficult to apply since it appears to be too conservative in the high cycle fatigue regime for some materials. Material specific, high cycle Design Fatigue Curves may be preferred in some cases.

Hypothesis

This gap relates to Hypothesis 5 (Category C) and is allocated a LOW PRIORITY

Context from the Gap Analysis [Page 9-1]

In addition to addressing environmental effects, NUREG/CR-6909 identified that the air curve for stainless steels in the ASME Section III code at the time of writing that report was inconsistent with the body of available data for austenitic stainless steels and a revised mean air curve was therefore proposed for evaluation of fatigue usage for ASME Class 1 stainless steel components. The adjustment factor used to derive the design curve from mean data was modified from 12 to 20 on cycles which provided some benefit in the low cycle, high stress range regime. However, the modified design fatigue curve predicts shorter fatigue lives than the earlier ASME curve in the mid to high cycle region due to incorporation of additional S-N data in the analysis and the fact that the adjustment factor on stress was left unchanged at 2. This change may present problems to designers, even without consideration of environmental influences. A heat-to-heat sensitivity is also apparent for stainless steel high cycle fatigue which is not so significant for stainless steel low cycle fatigue. A generic stainless steel fatigue design curve for stainless steels may therefore be difficult to apply and material specific, high cycle Design Fatigue Curves may be required.

Research and Development Need

If there is a need to refine the inert fatigue curve for specific material grades, additional high cycle fatigue initiation life data will be required. Alternatively, or additionally, it may be possible to argue that the factor of 2 applied on stress in the high cycle regime is too conservative, see Gap 3.

Outline Work Program

S-N tests for specific grades of stainless steel are required to account for heat-to-heat variability. Data are required specifically in the mid cycle to high cycle regime. These data could be used to develop grade specific Design fatigue Curves.

This gap applies to all material in both PWR and BWR water environments, but may be particularly significant for stainless steel materials.

Sequence

The grade specific S-N data would sensibly follow from Gap 46 (Priority 1), *stakeholder testing data base*, and should follow from it. The development of Design Fatigue Curves will require the resolution of Gap 3 (Priority 1), *revised correction factors on stress*, Gaps 6 (Priority 2), *application of Goodman correction for strain and cyclic hardening materials* and Gap 44 (Priority 2), *understanding of mean stress effects on LCF and HCF*, and follow from them.

Outcome

Reduced conservatism in Design Fatigue Curves for some grades of stainless steel, in the mid to high cycle regimes may result.

Gap 10: Material Specific Thresholds for EAF

Gap 10 states that there is a lack of data concerning the definition of material specific thresholds for the occurrence of EAF. This is likely to contribute importantly to the identification of components for which h consideration of environmental effects is not required. This is particularly so for stainless steel.

Hypothesis

This gap relates to Hypothesis 5 (Category C) and is allocated a LOW PRIORITY

Context from the Gap Analysis [Page 9-1]

In NUREG/CR-6909, the F_{en} factor for ferritic and austenitic steels is determined quantitatively from transformed values based on applied strain rate ($\dot{\varepsilon}^*$), temperature (T*), DO content (O*), and, for ferritic steels only, on steel sulfur content (S*). Some of these transformed values are subject to threshold values such that the transformed parameter is zero if its threshold value is not satisfied. Environmental effects on fatigue life are significant only when critical parameters (temperature, strain rate, DO level and strain range) meet certain threshold values. Environmental effects are moderate, e.g. less than a factor of 2 decrease in life, when any one of the threshold conditions is not satisfied. NUREG/CR-6909 has proposed revised fatigue design curves for use for non wetted defects in carbon steels, low alloy steels and stainless steels. In the high cycle regime, the proposed carbon and low alloy steels design curves are less conservative than the original ASME curves. For stainless steels, the proposed curves are considerably more conservative, typically by an additional factor of two on strain range. Application of the environmental enhancement factor (F_{en}) approach to these modified air curves is likely to present problems to designers under some conditions. A heat-to-heat sensitivity is apparent for stainless steel high cycle fatigue which is not so significant for stainless steel low cycle fatigue. A generic stainless steel fatigue design curve for stainless steels may therefore be difficult to apply and material specific, high cycle Design Fatigue Curves may be required.

Research and Development Need

High cycle EAF initiation threshold data may be required for different grades of stainless steels. The possibility of heat-to-heat variability may also need to be considered. The thresholds may relate most significantly to the strain range below which consideration of environmental effects is not necessary. Temperature thresholds should also be considered.

Outline Work Program

Environmental fatigue initiation S-N tests may be required with zero mean stress for specific grades of stainless steel, to investigate the grade specific strain range below which, or the number of cycles above which a F_{en} factor need not be applied. These tests should be isothermal at various temperatures, include various strain rates and various levels of DO. For stainless steels, various levels of sulfur content may also be important, although this has not been demonstrated so far, see Gap 20. It may also be necessary to consider mean stress effects in the grade specific thresholds.

This gap applies to all materials in both PWR and BWR water environments, but is particularly significant for stainless steels.

Sequence

The grade specific threshold data would sensibly follow from Gap 46 (Priority 1), *stakeholder testing data base*, and should follow from it. The inclusion of mean stress effects will require the resolution of Gaps 6 (Priority 2), *application of Goodman correction for strain and cyclic hardening materials* and Gap 44 (Priority 2), *understanding of mean stress effects on LCF and HCF*, and follow from them.

This gap and Gap 9 (Priority 3) concerned with grade specific S-N curves in air require a very similar testing approach and could be combined into a single work package.

Outcome

Improved understanding of threshold behavior will result, identifying any conditions for which corrosion fatigue assessment is not required.

Gap 11: Mean Stress Effects on S-N Design Curves

Gap 11 states that there is likely to be a significant influence of mean stress on EAF which is not adequately quantified by existing test data.

Hypothesis

This gap relates to Hypothesis 2 (Category A) and is allocated a LOW PRIORITY

Context from the Gap Analysis [Page 9-2]

The Criteria of the ASME Boiler and Pressure Vessel Code document specifies that a modified Goodman approach should be used to adjust the high cycle laboratory fatigue data for the most conservative effect of mean stress. For low cycle fatigue, the mean stress for test data is always zero. This is because plastic strain occurs at both the positive stress/strain quadrant and the negative stress/strain quadrant of the hysteresis loop so that the cycle will become symmetrical at zero mean stress. Therefore, a mean stress correction is not appropriate for low cycle fatigue. For high cycle fatigue and for materials where the yield stress is greater than the endurance limit, it is possible for the stress cycle to be from tensile yield downwards, so that a positive mean stress can exist. Thus the Criteria document specifies that the most conservative mean stress correction be applied to high cycle fatigue data on this basis, where applicable. The adjustment is applied to carbon and low alloy steels since the endurance limit is less than the yield stress but is not normally applied to stainless steel since the endurance limit is stated to be greater than the yield stress.

NUREG/CR-6909 states that the modified Goodman mean stress correction has been applied to stainless steel in deriving the revised Design curves. However, no details are given as to how this was done.

Research and Development Need

There is a need to develop additional data to establish the influence of positive and negative mean stress.

Outline Work Program

Isothermal S-N data required with non-zero mean stress, both positive and negative. Testing at various strain rates, temperature and DO are required.

This gap applies to all materials in both PWR and BWR water environments, but is particularly significant for stainless steels.

Sequence

This gap follows from Gap 46 (Priority 1), *stakeholder testing data base.* This gap relates closely to the analytical tasks of Gap 6 (Priority 2), *applicability of the Goodman correction for strain and cyclic hardening materials* and Gap 44 (Priority 2) *understanding of mean stress effects on LCF and HCF* and follows from them to provide additional supporting data.

Outcome

The influence of positive and negative mean stress will be established leading to improved assessment procedures.

Gap 21: S-N Data for Alloy 690

Gap 21 states that the existing data for nickel based alloys (Alloy 600, 182 and 82) are limited. NUREG/CR-6909 provides F_{en} factors for nickel based alloys based on these limited data and Regulatory Guide 1.207 recommends that these factors be applied to the new austenitic stainless steel air curve. Data on Alloy 690 and its weld metals are very limited.

Hypothesis

This gap relates to Hypothesis 5 (Category C) and is allocated a LOW PRIORITY

Context from the Gap Analysis [Page 3-17]

It was highlighted in NUREG/CR-6909 that fatigue data for Ni-Cr-Fe alloys in LWR environments are very limited in quantity. Where comparisons were possible it was observed that the effects of key loading and environmental parameters on fatigue life are similar to those for austenitic stainless steels. For example, it was noted that the fatigue lives of these alloys decrease logarithmically with decreasing strain rate, and also that the effects of environment are greater in the low-DO PWR water than the high-DO BWR water. The existing data were considered inadequate to determine accurately the functional form for the effect of temperature on fatigue life. As a result of the limited database and identified uncertainties, Regulatory Guide 1.207 recommends that the new austenitic stainless steels air design curve given in NUREG/CR-6909 are acceptable for use in Cr-Ni- Fe alloys environmental fatigue F_{en} evaluations.

