New Reactors Programme

GDA close-out for the AP1000 reactor

GDA Issue GI-AP1000-SI-01: Avoidance of Fracture

Assessment Report: ONR-NR-AR-16-009
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EXECUTIVE SUMMARY

Westinghouse is the design company for the **AP1000®** reactor. Westinghouse completed Generic Design Assessment (GDA) Step 4 in 2011 and paused the regulatory process. It achieved an Interim Design Acceptance Confirmation (IDAC), to which 51 GDA issues were attached. These issues require resolution prior to award of a Design Acceptance Confirmation (DAC) and before any nuclear safety related construction can begin on site. Westinghouse re-entered GDA in 2014 to close the 51 issues.

This report is the Office for Nuclear Regulation's (ONR's) assessment of the Westinghouse **AP1000** reactor design in the area of structural integrity. Specifically, this report addresses GDA Issue GI-AP1000-SI-01 – Avoidance of Fracture. This GDA issue arose in Step 4 of GDA because:

- evidence to demonstrate fracture avoidance for the sample of Highest Safety Significance (HSS) welds considered in GDA arrived too late for detailed assessment in Step 4 of GDA.

The Westinghouse GDA issue resolution plan identified its approach to close the issue was to:

- provide sufficient evidence to demonstrate fracture avoidance for the sample of HSS welds considered in GDA; and
- provide adequate responses to any questions arising from assessment by ONR.

My assessment conclusion is:

- Westinghouse has provided adequate demonstration of fracture avoidance for the sample of HSS welds considered in GDA.
- I consider that from a structural integrity perspective, the **AP1000** plant design is suitable for construction in the UK.

My judgement is based upon the following factors:

- Westinghouse has applied the suitably demanding R6 procedure for fracture analysis of the HSS welds.
- Westinghouse has applied the sufficiently robust European Network for Inspection and Qualification (ENIQ) methodology to show that inspections of the HSS welds can be qualified.
- In conjunction, these establish an acceptable margin between limiting defect sizes and the defect sizes that can reliably be detected.

The following matters remain, which are for a future licensee to consider and take forward in its site-specific safety submissions. These matters do not undermine the generic safety submission and require licensee input/decision relating to the following aspects:

- Consideration of multiple failure of closures and supports in HSS and HI components.
- Further demonstration of the structural integrity of the Passive Residual Heat Removal Heat Exchanger outlet penetration, or implementation of alternative design measures to prevent unacceptable loss of heat sinks.
- Independent verification and validation of fracture analyses.
- Consideration of whether specification of in-service hydrostatic testing conforms with current good practice.
- Detailed consideration to identify the limiting transient/time point as input to fracture analysis.
- Classification of dissimilar metal welds between vessel nozzles and safe-ends.

- Sensitivity studies for fracture analyses.
- Measures to facilitate manufacturing and in-service inspection.
- Fracture toughness testing of forged material of HSS components.
- Evidence of the absence of manufacturing defects and the achievement of acceptable material properties for the HSS forgings.

In summary, I am satisfied that GDA Issue GI-AP1000-SI-01 can be closed.

ABBREVIATIONS

ALARP	As Low As Reasonably Practicable
AR	Aspect Ratio
ASTM	American Society for Testing and Materials
BMS	Business Management System
CMT	Core Makeup Tank
CRE	Control Rod Ejection
DAC	Design Acceptance Confirmation
DEGB	Double-Ended Guillotine Break
DMW	Dissimilar Metal Weld
DSM	Defect Size Margin
DVI	Direct Vessel Injection
ELLDS	End of Life Limiting Defect Size
ENIQ	European Network for Inspection and Qualification
FAD	Failure Assessment Diagram
FCG	Fatigue Crack Growth
FEA	Finite Element Analysis
GDA	Generic Design Assessment
HAZ	Heat Affected Zone
HI	High Integrity
HSS	Highest Safety Significance
IDAC	Interim Design Acceptance Confirmation
IP	Inspection Plan
IRWST	In-Containment Refuelling Water Shortage Tank
ISI	In-Service Inspection
IVC	Inspection Validation Centre
LFCG	Lifetime Fatigue Crack Growth
LOCA	Loss Of Coolant Accident
MCL	Main Coolant Loop
MSL	Main Steam Line
NDT	Non-Destructive Testing
ONR	Office for Nuclear Regulation
PCSR	Pre-Construction Safety Report
PRHR HX	Passive Residual Heat Removal Heat Exchanger
PRZ	Pressurizer
QEDS	Qualified Examination Defect Size
Ra	Roughness Average
RGP	Relevant Good Practise
RPV	Reactor Pressure Vessel

RQ	Regulatory Query
SAP	Safety Assessment Principles
SG	Steam Generator
SIF	Stress Intensity Factor
TAG	Technical Assessment Guide
TSC	Technical Support Contractor

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Introduction

1.1 Background

1. Westinghouse completed Generic Design Assessment (GDA) Step 4 in 2011 and paused the regulatory process. It achieved an Interim Design Acceptance Confirmation (IDAC) to which 51 GDA issues were attached. These issues require resolution prior to award of a Design Acceptance Confirmation (DAC) and before any nuclear safety related construction can begin on site. Westinghouse re-entered GDA in 2014 to close the 51 GDA issues.

2. This report is the Office for Nuclear Regulation's (ONR's) assessment of the Westinghouse **AP1000** reactor design in the area of structural integrity. Specifically, this report addresses GDA Issue GI-AP1000-SI-01 Revision 5 – Avoidance of Fracture.

3. The GDA Step 4 structural integrity assessment of the Westinghouse **AP1000** reactor (Ref. 1) is published on our website (Ref. 2) and describes the origin of the GDA issue. General information on the GDA process is also available on our website (Ref. 3).

4. GDA Issue GI-AP1000-SI-01 was raised in Ref. 1 because Westinghouse provided important evidence, relating to the avoidance of fracture, too late in Step 4 for detailed assessment by ONR. My assessment of evidence for the avoidance of fracture is described in this report.

1.2 Scope

5. The scope is described in my assessment plan (Ref. 4) and includes a review of Westinghouse submissions related to this issue. The purpose is to confirm that sufficient evidence for the avoidance of fracture is established. There are three actions associated with this issue, relating to the following topics:

   - fracture analysis (GI-AP1000-SI-01.A1).
   - inspection qualification (GI-AP1000-SI-01.A2).
   - materials properties testing (GI-AP1000-SI-01.A3).

6. The resolution plan (Ref. 5) identifies actions planned by Westinghouse to promote closure of GDA Issue GI-AP1000-SI-01 as follows:

   - Adequately respond to questions arising from my assessment of documents submitted by Westinghouse in connection with this GDA issue.
   - Update the conclusion on avoidance of fracture resulting from the reconciliation between fracture analyses and detection capabilities. Also, where necessary, update documents which inform that reconciliation.
   - Provide formal proposals for additional materials testing to underpin fracture toughness values applied in the fracture analyses.

7. The scope of my assessment is appropriate for GDA because, in the UK, robust evidence of fracture avoidance is expected for the highest reliability components, those where it is claimed that the probability of gross failure is so low that it can be discounted.

8. During my assessment, Westinghouse revised its classification of components of UK **AP1000** plant. This reduced the number of components classified as Highest Safety Significance (HSS) and so altered the scope of my assessment. In conjunction with

ONR internal hazards inspectors, I have assessed the basis for this revised classification. I have also considered other developments in the structural integrity safety case that have arisen during my assessment. These include the need for consideration of multiple failures of redundant components that form part of HSS pressure boundaries, and consideration as to whether current classifications adequately reflect both the direct and indirect consequences of postulated gross failure in the case of the Passive Residual Heat Removal Heat Exchanger (PRHR HX) outlet line.

9. The scope of my assessment does not include matters already found by ONR to be satisfactory, as reported in Ref. 1.

1.3 Method

10. This assessment complies with ONR guidance on the mechanics of assessment (Ref. 6) and with the requirements of the ONR Business Management System (BMS) document "Purpose and Scope of Permissioning" (Ref. 7) which defines the process of assessment within the ONR.