The JSME method for NPP component environmental fatigue evaluation provides expressions to calculate F_{en} for Ni-Cr-Fe alloys and their welds in LWR environments:

$$\ln(F_{en}) = (C - \dot{\varepsilon}^*)T^*$$

where T^* and $\dot{\varepsilon}^*$ are transformed temperature and strain rate respectively. Expressions for PWR primary and secondary, and BWR environments are provided.

The database from which these equations were developed was generated primarily from testing of Alloy 600. NUREG/CR-6909 states that fatigue S-N data for Ni-Cr-Fe alloys indicate fatigue lives of Alloy 690 are comparable to those of Alloy 600, although it was acknowledged that this observation is based on a limited quantity of data for Alloy 690. Fatigue lives of the Ni-Cr-Fe alloy welds were considered comparable to those of the wrought Alloys 600 and 690 in the low-cycle regime, i.e., $<10^5$ cycles, and slightly superior to the lives of wrought materials in the high-cycle regime.

Research and Development Need

Further data on nickel based alloys would lead to refinement of the F_{en} values; however the effects are significantly less than for stainless steel and, in practice, for Alloy 600, SCC is likely to be more significant. However, this is unlikely to be the case for Alloy 690 which is much more resistant to SCC. More data to confirm behavior for Alloy 690 (and weld metals) may be warranted.

Outline Work Program

Isothermal S-N data for Alloy 690 (and weld metals) are required with various mean stress levels, zero, positive and negative. Testing at various strain rates and temperatures may be required. Because of the expectation of higher corrosion fatigue endurance than for stainless steels, testing at non-zero mean stress may be less important.

This gap relates to nickel based alloys in PWR environments. Alloy 690 is not currently used for BWR applications.

Sequence

This gap follows from Gap 46 (Priority 1), *stakeholder testing data base.*

Outcome

Reduced conservatism in F_{en} factors for Alloy 690 (and weld metals) may result.

Gap 25: Incorporate Retardation Effects for Crack Growth in Stainless Steel

Gap 25 states that the effects of parameters influencing when retardation of enhanced crack growth occurs are not adequately understood. The possibility of crack growth rate retardation is not evident in the available data for BWR environments.

Hypothesis

This gap relates to Hypothesis 5 (Category C) and is allocated a LOW PRIORITY

Context from the Gap Analysis [Page 10-7]

For stainless steels, no crack growth reference curves are available in ASME Section XI for water wetted defects. However, the available fully enhanced data in PWR environments are fairly well described by the Mills model which forms the basis for the ASME Code Case N-809 now being developed. Data in BWR environments are somewhat more limited but appear to follow similar trends with regard to rise time dependency; recent data suggest that growth rates are slightly higher than in PWR environments which differ from the observed effects on fatigue initiation life. In some instances, the fully enhanced crack growth rates in PWR environments are not observed, with retardation of crack growth to rates quite close to the air line occurring following an increase in the rise time of the applied load. The factors influencing retardation are not sufficiently well characterized to allow benefit to be claimed in assessment procedures, but there are indications of an influence due to variations in R ratio, temperature, coolant flow rate and material composition. High sulfur content steels have been shown to be particularly prone to retarded crack growth, although the reasons are not adequately understood. More data are required if benefit is to be demonstrated from retarded rates, although material composition effects may make it difficult to provide generalized substantiation of retardation. No sources of data have been identified that show similar retardation under BWR normal water chemistry, but is likely that similar effects may occur in hydrogen water chemistry.

Research and Development Need

Further tests are required to identify the circumstances that may lead to crack growth rate retardation, and to quantify any predictable effect. If retarded rates could be demonstrated in a reproducible manner, this would allow benefit to be taken in assessment, removing unnecessary conservatism. However the large number of influencing variables may make it difficult to ensure that retarded will always be observed in specific circumstances.

Outline Work Program

A series of crack growth tests in simulated PWR coolant are required over a range of test conditions, including stress ratio (R), stress intensity factor range (ΔK) and water temperature. A number of different material compositions should be included in the test matrix, because it is known that some trace elements, such as sulfur, substantially influence retardation. An appropriate test methodology is to decrease rise times in a stepwise manner, initially by an order of magnitude at each step, until (or if) retardation is observed. After reverting to a short rise time, the sequence should be repeated to ensure consistence of the observations, using perhaps smaller step increments where appropriate. Definition of conditions for retardation has been shown to occur at a consistent value of ASME air crack velocity ($\dot{a}_{air}$) for specific heats of material, temperature, R ratio and water flow rate; it is therefore recommended that the time domain ($\dot{a}_e$ versus $\dot{a}_{air}$) approach to data presentation be used in evaluating the retardation threshold. If consistent behavior can be demonstrated, testing could be extended to BWR hydrogen water chemistry.

Sequence

This gap follows from Gap 46 (Priority 1), *stakeholder testing data base.*

Outcome

If consistent data confirming conditions under which retardation occurs can be obtained, this would lead to less conservative crack growth reference curves for austenitic stainless steel under certain conditions in PWR (and perhaps BWR HWC) environments.

Gap 32: Possible Synergy Between Mechanisms of Corrosion Fatigue and SCC for Stainless Steel and Alloy 690

Gap 32 states that existing uncertainties concerning SCC propagation behavior in Alloy 690 may have any implications for EAF, for which the available database is very limited.

Hypothesis

This gap relates to Hypothesis 5 (Category C) and is allocated a LOW PRIORITY

Context from the Gap Analysis [Page 5-6 & 8-3]

Environmentally assisted cracking (EAC) is a generic term which relates to cracking of susceptible materials in an appropriate environment over a range of different loading conditions. In all cases, there are three necessary conditions for cracking to occur: an appropriate stress (which may be constant, monotonically varying or cyclic); an environment which promotes EAC (high temperature water is relevant for reactor materials) and a susceptible material or material condition. When reviewing field experience of component failure that is attributed, in whole or in part, to environmental effects, it is necessary to be able to differentiate between EAF and other related mechanisms such as stress corrosion cracking (SCC), but this is not always easy. Where cracking occurs in plants, it is important that the correct degradation mechanism is identified in order that any corrective action is effective.

For austenitic stainless steels, there appear to be some similarities in materials composition effects on corrosion fatigue crack growth and SCC, the later occurring in PWR environments only when the material is in a cold worked condition. For example, high sulfur steels show much lower propensity to SCC in PWR chemistry than their low sulfur analogs, and retardation of corrosion fatigue crack growth also occurs much more readily for high sulfur steels. This suggests similar mechanistic influences, despite the difference in fracture morphologies. In the case of Alloy 690, moderate to high SCC growth rates are also measured for some heats when in a highly cold worked condition, despite this alloy usually being considered highly resistant to SCC. There is a need to consider whether these observation have any implications for corrosion fatigue in Alloy 690.

Research and Development Need

There is an initial requirement for additional data to expand the available database for corrosion fatigue crack growth of Alloy 690 in PWR environments (see Gap 27). Large variability in SCC susceptibility has been observed for different heats of this Alloy in a cold worked condition. It needs to be established whether similar variability in crack growth behavior might occur.

Outline Work Program

Additional test data on corrosion fatigue crack growth of Alloy 690 in a PWR environment is required to support Gap 27. The possible influence of Alloy composition and processing history needs to be considered. Guidance might be obtained from examining variability in SCC behavior.

The knowledge gap relates to nickel based alloys in PWR water environments.

Sequence

This gap follows from Gap 27, *Crack Growth Data for Alloy 690 and its weld Metals.*

Outcome

Additional data would lead to improved crack growth reference curves for Alloy 690 in PWR environments.

Gap 34: PWR Secondary Environment Data

Gap 34 states that very few data are available to establish the influence of PWR secondary water on EAF.

Hypothesis

This gap relates to Hypothesis 5 (Category C) and is allocated a LOW PRIORITY

Context from the Gap Analysis [Page 3-16]

The JSME rules are similar to NUREG/CR-6909, with the following notable difference. The JSME procedure is claimed to be applicable for both primary and secondary PWR environments. Secondary PWR environments are not addressed by NUREG/CR-6909. It is unclear what data are available to support applicability of the EFEM rules to secondary water conditions.

Research and Development Need

Generation of relevant data may be appropriate, e.g. for steam generator shells or tubing, but a benefit needs to be established first.

Outline Work Program

A review is required of available S-N data in secondary water to establish if sufficient data exist to derive F_{en} factors. Depending on the outcome, isothermal S-N data may be required with various means stress levels, zero, positive and negative. Testing at various strain rates, temperature and DO may be required.