1.3.1 Sampling Strategy

11. It is rarely possible or necessary to assess an entire safety submission, therefore ONR adopts an assessment strategy of sampling. Ref. 7 explains the process for sampling safety case documents.

12. The sampling strategy for this assessment was to seek evidence of relevant good practice (RGP) in the following areas:

- fracture analysis
- inspection capability
- determination of materials properties

2 ASSESSMENT STRATEGY

2.1 Pre-Construction Safety Report (PCSR)

13. ONR's GDA Guidance to Requesting Parties (Ref. 8) states that the information required for GDA may be in the form of a PCSR, and Technical Assessment Guide (TAG) 051 (Ref. 9) sets out regulatory expectations for a PCSR.

14. At the end of Step 4, ONR and the Environment Agency raised GDA Issue GI-AP1000-CC-02 (Ref. 10) requiring that Westinghouse submit a consolidated PCSR and associated references to provide the claims, arguments and evidence to substantiate the adequacy of the **AP1000** plant design reference point.

15. A separate regulatory assessment report is provided to consider the adequacy of the PCSR and closure of GDA Issue GI-AP1000-CC-02, and therefore this report does not discuss the structural integrity aspects of the PCSR. This assessment focused on the supporting documents and evidence specific to GDA Issue GI-AP1000-SI-01.

2.2 Standards and Criteria

16. The standards and criteria adopted within this assessment are principally the Safety Assessment Principles (SAPs) (Ref. 11), internal TAGs, relevant standards and RGP informed by existing practices adopted on UK nuclear licensed sites.

2.2.1 Safety Assessment Principles

17. The key SAPs applied in this assessment are listed in Table 1.

2.2.2 Technical Assessment Guides

18. The TAGs that have informed this assessment are listed in Table 2.

2.2.3 National and International Standards and Guidance

19. Standards and guidance that have been used as part of this assessment are listed in Table 3.

2.3 Use of Technical Support Contractors (TSCs)

20. A Technical Support Contractor (TSC) was engaged to support closure of GDA Issue GI-AP1000-SI-01. The TSC, Frazer-Nash Consultancy Limited (Frazer-Nash), provided independent expert advice on methodology and undertook confirmatory fracture analyses.

2.4 Integration with Other Assessment Topics

21. GDA requires the submission of an adequate, coherent and holistic generic safety case. Regulatory assessment cannot therefore be carried out in isolation as there are often safety issues of a multi-topic or cross-cutting nature. I have consulted with ONR specialists in fault studies, internal hazards and probabilistic safety analysis to inform my assessment.

2.5 Out of Scope Items

22. This report does not consider structural integrity aspects of the PCSR, which is addressed by a separate ONR cross-disciplinary assessment.

3 REQUESTING PARTY'S SAFETY CASE

23. Westinghouse identified three* components of **AP1000** plant where it is necessary to show that the likelihood of gross failure is so low that it can be discounted and has classified these as HSS. The HSS components are as follows

- Reactor Pressure Vessel (RPV)
- Pressurizer (PRZ)
- Steam Generator (SG) (channel head, tubesheet and secondary side shell)

24. For HSS components, evidence to show that the likelihood of failure is so low that it can be discounted includes an avoidance of fracture demonstration. This integrates fracture mechanics analyses, material toughness and qualification of manufacturing inspections. The objective is to demonstrate a margin between a limiting defect size and the defect size that can reliably be detected and sized, with an allowance for through life fatigue crack growth.

25. The limiting defect size is termed the End of Life Limiting Defect Size (ELLDS); the crack size that can be detected and sized with high confidence is the Qualified Examination Defect Size (QEDS); and the through life fatigue crack growth the Lifetime Fatigue Crack Growth (LFCG). The margin between the ELLDS and the QEDS plus LFCG is termed the Defect Size Margin (DSM). Expressed as an equation:

DSM = ELLDS / (QEDS + LFCG)

26. The Westinghouse approach for fracture analysis, given in Ref. 12, is based on the R6 defect assessment procedure (Ref. 13). Westinghouse has reported the following fracture analyses:

- RPV welds (Ref.14)
- PRZ welds (Ref.15)
- PRZ surge nozzle to safe-end weld (Ref.16)
- SG welds (Ref.17).