The knowledge gap relates to PWR environments, in carbon and low alloy steels, austenitic stainless steel and nickel based alloys.

Sequence

This gap follows from Gap 46 (Priority 1), *stakeholder testing data base.*

Outcome

F_{en} factors for use in secondary water environments will be the outcome.

Gap 37: S-N Data for Weldments

Gap 37 states that data on weld metal are more limited than on parent materials but, where studied, appear to be bounded by parent data.

Hypothesis

This gap relates to Hypothesis 5 (Category C) and is allocated a LOW PRIORITY

Context from the Gap Analysis [Page 9-13]

Various approaches to considering the influence of weld features such as the use of fatigue strength reduction are discussed under Gap 38. The present Gap concerns the lack of available data for weld metal for comparison with parent material. Very few experimental data have been presented concerning the treatment of weld metal in a corrosion fatigue environment. Some Japanese experimental data are available which suggest that corrosion fatigue behavior of weld metal is bounded by wrought material. Similarly, UK data suggest that environmental fatigue crack growth rates in Type 308L weld metal are bounded by those for Type 304/304L stainless steel. NUREG/CR-6909 makes no mention of weld metal or weldments for carbon steels, low alloy steels and stainless steels. For nickel based alloys, the same F_{en} factors are specified for parent metal and welds. The Japanese EFEM procedure specifies the same F_{en} factors for each of these three material types and their corresponding welds.

Research and Development Need

Gap 37 relates to possible differences in the intrinsic S-N behavior of weld metals relative to wrought materials. More data on the behavior of weld metals are required and their may be a need for heat specific data.

Outline Work Program

Isothermal S-N data may be required for various weld metals with various mean stress levels, zero, positive and negative. Testing at various strain rates, temperature and DO are required. The requirement for this depends on the outcome from Gap 38 (Priority 2), *assessment procedure for weldments*. If the resolution of Gap 38 indicates that the distinctive features of weldments need not be considered specifically, then Gap 37 need only confirm that parent metal bounds the behavior of weld metal. If that is not the case, then a more comprehensive assessment of weld metals will be required to develop corrosion fatigue rules for the treatment of weldments.

The knowledge gap relates to PWR and BWR water environments, in carbon and low alloy steels, austenitic stainless steel and nickel based alloys.

Sequence

This gap follows from Gap 46 (Priority 1), *stakeholder testing data base*. It also follows from Gap 38 (Priority 2), *assessment procedure for weldments*, and should follow from it.

Outcome

Corrosion fatigue assessment procedures for the treatment of weldments will result.

7 ROADMAP OPTIONS

On the basis of the information presented here, two options are available on which a work program may be developed. Option 1 is to address knowledge gaps by grouping them in the order of priority and to consider each of these groupings in the context of the knowledge evaluation scheme. Option 2 is to consider individual hypotheses with all their associated knowledge gaps, high, medium and low priority, again in the context of the knowledge evaluation scheme. These two options are discussed below.

Option 1 is concerned with the testing of a large number of low level hypotheses which are each associated with resolving individual knowledge gaps. Option 2 is concerned with testing high level hypotheses which may be founded on a fundamental aspect related to stress-strain states, to conservatism inherent in design codes or mechanistically based.

Option 1 – Resolution of Knowledge Gaps by Priority

In the first instance, high priority knowledge gaps are resolved in the context of the knowledge evaluation scheme which is summarized in Figure 4-1. To do this it will be necessary to define a low level hypothesis specific to each knowledge gap which the resolution of the knowledge gap is intended to test. The main objective of addressing the high priority knowledge gaps is to consider differences between loading conditions in plant components compared to those in laboratory tests which is cited as one possible reason for the apparent discrepancy between plant experience and predictions of fatigue life based on laboratory test data (Category 1 in Section 3). This issue has been captured in Gaps 2 (Lack of correlation of predictions from laboratory data with plant experience) and Gap 4 (Reasons for differences between laboratory tests and plant conditions). In support of this objective, major work program activities identified include the following high priority knowledge gaps.

Database development

1. Development of a stakeholder testing database (Gap 46)

Development of assessment procedures to include

1. Revision of lower bound F_{en} value (Gap 1)
2. Revision of correction factor on stress in S-N design curve (Gap 3)
3. S-N curves for lower strength ferritic steels (Gap 5)
4. Strain rate calculation methodology for complex and variable strain rate transients (Gaps 39 and 41)
5. Codification of environmental effects on crack growth for stainless steel. This should include any benefit from threshold or retardation effects if this can be adequately justified (Gap 23)
6. Guidance for mitigated locations according to dissolved oxygen content (Gap 47)

Generation of component and plant test data in support of the following knowledge gaps

1. Thermal cycling S-N features tests (Gap 16)
2. S-N testing with complex transient loading (Gap 18)
3. Spectrum loading crack growth tests (Gap 28)
4. Testing for plant component representative geometries and loading (Gap 33)
5. Influence of multiaxial loading (Gap 36)

Generation of materials test data in support of the following knowledge gaps

1. S-N data for a wider range of temperature and strain rate combinations (Gap 13)
2. Non-isothermal S-N tests, both in- and out-of-phase (Gap 15)
3. Data to support strain rate calculation (Gap 17)

Understanding of plant transients

1. Development of improved understanding of real (as opposed to "design") plant transients (Gap 35)

Development of mechanistic understanding to address

1. Dependence of degree of environmental enhancement on strain amplitude of cycles (Gap 7)
2. Reasons for enhancement (and retardation) of crack growth in stainless steels (Gap 31)

Some of the above activities involve re-evaluation of existing data and may therefore provide benefit on a relatively short timescale such as possible revision of the high cycle air fatigue design curve and reduced environmental influence for low strain ranges. The development of a stakeholder database will support these shorter term developments. Certain test programs can begin in the relatively short term since they have no direct dependencies on other test programs. These include non-isothermal testing using in-phase and out-of-phase loading, crack growth testing using more representative cycles and examination of the appropriateness of non-contiguous cycle analysis. Certain test programs require input from other activities. Benefits will therefore accrue over longer timescales but have the potential to be substantial. These activities include generation of S-N data over a wider range of combinations of temperature and strain rate conditions, test data to evaluate methods of calculating strain rate for complex cycles, and thermal cycling features tests. The ultimate aim of developing improved and substantiated assessment procedures, consistent with mechanistic understanding and plant operating experience, necessarily requires resolution of a significant number of existing knowledge gaps. A sequence is suggested in Figure 4-2 by which those gaps could be addressed according to the dependencies between them and the need to acquire benefits in the short term, to be followed later by medium and longer term benefits. These are summarized at the beginning of Section 4 and given here as:

Short term benefits

Data may be identified which benefit designers, including circumstances where the influence of corrosion on fatigue damage is less marked or not relevant. Such benefits accrue from the re-evaluation of existing data and relate to:

1. correlations identified from the availability of a complete testing data base;
2. revision to the high cycle air fatigue design curve;
3. reduced environmental influence for low strain ranges;
4. possible mitigation due to close control of dissolved oxygen.

Intermediate term benefits

Certain test programs can begin in the short term since they have no dependencies on other programs. These tests may identify circumstances by which the rules for the treatment of corrosion fatigue can be mitigated to reduce conservatism. These aspects relate to:

1. comparison of in-phase and out-of-phase S-N test data;
2. treatment of non-contiguous cycles;
3. evaluation of crack growth with more representative cycles.

Longer term benefits

The designs of certain test programs are dependent on the outcome of other work. Also, some evaluation tasks require input from the resolution of knowledge gaps. Benefits from these aspects will accrue over a longer term and relate to:

1. S-N data for a wider range of temperature and strain rate conditions,
2. test data to validate the ‘modified rate’ approach or alternative approaches;
3. evaluation of differences between test data and plant conditions;
4. thermal cycling features tests;
5. improved and substantiated assessment procedures, consistent with mechanistic understanding and plant operating experience.

Following the resolution of high priority knowledge gaps, the knowledge evaluation scheme is then applied to medium priority gaps as shown in Figure 5-1. Again a sequence is suggested as shown in Figure 5-2 by which those gaps could be addressed according to the dependencies between them, although few have been identified, but recognizing more significantly dependencies from the High Priority Roadmap.

The knowledge evaluation scheme is then applied to low priority gaps shown in Figure 6-1 according to the sequence shown in Figure 6-2. In this case, no dependencies between them have been identified. There are however some dependencies from the High Priority and Medium Priority Roadmaps.

Option 2 – Resolution of Knowledge Gaps by Hypotheses

Section 3 lists seven high level hypotheses and their associated high priority, medium priority and low priority knowledge gaps. Each identified knowledge gap of any priority has been allocated against one of these hypotheses in Section 3. The list of high level hypotheses is not exhaustive and individual hypothesis will change as new knowledge is evaluated. In this option a specific hypothesis is tested by evaluating all of the associated knowledge gaps, high, medium and low priority. A high level review of these hypotheses is given below with a subjective view on the outcome of evaluating them.