27. As an exercise in validation, Westinghouse has reviewed a selection of these fracture analyses against comparative studies performed on its behalf by AMEC Foster Wheeler. These comparisons are reported in Refs. 18, 19 and 20 for RPV, PRZ and SG welds respectively.

28. In Ref. 21 Westinghouse define a programme of fracture toughness testing, intended to demonstrate that true properties of materials validate those assumed in the fracture analyses.

29. At Step 4 of GDA, Ref. 1 identified that manufacture of HSS components is subject to high levels of quality assurance and inspection throughout. The final non-destructive testing (NDT) will be qualified according to the European Network for Inspection and Qualification (ENIQ) methodology (Ref. 23) with the intention that it will be qualified as

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* At Step 4 of GDA Westinghouse classified the Main Steam Line (MSL) inside containment as HSS, as reflected in Ref. 1. The structural integrity classification report (Ref. 22) has since been revised and Westinghouse now classifies the MSL inside containment as Standard Class 1.

capable of reliably detecting all defects significantly smaller than the limiting defect size determined in the fracture mechanics assessment. A minimum DSM of 2.0 is the target.

30. To demonstrate that reliable manufacturing inspections can be performed on the welds of HSS components, Westinghouse has produced a series of NDT inspection plans (IPs) (including Refs. 24, 26 and 27). Ref. 1 identifies that these IPs have been developed by Westinghouse with the Inspection Validation Centre (IVC) acting as a quasi-Qualification body.

31. To confirm that fracture mechanics analyses, material toughness and qualification of manufacturing inspections are reconciled, Westinghouse submitted a report as Enclosure 3 of Ref. 28. To demonstrate avoidance of fracture, Ref. 28 concludes that a minimum DSM of 2.0 is established for each HSS weld considered in GDA.

4 ONR ASSESSMENT OF GDA ISSUE GI-AP1000-SI-01

33. GDA Issue GI-AP1000-SI-01 arose because evidence of the avoidance of fracture arrived too late to be assessed in detail at Step 4 of GDA. That evidence is this subject of this assessment, which has been conducted according to ONR BMS document “Purpose and Scope of Permissioning” (Ref.7).

4.1 Scope of Assessment Undertaken

34. The scope of my assessment has included submissions by Westinghouse as evidence for the avoidance of fracture. These are described in Section 3; several have been revised during the period of my assessment.

35. I raised a series of questions in the course of my assessment and have subsequently assessed responses by Westinghouse to my Regulatory Queries (RQ).

36. I held a number of level 4 technical engagements with Westinghouse where I discussed:

- my regulatory expectations, based on RGP, see Section 2.2; and
- technical and safety aspects of each Westinghouse submission.

37. My assessment was conducted with TSC support: Frazer-Nash undertook a detailed review of both the Westinghouse fracture analysis method and its application, reported in Refs. 29 and 30.

38. My interest in this assessment was to:

- establish whether Westinghouse applied RGP for its fracture analysis, and whether the outcome of analysis was acceptable and substantiated by the necessary evidence;
- establish whether Westinghouse applied RGP in its work to support inspection qualification, and whether the outcome provided the necessary confidence that inspections could be qualified as required in future;
- establish whether Westinghouse applied RGP in its proposals for future materials properties testing to validate assumptions in its fracture analyses;
- consider the strength of the safety case for HSS components by examination of safety margins declared by Westinghouse, which are based on its reconciliation of the outcome of fracture analyses with evidence of qualified inspection capability.

4.2 Outline of the R6 Defect Assessment Procedure

39. I noted earlier that the Westinghouse approach for fracture analysis is based on the R6 Defect Assessment Procedure (Ref. 13). To inform the reader, and before describing my assessment in detail, a brief outline of the R6 Defect Assessment Procedure, as applied to address this GDA issue, is provided here.

40. The R6 procedure has been used in UK based nuclear safety cases for many years. At Step 4 of GDA, ONR expressed satisfaction that it is an appropriate methodology for calculating the limiting defect sizes in the HSS welds (Ref. 1).

41. In simple terms, the R6 procedure is based on a Failure Assessment Diagram (FAD), which illustrates proximity to failure, and indicates the predicted failure mode. The vertical axis of the FAD (Kr) represents the ratio of applied stress intensity factor to the fracture toughness of the material. This provides a measure of the proximity to failure by fracture. The horizontal axis (Lr) represents the ratio of the applied load to the load

required to cause plastic collapse of the section containing the postulated flaw. This provides a measure of the proximity to failure by loss of material strength. The interaction between the two failure modes is represented by the failure assessment line, which is determined based on the tensile properties of the component material. An example of FAD is illustrated in Figure 1.

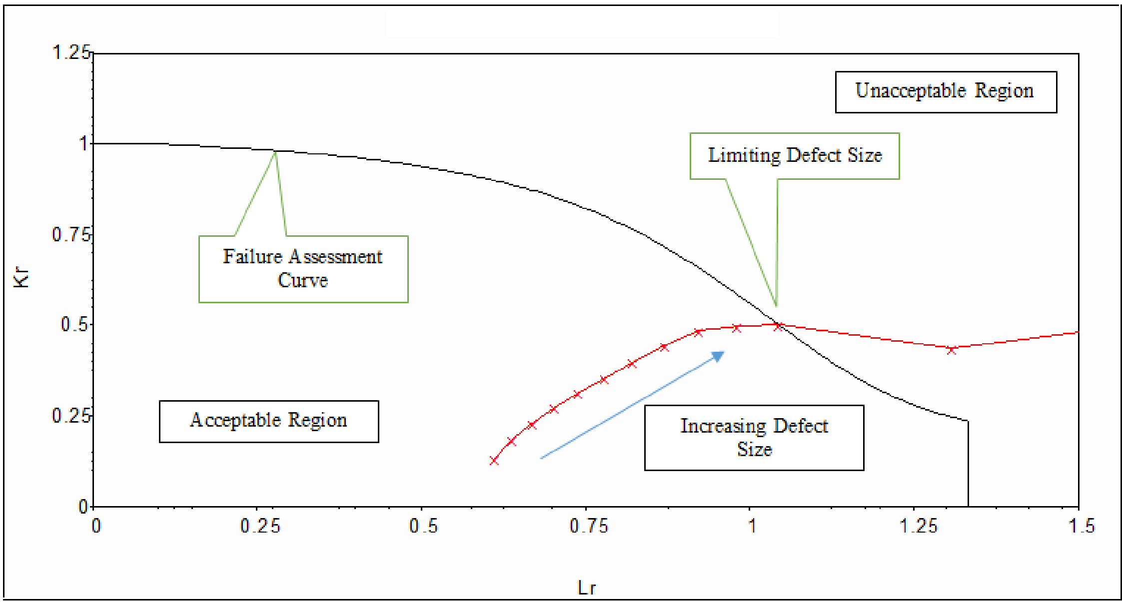

Figure 1 Example of R6 Failure Assessment Diagram

42. Westinghouse has applied the software based implementation of the R6 procedure, R-Code (Ref. 31) to undertake the limiting defect size calculations. The stress distributions used in the assessments are taken from the existing elastic finite element stress analyses of the components, and resolved into primary and secondary loading. The residual stresses are then added as an additional secondary load set. Recognised stress intensity factor solutions and plastic collapse solutions from R-Code are then used to undertake the limiting defect size calculation. All the fracture assessments are based on this standard approach. At Step 4 of GDA, ONR noted general contentment with such an approach and the use of R-Code to implement the R6 procedure.