Hypothesis 1 This concentrates on the nature of thermally induced stress cycles and suggests that they are not adequately represented by test data which are usually isothermal. This is not to say that thermal strain is fundamentally different to mechanical strain but rather that the behavior of cycles with the change of strain out-of-phase with the change of temperature is fundamentally different to isothermal test data. If this hypothesis is true, it will be a generic issue since most fatigue damage occurs from plant thermal transients.

Hypothesis 2 This advocates that compressive stress does not contribute to corrosion fatigue damage so that those parts of a stress-strain cycle where the surface stress is compressive should be disregarded. If this hypothesis is true it would influence certain components with certain transients but would not be a generic issue relating to all circumstances.

Hypothesis 3 This advocates that conservatism due to the use of bounding transients at design is sufficient such that the addition use of a F_{en} factor is not required. This hypothesis is likely to be true in certain circumstances but can only be demonstrated on a case-by-case basis where actual plant transients are known and may not be generic. It may be possible to develop screening rules for certain components for inclusion in design codes. It is unlikely that the case can be made that F_{en} factors are never required.

Hypothesis 4 This advocates that conservatism in the current treatment of non-contiguous cycles for design purposes may partly account for environmental influences in fatigue. Since most fatigue damage is from thermal transients then this hypothesis, if true would be a generic issue. However, the hypothesis is difficult to test in a specifically designed test program and in the short term. It can only be tested on the basis of developments in mechanistic understanding of both crack initiation and crack growth. This requires long term programs.

Hypothesis 5 This advocates that conservatism is introduced in plant assessment through the use of inadequate material test data which does not represent realistic plant conditions. While quite possibly true, the resolution of this issue would require an extensive material testing program. Twenty one associated knowledge gaps have been identified. The cost of fully addressing this issue is likely to be prohibitive.

Hypothesis 6 This advocates that conservatism is introduced into the calculation methods for the determination of F_{en} factors through inadequate consideration of the relevant parameters and their time dependent influences. This hypothesis, if true would be a generic issue. Since the calculation of F_{en} factors in the F_{en} factor approach is the way in which knowledge is incorporated into design, then this is also a very important issue. Nine high priority and three medium priority knowledge gaps have been associated with the testing of this hypothesis.

Hypothesis 7 This advocates that improved mechanistic understanding would identify circumstances where application of the F_{en} factor approach is not required. If true, some benefit would accrue to certain components under certain circumstances.

The main benefit of improved mechanistic understanding is that it enables judgments to be extrapolation outside the testing database, which can never be fully exhaustive.

8 CONCLUSIONS

Background and Need

Established fatigue initiation life curves, such as those given in Section III of the ASME Boiler and Pressure Vessel Code, provide the design basis for NPP components. These curves do not explicitly account for the effect on fatigue initiation life of the high temperature water environments to which components of the reactor coolant system in LWRs are typically exposed. Low Cycle Fatigue data, obtained by laboratory testing of small specimens, has demonstrated that substantial reductions in fatigue life may occur in LWR environments. Additionally, crack growth test data indicate that significant environmental enhancement of fatigue crack growth can occur under some LWR environmental conditions.

The NRC, in Regulatory Guide 1.207, has prescribed new assessment rules for fatigue initiation life of new nuclear power plants in the U.S. These rules were developed by Argonne National Laboratory based on a review of small specimen fatigue initiation life test data and introduce an environmental penalty factor, F_{en}, by which fatigue lifetime is reduced. ASME is developing Code Cases for assessing fatigue life in LWR environments, either using an approach similar to that prescribed by the NRC, or based on fatigue curves fitted to the experimental data in water environments. Application of any of these alternative rules results in higher fatigue usage factors for some LWR components, as compared with calculations based on current ASME Section III design codes. This can represent a significant challenge in justifying safe long term nuclear plant operation.

The more onerous rules for lifetime assessments, intended to account for environmental effects, appear inconsistent with experience of the relatively few reported fatigue failures of components in existing LWR plant, many of which appear to be explicable in terms of transient loadings which were not anticipated at the design stage. Consequently there is a perception that the rules are excessively conservative. Reasons which have been suggested for the apparent discrepancy between plant experience and predictions based on laboratory data can be grouped into four main categories:

Category A. The loading conditions used in the laboratory testing may be different than the loading experienced in LWR components. For example, in almost all the environmental fatigue tests, the testing was done at constant temperature with strain controlled load cycling. In reality, fatigue cycling in power plant components is predominantly due to temperature transients.

Category B. There may be conservatisms in the current ASME Code fatigue analysis procedures that bound any adverse effect due to environment.

Category C. Conservatism is introduced through the use of inadequate material data and the calculation methods derived from them which do not fully represent relevant plant conditions.

Category D. Inadequate mechanistic understanding leads to conservative assessment procedures or inappropriate application of procedures to some components or plant conditions.

There is a need to resolve current uncertainties and knowledge gaps to improve the understanding and treatment of EAF for lifetime justification of LWR components.

Gap Analysis

In response to the need to resolve uncertainties a knowledge gap analysis has been performed which identified the specific technical areas where uncertainties exist. In that analysis the status of existing research and design code developments was reviewed to address EAF for ferritic steels, austenitic stainless steels and nickel based alloys in PWR and BWR environments. A critical review of design code developments was then undertaken and a statement given of the individual knowledge gaps identified therein. A more general discussion followed which identified further knowledge gaps and drew together the interaction between the knowledge gaps. The results were presented in the Gap Analysis report (EPRI Product ID 1023012 published in December 2011) which formed the basis for development of a Roadmap for future EAF Research.

Priorities

The results of the gap analysis were presented to two meetings of the EPRI EAF Expert Panel in August and November 2011, and to a separate Focus Group convened by EPRI in February 2012, the objective being to bring together key stakeholders from both the research and practitioner arenas to prioritize the identified knowledge gaps, and define key project milestones.

The EPRI Expert Panel prioritized the gaps as High, Medium or Low using a ranking sheet which was subsequently circulated to non-attendees for further views. At the Focus Group Meeting, priorities were attributed to the knowledge gaps as Priority 1, Priority 2 or Priority 3 using a voting system. The priorities accounted for the timescale to achieve results, the technical benefit to be expected, the probability of success and the range of applicability to BWRs, PWRs and the materials used in plants.

Roadmap Development

Following the prioritization meetings, a more detailed scheme for knowledge evaluation has been developed which is described in this report. This scheme focuses on the need to propose and test hypotheses which aim ultimately to explain the anomalous position between the expectations from test data and plant experience, where knowledge gained is rationalized by the development of mechanistic understanding. The hypothesis based approach is intended to gain maximum understanding from testing, analysis or review work, rather than to simply add further data to an already considerable database.

Low level hypotheses may be associated with resolving individual knowledge gaps. High level hypotheses may be founded on a fundamental aspect related to stress-strain states, to conservatism inherent in design codes or mechanistically based.

The following seven high level hypotheses have been identified as worthy of further examination although additional hypotheses could be proposed:

Hypothesis 1. Cyclically variable parameters in a thermally-induced stress cycle reduce or negate the environmental influence on fatigue,

Hypothesis 2. Compressive stress does not contribute to the corrosion fatigue damage mechanism,

Hypothesis 3. Conservatism due to the use of bounding transients for design purposes is sufficient to accommodate environmental enhancement of fatigue damage,

Hypothesis 4. Conservatism in the current treatment of non-contiguous cycles for design purposes may partly account for environmental influences on fatigue,

Hypothesis 5. Conservatism is introduced in plant assessment through the use of available material data which is insufficiently comprehensive in terms of the parameters considered and the range of those parameters to adequately represent realistic plant conditions,

Hypothesis 6. Conservatism is introduced by the calculation methods recommended for the determination of F_{en} factor which are largely unsubstantiated and do not adequately consider the relevant parameters and their time dependent influences,

Hypothesis 7. Improved mechanistic understanding would identify circumstances where the application of the F_{en} factor approach is not required.

Proposed Work Program

On the basis of the information presented here, two options are available on which a work program may be developed. Option 1 is to address knowledge gaps by grouping them in the order of priority and to consider each of these groupings in the context of the knowledge evaluation scheme. To do this it will be necessary to define a low level hypotheses associate with each knowledge gap, which the resolution of the knowledge gap is intended to test. Option 2 is to consider the seven high level hypotheses with all their associated knowledge gaps, high, medium and low priority, again in the context of the knowledge evaluation scheme. These two options have been considered and a recommendation made on the basis of perceived minimum cost, perceived shortest timescale and perceived maximum benefit.