43. The fatigue crack growth has been calculated using Paris Law crack growth equations, given in the American Society of Mechanical Engineers (ASME) Code, with transients applied in sequence based on the total number of transients specified for the 60-year design life. At Step 4 of GDA, ONR noted that this is a standard approach and expressed satisfaction with the method (Ref. 1).

4.3 Assessment

44. This part of the report is divided into four sections, which describe in turn the following aspects of my assessment:

- fracture analysis
- inspection qualification
- materials properties testing
- key assessment considerations and regulatory judgements

4.3.1 Fracture Analysis

45. This section of the report is divided into two parts; the first part covers assessment of the Westinghouse benchmarking and its fracture analysis methodologies, and the second part covers the application of the Westinghouse methods via comparative fracture analysis work. Each part is structured as follows:

- an outline of my assessment approach/sampling strategy; and
- an outline of my RQs and the Westinghouse responses.

46. At the end of the section I present my key regulatory judgements and outcomes and draw conclusions on whether Westinghouse has adequately addressed GDA GI-AP1000-SI-01 A1.

4.3.1.1 Fracture Mechanics Methodology and Benchmarking

47. As a result of the GDA Step 4 assessment (Ref. 1), ONR placed the following action on Westinghouse:

"Support assessment of the fracture analysis approach by providing adequate responses to any questions arising from assessment by ONR of documents submitted during GDA Step 4 but not reviewed in detail at that time.

A number of important fracture assessment reports arrived much later in the Step 4 assessment timeframe than had been originally planned. ONR undertook a high level review of the reports to gain confidence in the approach but was unable to undertake a full assessment within the timescales allowed for GDA Step 4. This GDA Issue Action has been created to support the full assessment of these reports.

Activities by Westinghouse should comprise:

Provide adequate responses to questions arising from ONR assessment of documents submitted during GDA Step 4 or in response to this Action.

With agreement from the Regulator this action may be completed by alternative means."

48. I carried out an initial assessment of the Westinghouse benchmarking document. The aim of my initial assessment was to gain confidence that Westinghouse was progressing its understanding of the application of the R6 procedure post GDA Step 4. I viewed evidence that Westinghouse had taken measures to improve its understanding of the R6 procedure as an important prerequisite to the progression of my assessment.

49. I subsequently engaged Frazer-Nash to undertake a more detailed review of the Westinghouse benchmarking document (Ref. 32) and R6 fracture mechanics methodology (Ref. 12). The aim of the Frazer-Nash review was to confirm that Westinghouse (Ref. 1) had identified and addressed the key points relating to the Westinghouse fracture analyses raised in ONR's GDA Step 4 structural integrity report.

Initial Assessment

50. In view of the uncertainties relating to the adequacy of the Westinghouse R6 fracture mechanics methodologies identified at GDA Step 4 and the significance of the limiting defect size calculations to the fracture avoidance demonstration early engagement with Westinghouse was essential.

51. I wanted to understand the areas of agreement and difference between the fracture analyses undertaken by EASL (on behalf of ONR at GDA Step 4) and Westinghouse. I raised an RQ which covered the following key themes:

- The Westinghouse understanding of areas of agreement and difference between its R6 fracture assessment calculations and those of EASL at GDA Step 4.
- The implications, if any, for updating the Westinghouse R6 fracture mechanics assessments for the HSS components.
- The Westinghouse provisions to provide confidence in the veracity of the fracture assessments for an **AP1000** plant construction in the UK.

52. In its response, Westinghouse reviewed and compared its R6 calculations for the RPV and PRZ with those undertaken by EASL at GDA Step 4 (Ref. 33). For the PRZ upper head to shell weld similar through-wall ELLDS values of 41.0 mm and 42.8 mm, between Westinghouse and EASL were obtained. There were various levels of conservatism used in the calculations undertaken by both EASL and Westinghouse, which for the PRZ upper head to shell weld tended to cancel one another out. Overall, Westinghouse had incorporated levels of conservatism in its fracture analyses comparable to EASL.