9 ROADMAP RECOMMENDATIONS

The various options have been considered and a recommendation made here on the basis of perceived minimum cost, perceived shortest timescale and perceived maximum benefit (judged according to generic application). The following recommendations are subjective. The best option depends on actual funds available, actual timescale by which results are required and attitude to risk.

On the basis of the information presented here, two options are available on which a work program could be developed. Option 1 is to consider the high priority knowledge gaps in the first instance in the context of the knowledge evaluation scheme. Following this, progress may be made to medium and low priority gaps only as necessary. Option 2 is to consider individual hypotheses with all their associated knowledge gaps, high, medium and low priority, again in the context of the knowledge evaluation scheme.

Option 1 is a comprehensive program to consider priority 1 knowledge gaps which if completed would provide significant insight into the anomalous position between test data and plant operating experience. This roadmap is shown in Figure 4-1 a suggested time sequence Figure 4-2. However, it will be very expensive and require a long time period to complete. Short term, intermediate term and log term benefits are listed at the beginning of Section 4 and discussed further in Section 7.

On the basis of high cost and long timescale, Option 1 is not recommended.

Option 2 tests high level hypotheses which, if true, would either provide generic benefits in all circumstances or specific benefit in certain circumstances. The knowledge gaps associated with each high level hypothesis are given in Section 3. The cost and timescale to test each high level hypothesis will be less than for Option 1. On the basis of the review given in Section 7, the following recommendations are given concerning the testing of high level hypotheses.

Hypothesis 1 (concerning the nature of thermal cycling) if true will be a generic issue since most fatigue damage occurs from plant thermal transients.

It is recommended that Hypothesis 1 should be tested in the first instance by resolving the associated knowledge gaps in the context of the knowledge evaluation scheme.

Hypothesis 6 (concerning the inadequacy of calculation procedures) if true will be a generic issue since the calculation of F_{en} factors in the F_{en} factor approach is the way in which knowledge is incorporated into design.

It is recommended that Hypothesis 6 should be tested in a parallel program with Hypothesis 1 in the first instance by resolving the associated knowledge gaps in the context of the knowledge evaluation scheme.

Hypothesis 3 (the use of bounding transients) is unlikely to be generic but may provide significant benefit through the development of screening rules for incorporation into design codes.

> **It is recommended that Hypothesis 3 should be tested in a parallel with Hypotheses 1 and 6 by resolving the associated knowledge gaps in the context of the knowledge evaluation scheme.**

Hypothesis 5 (concerning inadequacy in material data) would require an extensive material testing program to resolve. The cost of fully addressing this issue is likely to be prohibitive.

> **The testing of Hypothesis 5 is not recommended in the first instance on the basis of high cost and long timescale. This should be considered over a longer timescale.**

Hypothesis 7 (concerning inadequate mechanistic understanding) when resolved would accrue benefit to certain components under certain circumstances but the main benefit is that it enables judgments to be extrapolation outside the testing database.

> **The testing of Hypothesis 7, although important, is not recommended in the first instance because of limited immediate applicability. This should be considered over a longer timescale.**

Hypothesis 4 (concerning conservatism in the treatment of non-contiguous cycles), if true would be a generic issue since most fatigue damage is from thermal transients. However, the hypothesis is difficult to consider in a short term test program due to the nature of non-contiguous cycles. It can only be tested sensibly on the basis of developments in mechanistic understanding of both crack initiation and crack growth.

> **The testing of hypothesis 4, although a generic issue is not recommended in the first instance since it can only be addressed sensibly on the basis of mechanistic understanding. This should be considered as mechanistic understanding improves.**

Hypothesis 2 (concerning conservatism in the treatment of compressive stress), if true would influence certain components with certain transients but would not be a generic issue relating to all circumstances.

> **The testing of Hypothesis 2 is not recommended in the first instance because of limited applicability.**

10
REFERENCES

1. US-NRC Regulatory Guide 1.207: “Guidelines for Evaluating Fatigue Analyses Incorporating the Life Reduction of Metal Components due to the Effects of the Light-Water Reactor Environment for New Reactors”, March 2007.
2. O. K. Chopra and W. J. Shack, “Effect of LWR Coolant Environments on the Fatigue Life of Reactor Materials”, U.S. Nuclear Regulatory Commission. NUREG/CR-6909 and ANL-06/08, February 2007.
3. D. R. Tice, D. Green and A. Toft, *Environmentally Assisted Fatigue Gap Analysis and Roadmap for Future Research – Gap Analysis Report*. EPRI 1023012, Project Manager L. Midmore, December 2011.
4. EPRI EAF Expert Panel Meeting, Boston, 8 August 2011.
5. EPRI EAF Expert Panel meeting, St Louis, 7 November 2011.
6. *Environmentally Assisted Fatigue Focus Group Meeting.* San Diego, California, 2nd February 2012, EPRI Project Manager – Letitia Midmore.
7. *Expert Panel Priority Ranking Sheet from the Gap Analysis Report [Product ID 1023012]*. EPRI Project Manager – Letitia Midmore.
8. EDF Energy, Assessment Procedure for the High Temperature Response of Structures, R5, Issue 3, 2003.

A
LISTS OF KNOWLEDGE GAPS

Table A-1 shows the list of gaps taken from the gap analysis report [1]. The material and reactor system of relevance are indicated together with a statement of the gap and the research and development need. The gaps are also ordered according to the following categories:

i) anomalous positions which should be resolved,

ii) areas where further application of existing knowledge would be helpful,

iii) requirements for further S-N Data

iv) requirements for further crack growth data,

v) reconciliation of test data with field experience,

vi) requirements for multiaxial loading data,

vii) requirements for weldments data,

viii) improvements in fatigue initiation life assessment methods,

ix) implications for inspection requirements.

To the list of gaps in Table A-1 has been added the appropriate page number from the gap analysis report [1] together with the priorities allocated using the EAF Expert Panel ranking sheet [7] and at the EPRI Focus Group meeting [6]. There is some consistency between the two allocations, but understandably the allocations are not identical.

In Table A-2, overall priorities have been allocated here according to the following:

High priority where a gap was allocated *either* High by the EAF Expert Panel *or* Priority 1 at the EPRI EAF Focus Group meeting,

Medium priority where a gap was allocated *either* Medium by the EAF Expert Panel *or* Priority 2 at the EPRI EAF Focus Group meeting,

Low priority where a gap was allocated *both* low by the EAF Expert Panel *and* 3 at the EPRI EAF Focus Group meeting.

In Table A-2, the overall priorities have been color coded and sorted in order from highest to lowest.

Table A-1
Elements of an EAF Roadmap

Gap No. { } and Page Number ( ) from Gap Analysis Report [1]	Priority from EAF Expert Panel [5, 7]	Priority from EPRI Focus Group [6]	Material	PWR Environment	BWR Environment	Research or Development Need
Summary of Anomalous Positions Which Should be Resolved.						
{1} (9-4)	H	3	All	There is a disparity between the lower bound values of F_{en} derived by NUREG/CR-6909 and EFEM.		Further analysis of available test data is required.
{2} (9-14)	H	1	All	There is a lack of correlation between expectations from laboratory test data and plant operating experience which does not give confidence in the methods which are being developed for the treatment of corrosion fatigue in LWR environments.		A wide ranging investigation into the basis of the F_{en} factor, or similar, approaches, and their application to plant transient analysis is required.
{3} (2-12)	H	1		No comment is given on how the factor of 2 on stress was derived or why it is retained for both air and water environments. This issue requires resolution since the technical basis for design codes should be clearly understood.		Further review of the data underlying this methodology is warranted.
{4} (2-15)	H	1		The reasons for the apparent discrepancy between laboratory data and plant experience regarding the effects of environment on fatigue are not fully understood. Excessive conservatism in the current rules for design and/or the influence of complex loading may, at least in part, provide an explanation.		The reasons for this apparent discrepancy require to be understood. Many of the research needs identified in this report are ultimately aimed at resolution of this issue.

Table A-1
Elements of an EAF Roadmap (Continued)

Gap No. { } and Page Number ( ) from Gap Analysis Report [1]	Priority from EAF Expert Panel [5, 7]	Priority from EPRI Focus Group [6]	Material	PWR Environment	BWR Environment	Research or Development Need
Summary of Areas Where Further Application of Existing Knowledge Would be Helpful						
{5} (9-15)	H	3	Carbon and low alloy steels	The proposed new fatigue life curves for carbon and low alloy steels in water environments cover only high strength materials, whereas the current ASME curves cover also lower strength materials.		Additional assessment curves for low strength ferritic steels need to be developed.
{6} (9-2)	M	3	All	Stainless steels exhibit significant strain hardening and cyclic hardening so that a sharply defined yield stress does not exist. The Modified Goodman correction is used to adjust zero mean stress, fatigue endurance data to account for mean stress. The influence of using a higher yield stress in the Modified Goodman correction is to shift the influence of the mean stress correction towards low cycle fatigue. The extent to which this happens depends on the magnitude of the yield stress assumed.		Further analysis is required to consider how the Modified Goodman correction should be applied to stainless steel fatigue endurance data.
{7} (9-5)	H	1	All	Mechanistic understanding leads to the expectation that the degree of environmental enhancement of fatigue damage should depend on strain range. This is not consistent with the F_{en} factor approach.		Further analysis of available test data is required to determine the extent to which the environmental enhancement factor is a function of strain rate. If significant, an alternative to the F_{en} approach would be preferred.

Table A-1
Elements of an EAF Roadmap (Continued)

Gap No. { } and Page Number ( ) from Gap Analysis Report [1]	Priority from EAF Expert Panel [5, 7]	Priority from EPRI Focus Group [6]	Material	PWR Environment	BWR Environment	Research or Development Need
{8} (9-6)	M	3	All	For non-isothermal cycles, the issue of temperature selection appropriate to the full calculation procedure of thermal analysis, elastic stress analysis, strain analysis and F_{en} factor calculation requires further consideration.		Further analysis of available test data is required to assess the most appropriate temperature to use for analysis for non-isothermal cycles.
S-N Data						
{9} (9-1)	L	3	All	A generic stainless steel inert fatigue design curve for stainless steels may prove difficult to apply since it appears to be too conservative in the high cycle fatigue regime for some materials. Material specific, high cycle Design Fatigue Curves may be preferred in some cases.		If there is a need to refine the inert fatigue curve for specific material grades, additional high cycle fatigue initiation life data will be required.
{10} (9-1)	L	3	All	There is a lack of data concerning the definition of material specific thresholds for the occurrence of EAF. This is likely to contribute importantly to the identification of components for which consideration of environmental effects is not required. This is particularly so for stainless steel.		High cycle fatigue initiation threshold data may be required for different grades of stainless steels. The possibility of heat-to-heat variability may also need to be considered. The thresholds may relate most significantly to the strain range below which consideration of environmental effects is not necessary. Temperature thresholds should also be considered.

Table A-1
Elements of an EAF Roadmap (Continued)

Gap No. { } and Page Number ( ) from Gap Analysis Report [1]	Priority from EAF Expert Panel [5, 7]	Priority from EPRI Focus Group [6]	Material	PWR Environment	BWR Environment	Research or Development Need
{11} (9-2)	L	3	All	There is likely to be a significant influence of mean stress on EAF which is not adequately quantified by existing test data.		There is a need to develop additional data to establish the influence of positive and negative mean stress.
{12} (9-3)	M	2	All	Conservatism is included in NUREG/CR-6909 concerning the derivation of the adjustment factor of 12, which is used to relate test endurance data in air to component endurance data. Insufficient data exist concerning the values for the individual factors which are combined and the means by which they should be combined.		Further test data are likely to be required to relate smooth specimen fatigue initiation life to engineering component fatigue initiation life by accounting for material variability, size effects, surface finish and loading history.
{13} (9-3)	M	1	All	Comprehensive test data to define the environmental enhancement factor and encompassing the full range of relevant parameters as independent variables are not available.		Further test data are required to cover a wider range of the independent variables of temperature and strain rate, which are relevant to the F_{en} factor definition.
{14} (9-7)	M	3	All	The strain range and the associated number of cycles for which the consideration of environmental effects on fatigue is not required is based on zero mean stress test data only. The situation may be different for positive or negative mean stress. The lack of non-zero mean stress test data prevents this analysis being undertaken.		The need for non-zero mean stress testing was noted in gap 8. Further test data are required to identify the strain range threshold for non-zero mean stress, both tensile and compressive.

Table A-1
Elements of an EAF Roadmap (Continued)

Gap No. { } and Page Number ( ) from Gap Analysis Report [1]	Priority from EAF Expert Panel [5, 7]	Priority from EPRI Focus Group [6]	Material	PWR Environment	BWR Environment	Research or Development Need
{15} (9-7)	H	1	All	Limited data are available on the influence of variable temperature and variable strain rate within test cycles and of the influence of out-of-phase variations of temperature and strain rate.		Testing with mixed thermal/mechanical loading both in and out of phase. Resolution of this issue is likely to prove difficult, but there is the potential to justify significant benefit.
{16} (9-7)	H	1	All	Test data supporting averaging procedures for complex non-isothermal transients are very sparse and this represents a significant uncertainty. Therefore, the averaging procedures are based largely on assumptions. Mechanistic understanding is required as a basis for identifying those parts of the cycle for which water environment is damaging. This understanding can then be used as the basis for developing averaging procedures, which should then be validated with test data involving cyclically variable parameters.		Further tests similar to the Bettis testing with welded pipe fittings and thermal cycling would be helpful in simulating plant conditions. Smaller scale testing with control temperature cycling would support further mechanistic understanding.
{17} (9-8)	H	1	All	NUREG/CR-6909 recommends a 'modified rate approach' for which a unique F_{en} factor is determined for each cycle. Only very limited test data are available to substantiate the modified rate approach or the use of partial FUFs.		Test data to validate the 'modified rate approach' or an alternative procedure are required.

Table A-1
Elements of an EAF Roadmap (Continued)

Gap No. { } and Page Number ( ) from Gap Analysis Report [1]	Priority from EAF Expert Panel [5, 7]	Priority from EPRI Focus Group [6]	Material	PWR Environment	BWR Environment	Research or Development Need
{18} (9-9)	H	1	All	There is no basis available for defining the treatment of non-contiguous cycle pairs with regard to both crack initiation and growth in LWR environments. This is because of a lack of mechanistic understanding on which to formulate rules and a lack of test data with which to validate them.		Mechanistic understanding is required as a basis for formulating rules for the treatment of non-contiguous cycles. Validation testing with complex transient loading should be performed compared with predictions of current assessment methods for EAF.
{19} (9-3)	M	2	All	Further S-N tests are warranted to confirm the apparently differing influence of surface roughness between air and water environments. This may justify a reduction in the design margin applicable for components in water environments.		Further S-N tests are warranted to consider the influence of surface roughness between air and water environments.

Table A-1
Elements of an EAF Roadmap (Continued)

Gap No. { } and Page Number ( ) from Gap Analysis Report [1]	Priority from EAF Expert Panel [5, 7]	Priority from EPRI Focus Group [6]	Material	PWR Environment	BWR Environment	Research or Development Need
{20} (10-5 & 10-6)	M	3	Austenitic stainless steel	1) NUREG/CR-6909 acknowledges conservatism in its model regarding the influence of DO level. This particularly applies to some grades of stainless steel in high-DO water. Further refinement of the model to recognize an effect of DO (i.e. a difference between PWR and BWR/NWC) may be warranted. 2) There are no data on the influence of DO in PWR water containing boric acid and lithium hydroxide (i.e. under transient conditions) 3) The effect of steel sulfur content on fatigue initiation life of stainless steel has not been established – it has a substantial influence on fatigue crack growth rate. 4) Only limited data are available for BWR HWC. Whilst PWR data may be bounding, this remains to be established.		Issue (1) is currently being revisited in ongoing NRC work and there may be sufficient data to revise the model for BWR NWC. If insufficient data are available to justify a change, further tests are warranted to better establish the influence of DO level on the fatigue life of austenitic stainless steels. There is a need to establish if a benefit is likely from more data regarding (2) and (4). Item (3) warrants study since this effect may be significant.

Table A-1
Elements of an EAF Roadmap (Continued)

Gap No. { } and Page Number ( ) from Gap Analysis Report [1]	Priority from EAF Expert Panel [5, 7]	Priority from EPRI Focus Group [6]	Material	PWR Environment	BWR Environment	Research or Development Need
{21} (3-17)	L	3	Nickel based alloys	The existing data for nickel based alloys (Alloy 600, 182 and 82) is limited. NUREG/CR-6909 provides F_{en} factors for nickel based alloys based on these data and Regulatory Guide 1.207 recommends that these factors be applied to the new austenitic stainless steel air curve. Data on Alloy 690 and its weld metals are very limited.		Further data on nickel based alloys would lead to refinement of the F_{en} values; however the effects are significantly less than for stainless steel and, in practice, SCC in Alloy 600 is likely to be more significant. However, this is unlikely to be the case for Alloy 690 which is much more resistant to SCC. More data to confirm behavior for Alloy 690 (and weld metals) may be warranted.
Crack Growth Data						
{22} (9-19)	M	3	All	The lack of relevant environmental crack growth data for some materials (e.g. Alloy 690 and its weld metals) or grades of material (e.g. Types 316L(N) or 347 stainless steel) represents a knowledge gap. Heat to heat variability also appears to be important, especially the influence of sulfur for stainless steel but is not adequately understood. There is also a lack of threshold ΔK data for many materials.		Further corrosion fatigue crack growth data are required, especially under near threshold conditions.