53. In contrast, for the RPV lower shell to upper shell weld, there were discrepancies in both the limiting defect sizes and the identification of the limiting time point. The concern was that these discrepancies may lead to the incorrect capture of the limiting transient / time point with the potential for a non-conservative ELLDS calculation. Westinghouse identified the following reasons for the discrepancies:

- Accounting for the interaction between primary and secondary stress in the stress intensity factor (SIF) calculation.
- Consideration of out-of-plane hoop stresses for circumferential defects.
- Plastic collapse solution choice eg local versus global solutions.
- Limitations with the use of the Westinghouse propriety software WESTEMS to predict thermal stresses with severe transients and significant geometry variability.
- Limitations of the curve fits to capture the through-wall stress variation for SIF calculations.
- Identification of the limiting crack position eg surface or deepest point.

54. Westinghouse recalculated the ELLDS at the limiting time step taking cognisance of the key factors above and obtained results comparable to the EASL analysis.

55. To reflect the insights and learning gained from its evaluation Westinghouse committed to make changes to its R6 fracture mechanics methodology document before updating its post-Step 4 GDA R6 fracture mechanics calculations. Westinghouse introduced several barriers aimed at reducing the risk of a reoccurrence of similar oversights/errors in its post-Step 4 GDA, R6 fracture analyses:

- A qualification programme to assure Westinghouse personnel are suitably qualified and experienced to perform R6 fracture mechanics calculations.

- Training to cover revision of the R6 fracture mechanics methodologies and R-Code inputs.
- Engagement of a UK contractor experienced in the application of the R6 procedure to provide consultancy.
- Engagement of a UK contractor to undertake independent ELLDS calculations on a subset of HSS welds for RPV, PRZ and SG.
- Commitment to update its R6 fracture mechanics methodology document.

56. I concluded that Westinghouse had gained valuable insights from its benchmarking studies to understand the differences between its ELLDS calculations and those of EASL for the PRZ and RPV at GDA Step 4. In my opinion Westinghouse offered plausible reasons for the observed differences in its R6 calculations and those of EASL at GDA Step 4. I also considered that Westinghouse had taken initiatives to reduce the likelihood of a recurrence of the oversights identified in its R6 fracture assessments at GDA Step 4. This notwithstanding, to support the closure of GI- AP1000-SI-01, I commissioned comparative work to provide further evidence.

57. I am therefore content that there was a reasonable basis for Westinghouse to progress the updating of its R6 fracture mechanics calculations. However, to meet the GDA timescales, the Westinghouse update of its R6 fracture mechanics calculations now proceeded in parallel with the revision of its R6 fracture mechanics methodology document.

Detailed Review of the Westinghouse Benchmarking and R6 Fracture Mechanics Methodology

58. I considered potential causes of the discrepancies between Westinghouse and the EASL calculations. I was also mindful of the importance of closing out the concerns identified by EASL and ONR at GDA Step 4. I viewed this as significant for both the GDA and future licensing. I commissioned Frazer-Nash to undertake a more detailed independent review of the Westinghouse benchmarking (Ref. 32) and fracture mechanics methodology (Ref. 12). The scope of the Frazer-Nash review covered:

- confirmation that Westinghouse addressed appropriately all significant issues relating to the Westinghouse fracture analyses raised by ONR at GDA Step 4;
- review of the Westinghouse benchmarking document; and
- review of the updated Westinghouse fracture mechanics methodology document.

59. Frazer-Nash provided a report covering detailed reviews of the Westinghouse benchmarking and recently updated R6 fracture mechanics methodology documents (Ref. 29). I concluded that Westinghouse had adequately addressed the majority of the ONR/EASL comments raised against the PRZ and the RPV fracture analyses at GDA Step 4. However, ONR and Frazer-Nash raised new comments. I raised an RQ to progress my assessment, which covered the following key themes:

- Adequacy of material property data to underpin the failure assessment curves.
- Limitations of the Westinghouse propriety software WESTEMS to derive thermal stresses.
- Consistency of the stresses with the SIF and plastic collapse solutions.

- Whether the stresses in Dissimilar Metal Welds (DMWs), including the Heat Affected Zone (HAZ) and the unaffected adjacent parent material were conservative.