Table A-1
Elements of an EAF Roadmap (Continued)

Gap No. { } and Page Number ( ) from Gap Analysis Report [1]	Priority from EAF Expert Panel [5, 7]	Priority from EPRI Focus Group [6]	Material	PWR Environment	BWR Environment	Research or Development Need
{23} (2-13, 2-15, 4-2, 9-17, 10-4)	H	2	Austenitic stainless steel	ASME XI does not include a fatigue crack growth law for wetted flaws. A Code Case has been proposed based on an extensive database but is not currently incorporated in the Code.		There is a need to follow ASME CC developments and consider the need for further data to support development of the draft CC.
{24} (4-10 & 10-11 to 10-13)	M	3	Austenitic stainless steel		ASME XI does not include a fatigue crack growth law for wetted flaws. Fewer relevant data are available for BWR environment although recent data suggest environmental effects are somewhat greater in BWR NWC than HWC or PWR (this is in contrast to S-N data).	Need to evaluate significance of recent BWR NWC and HWC data and ascertain whether further work is necessary to develop an assessment methodology for BWRs.
{25} (10-7)	L	3	Austenitic stainless steel	The effects of parameters influencing when retardation of enhanced crack growth occurs are not adequately understood.	The possibility of crack growth rate retardation is not evident in the available data for BWR environments.	Further tests are required to identify the circumstances that may lead to crack growth rate retardation, and to quantify any predictable effect. This may prove difficult because of the number of influencing variables.

Table A-1
Elements of an EAF Roadmap (Continued)

Gap No. { } and Page Number ( ) from Gap Analysis Report [1]	Priority from EAF Expert Panel [5, 7]	Priority from EPRI Focus Group [6]	Material	PWR Environment	BWR Environment	Research or Development Need
{26} (4-13 to 4-17)	M	3	Nickel based alloys	Some data are available for Alloy 600 and its weld metals which have enabled an assessment curve to be incorporated in ASME XI. Alternative curves have also been published which appear more conservative.		Need to understand basis of alternative assessment curves.
{27} (9-19, 10-6 & 10-7)	M	3	Nickel based alloys	Very limited data available for Alloy 690 (and 52, 152 and variants).		More fatigue crack growth data are needed for Alloy 690.
{28} (10-8)	H	1	All	Very few data are available under plant representative loading conditions and the influence of complex loading conditions (including hold times and spectrum loading) waveforms and combined loading are not well quantified. Crack growth data are obtained under isothermal conditions whereas many facility plant transients involve simultaneous temperature and load cycling (either in- or out-of-phase).		Further tests are required to investigate the influence of different loading waveforms and better represent the temperature and loading conditions experienced in real plant.

Table A-1
Elements of an EAF Roadmap (Continued)

Gap No. { } and Page Number ( ) from Gap Analysis Report [1]	Priority from EAF Expert Panel [5, 7]	Priority from EPRI Focus Group [6]	Material	PWR Environment	BWR Environment	Research or Development Need
{29} (10-4)	M	3	Carbon and low alloy steel	Reference crack growth curves are available covering both BWR and PWR but do not explicitly represent the influence of all significant factors on the degree of enhancement such as DO concentration and transient rise time. ASME CC N-643-2 provides alternative crack growth curves for PWR environments according to sulfur content and rise time.	Sufficient data are available but there is a requirement to develop an improved assessment code for BWR. For BWR HWC, ASME XI reference curves may be excessively conservative, but may be non-conservative for some BWR NWC conditions.	For BWR HWC it may be prudent to develop an approach based on ASME CC N-643-2, with different criteria for EAC/non-EAC.
{30} (4-2, 4-7, 5-5, 5-6, & 6-3)	M	3	Carbon and low alloy steel	Mechanistic understanding [of crack growth for ferritic steels] is better than for austenitic SS but some uncertainties remain, e.g. influence of time dependent material deformation behavior, e.g. dynamic strain aging.		Data relating to EAF in carbon and low alloy steels needs to be incorporated in crack growth codes, especially for BWR as noted above.

Table A-1
Elements of an EAF Roadmap (Continued)

Gap No. { } and Page Number ( ) from Gap Analysis Report [1]	Priority from EAF Expert Panel [5, 7]	Priority from EPRI Focus Group [6]	Material	PWR Environment	BWR Environment	Research or Development Need
{31} (10-7)	H	2	Austenitic stainless steel	The mechanism of environmental enhancement is not well understood. Why does enhancement occur and why does crack growth rate sometimes retard? Several possible mechanisms for crack growth retardation have been proposed but it is unclear which are operative under specific conditions. There is a lack of understanding regarding the reasons for effect of sulfur content on crack growth. Does this also affect S-N behavior? Effects of flow rate appear to differ between S-N and crack growth testing. Reasons for different influence of DO/corrosion potential on S-N and crack growth behavior are not known. *Note: Many observations relate to PWR data but may also be relevant to BWR.*		Mechanistic understanding is necessary to explain the apparent discrepancy between field and laboratory data. Specific areas to be addressed could include: - Mechanisms of retardation of enhanced crack growth. - Is hydrogen generated by corrosion implicated in enhancement? - Reasons for influences of material composition, e.g. sulfur content on crack growth enhancement or retardation. - Relevance of low and high flow rate laboratory data to plant conditions.

Table A-1
Elements of an EAF Roadmap (Continued)

Gap No. { } and Page Number ( ) from Gap Analysis Report [1]	Priority from EAF Expert Panel [5, 7]	Priority from EPRI Focus Group [6]	Material	PWR Environment	BWR Environment	Research or Development Need
{32} (5-6 & 8-3)	L	3	Nickel based alloys	Do existing uncertainties concerning SCC propagation behavior in Alloy 690 have any implications for EAF, for which the available database is very limited.		There is an initial requirement for additional data to expand the available database.
Reconciling Test Data With Field Experience						
{33} (Section 7 & 9-14)	H	2	All	More data using component like features with plant representative loading conditions are required to develop and validate methods for considering corrosion fatigue in LWR environments.		Analysis to identify conditions needed for testing to simulate plant conditions. Focused testing on geometries representative of components under plant relevant transient conditions. Testing of standard specimens under plant relevant loading noted above also supports this need. Testing should accurately simulate plant water chemistry, including transient chemistry where appropriate.

Table A-1
Elements of an EAF Roadmap (Continued)

Gap No. { } and Page Number ( ) from Gap Analysis Report [1]	Priority from EAF Expert Panel [5, 7]	Priority from EPRI Focus Group [6]	Material	PWR Environment	BWR Environment	Research or Development Need
{34} (3-16)	L	3	All	Very few data are available to establish the influence of PWR secondary water on EAF.		Generation of relevant data may be appropriate, e.g. for steam generator shells or tubing, but a benefit needs to be established first.
{35} (8-2 & 8-3)	H	2	All	For many PWR and BWR plants, there is a lack of knowledge of actual plant transients which is important because of the sensitivity of EAF to temperature and strain rate variations.		Plant monitoring may be required here and/or detailed thermodynamic modeling. Long term plant monitoring has been successfully carried out in German plant.
Multiaxial Loading						
{36} (9-11)	H	3	All	The basis for the selection of effective stress parameters for biaxial stress conditions is not established. Test data are required under conditions of biaxial loading for the treatment of plant thermal transients and non-proportional loading for combined thermal and mechanical transients. The most appropriate parameter may be different for the crack nucleation and subsequent propagation of microstructurally small cracks.		Test data are required to identify the appropriate multiaxial stress parameter for the treatment of biaxial condition in corrosion fatigue assessments.

Table A-1
Elements of an EAF Roadmap (Continued)

Gap No. { } and Page Number ( ) from Gap Analysis Report [1]	Priority from EAF Expert Panel [5, 7]	Priority from EPRI Focus Group [6]	Material	PWR Environment	BWR Environment	Research or Development Need
Weldments						
{37} (9-13)	L	3	All	Data on weld metal are more limited than on parent materials but, where studied, appear to be bounded by parent data.		More heat specific data on the behavior of weld metal may be required.
{38} (9-13)	M	3	All	Whilst there are some data concerning the behavior of welded features, there is a lack of data to account for aspects such as geometric stress concentration factor, weld defects, residual stress and multiaxiality, all of which may be influential.		There is a general need to understand whether weld related features can lead to differences in EAF behavior compared to parent materials.
Fatigue Initiation Life Assessment Methods						
{39} (10-11)	H	3	All	The calculation of strain rate is required to evaluate EAF initiation life. While methods for the determination of cycle effective strain rate can be proposed for conformance to ASME Code analysis, there are very few experimental data or plant data that can be used to validate the methods for use in corrosion fatigue assessments. Methods need to be consistent with mechanisms which operate under plant conditions.		Further work is required to establish a clear approach for calculation of strain rate. This is likely to include testing under complex loading conditions combined with analytical work to assess the suitability of different evaluation approaches for effective strain rate. Work to develop improved mechanistic understanding may also be required.

Table A-1
Elements of an EAF Roadmap (Continued)

Gap No. { } and Page Number ( ) from Gap Analysis Report [1]	Priority from EAF Expert Panel [5, 7]	Priority from EPRI Focus Group [6]	Material	PWR Environment	BWR Environment	Research or Development Need
{40} (9-7)	M	3	All	The method of stress indices commonly used for simplified piping analysis requires further development for corrosion fatigue assessments.		Further testing and analysis work is required to develop and validate simplified assessment methods for specific components.
{41} (9-17)	H	3	All	Interpreting a plant transient with variable strain rate in terms of the single strain rate curves is problematic, and no relevant guidance is available.		Further consideration is required to develop a methodology which is not unduly conservative.
{42} (9-7)	M	3	All	Procedures for determining a cycle specific F_{en} factor are very important since they underpin the application of test data to plant assessment. Test data supporting averaging procedures for treatment of cyclically varying temperature, strain rate and stress (tension or compression) are sparse and this represents a significant uncertainty. There is a need to understand real behavior under temperature variable conditions.		Analysis is required to understand how the necessary simple representation of complex plant transients results in conservatism.

Table A-1
Elements of an EAF Roadmap (Continued)

Gap No. { } and Page Number ( ) from Gap Analysis Report [1]	Priority from EAF Expert Panel [5, 7]	Priority from EPRI Focus Group [6]	Material	PWR Environment	BWR Environment	Research or Development Need
{43} (9-4 & 9-7)	M	3	All	NUREG/CR-6909 lacks guidance on the procedure to be followed for stainless steel when both strain rate and temperature vary during a cycle. Thus the NUREG/CR-6909 model does not consider the possibility that one or more of the influencing parameters may be outside its threshold value at all times during a cycle so that the combined influence may be reduced or negated.		The concept of the 'modified rate approach' could reasonably be applied as the weighted average of the combined F_{en} factor around the cycle. Work is required to develop and validate a suitable method for treatment of variations in both temperature and strain rate, and also to provide a realistic treatment of variable temperature transients.
{44} (10-10)	M	3	All	The extent, to which mean stress influences both low cycle fatigue and high cycle fatigue of stainless steel in air, and an appropriate means by which is should be accounted for is considered to be a significant knowledge gap.		Further analysis may be required to address this issue which is important to prevent undue conservatism.
Inspection Requirements						
{45} (10-12)	M	3	All	There is a lack of understanding of the extent to which the inclusion of environmental effects on fatigue will influence inspection programs with regard to how to inspect, when to inspect and where to inspect.		A review of the implications of corrosion fatigue to inspection requirements is required.

Table A-1
Elements of an EAF Roadmap (Continued)

Gap No. { } and Page Number ( ) from Gap Analysis Report [1]	Priority from EAF Expert Panel [5, 7]	Priority from EPRI Focus Group [6]	Material	PWR Environment	BWR Environment	Research or Development Need
From The Focus Group Meeting [3]						
{46}	Not Considered	1	All	A universal, stakeholders' testing data base should be established to provide a consistent basis for developments around the world.		Some gaps identify the need for further analysis of existing data. Other gaps identify the need to add to existing data. In both cases, a comprehensive and up-to-date data base is required. This will identify specifically where material data gaps exist and provide a basis for coherent International collaboration. The data base should be continually updated as new data become available.
{47}	Not Considered	1	All	The need exists to provide guidance on circumstances where the approach of NUREG/CR-6909 is not appropriate because of DO levels.		The gap analysis report comments on the treatment of DO in the F_{en} factor algorithms as follows. The influence of DO variability is included in the carbon and low alloy steel F_{en} factor algorithms with discontinuous influences at certain threshold values. The influence of DO is included in the stainless steel F_{en} factor algorithm although there is no recognized influence of DO variability.

Table A-2
Allocation of Overall Priorities (H or 1, M or 2, 3 or L)

Gap Number	Priority from EAF Expert Panel [5, 7]	Priority from EPRI Focus Group [6]	Hypothesis/ Category	Brief Description [Page Number from Gap Analysis Report]
{1}	H	3	6/C	[9-4] Revised lower bound F_{en} value
{2}	H	1	Not Applicable	[9-14] Correlation of predictions from laboratory data with plant experience
{3}	H	1	5/C	[2-12] Revised correction factor on stress
{4}	H	1	3/B	[2-15] Reasons for differences between laboratory tests and plant conditions
{5}	H	3	5/C	[9-15] S-N curves for low strength ferritic steels
{7}	H	1	6/C	[9-5] Dependence of degree of environmental enhancement on strain range of cycles
{13}	M	1	5/C	[9-3] S-N data for wider range of temp./strain rate combinations
{15}	H	1	1/A	[9-7] Non-isothermal S-N tests (in/out of phase)
{16}	H	1	6/C	[9-7] Thermal cycling features tests
{17}	H	1	6/C	[9-8] Data to support strain rate calculation
{18}	H	1	4/B	[9-9] S-N testing with complex transient loading
{23}	H	2	6/C	[2-13, 2-15, 4-2, 9-17, 10-4] ASME code developments for SS crack growth Incorporate crack growth retardation effects for SS/PWR
{28}	H	1	1/A	[10-8] Spectrum loading crack growth tests
{31}	H	2	7/D	[10-7]. Mechanistic understanding of enhanced crack growth in SS
{33}	H	2	1/A	[Section 7 & 9-14] Testing for plant component representative geometries and loading
{35}	H	2	3/B	[8-2 & 8-3] Improved understanding of real plant transients (inc. monitoring)
{36}	H	3	6/C	[9-11] Influence of multiaxial loading
{39}	H	3	6/C	[10-11] Strain rate calculation for complex transients
{41}	H	3	6/C	[9-17] Variable strain rate effects
{46}	Not considered	1	5/C	Stakeholders' testing data base
{47}	Not considered	1	6/C	Guidance for mitigated locations according to DO
{6}	M	3	2/A	[9-2] Applicability of Goodman correction for strain and cyclic hardening materials (SS)
{8}	M	3	1/A	[9-6] Choice of temp. for analysis of thermal transients
{12}	M	2	5/C	[9-3] S-N data on surface finish, loading history

Table A-2
Allocation of Overall Priorities (H or 1, M or 2, 3 or L) (Continued)

Gap Number	Priority from EAF Expert Panel [5, 7]	Priority from EPRI Focus Group [6]	Hypothesis/ Category	Brief Description [Page Number from Gap Analysis Report]
{14}	M	3	2/A	[9-7] Mean stress effects on threshold strain amplitude and upper cycle limit
{19}	M	2	5/C	[9-3] Further S-N tests to identify difference of surface roughness effect between air and water
{20}	M	3	5/C	[10-5 & 10-6] (Parts 1 to 4) Steel sulfur effects on S-N
{22}	M	3	5/C	[9-19] Crack growth threshold data
{24}	M	3	5/C	[4-10 & 10-11 to 10-13] SS crack growth data for BWR environments
{26}	M	3	5/C	[4-13 to 4-17] Compare ASME & Japanese crack growth curves for nickel alloys
{27}	M	3	5/C	[9-19, 10-6 & 10-7] Crack growth data for Alloy 690 and welds
{29}	M	3	5/C	[10-4] Improved crack growth curves for ferritic steels in BWR
{30}	M	3	7/D	[4-2, 4-7, 5-5, 5-6, 6-3] Dynamic strain ageing effects for ferritic steels
{38}	M	3	5/C	[9-13] Assessment procedures for weldments
{40}	M	3	6/C	[9-7] Application of simplified assessment procedures to EAF
{42}	M	3	1/A	[9-7] Analysis to aid understanding of methods for evaluation complex transients
{43}	M	3	1/A	[9-4 & 9-7] Rules for simultaneous temperature and strain variations
{44}	M	3	6/C	[10-10] Understanding of mean stress effects on LCF and HCF
{45}	M	3	6/C	[10-12] Implications for inspection requirements
{9}	L	3	5/C	[9-1] SN data to support material grade specific S-N design curves
{10}	L	3	5/C	[9-1] Material specific thresholds
{11}	L	3	2/A	[9-2] Mean stress effects on S-N
{21}	L	3	5/C	[3-17] S-N data for Alloy 690
{25}	L	3	5/C	[10-7] Incorporate retardation effects for crack growth in SS
{32}	L	3	5/C	[5-6, 8-3] Possible synergy between mechanisms of corrosion fatigue and SCC for SS and Alloy 690
{34}	L	3	5/C	[3-16] PWR secondary environment data
{37}	L	3	5/C	[9-13] S-N data for weldments

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