- Low-level comments relating to points of detail of the Westinghouse R6 fracture mechanics methodologies.

- Implementation of the Westinghouse verification process in its R6 fracture mechanics calculations.

60. In response, Westinghouse addressed the majority of my RQs and gave further commitments to update its R6 fracture mechanics methodology document (RQ-AP1000-1632 (Ref 34) There were however three ‘open’ items that required Westinghouse to either provide additional evidence or commitments:

- Confirmation that the adequacy of default stress fits with the R-Code software.

- Clarification and identification of the limitations of WESTEMS in deriving thermal stresses with severe thermal transients and significant geometry changes.

- The level of verification expected in the application of the R-Code software when performing R6 assessments.

61. Westinghouse responded with a further submission and further commitments (Ref. 35) to update to its R6 fracture mechanic methodology document (Ref. 12). Westinghouse confirmed a bounding curve fit method was applied for all its R6 fracture assessments. In addition, Westinghouse had strengthened the guidance in its methodology document to limit the use of WESTEMS to simple geometries and thermal transients. I am satisfied with the Westinghouse responses.

62. The question of the level of verification applied by Westinghouse when using the R-Code software was part of a wider question relating to the adequacy of the Westinghouse verification and approval arrangements for using the R6 procedure. UK civil nuclear good practice emphasises that verification of structural integrity calculations for components equivalent to the Westinghouse classification of HSS would normally require 100% checking of all calculations. In addition, there is an expectation that R6 fracture assessments are verified independently of the originator’s method ie if R-Code is used to originate, then a diverse method (eg a spreadsheet) would be expected for verification.

63. Westinghouse explained that it considered its fracture assessments to be ‘design analyses’ and as such are governed by a company-wide procedure covering verification and validation. This procedure allows review, alternative calculations, demonstration, or testing. In addition, individuals not directly involved in the design activity perform verification and validation activities. The verification method implemented for the fracture assessments was 100% checking of the entire assessment (ie independent review of the design / analysis) to include any calculations, R-Code program databases and documentation.

64. I noted that alternative methods (ie spreadsheet versus R-Code program) were not used for fracture assessment verification. The purpose of using these checks by an independent method is to seek to identify any situations where the R-Code software is unreliable in performing the intended R6 assessment. Westinghouse provided no additional evidence to justify the reliability of its application of R-Code, but captured the UK expectation in an update to its R6 fracture mechanics methodology document (Ref. 12).

4.3.1.2 Comparative Work

Sampling Strategy and Selection of HSS Welds for the Comparative Fracture Calculations.

65. Several considerations informed my sampling strategy and the selection of HSS welds for my comparative work:

- the Westinghouse classification of HSS & High Integrity (HI) welds
- the Westinghouse weld ranking for HSS welds
- sampling and selection of HSS welds.

Structural Integrity Classification – HSS and HI Welds

66. At GDA Step 4, ONR was satisfied that the structural integrity classification methodology adopted by Westinghouse could be used as a basis for identifying those components where the likelihood of failure is so low that the consequences of failure can be discounted. In the ONR SAPs these are referred to as highest reliability components, equivalent to the HSS structural integrity classification assigned by Westinghouse. Furthermore, for the purpose of the fracture avoidance demonstration, highest reliability components include the HI classification designated by Westinghouse (Ref. 1).

67. Post GDA Step 4, there were several developments which could potentially affect the Westinghouse listing of HSS components. For ease of presentation I grouped these developments under the following themes:

- developments in the structural integrity case, and
- the outcome of several cross-discipline GDA issues (GI-AP1000-FD-02, GI-AP1000-IH-03 and GI-AP1000-IH-05), that resulted in an update of structural integrity classification, reported in Ref. 36.

Developments in the Structural Integrity Case

68. ONR's assessment of structural integrity GDA Issues GI-AP1000-SI-03 and GI-AP1000-SI-06 is reported in separate GDA Structural Integrity Assessment Reports (Refs 37 and 38). Westinghouse provided adequate demonstrations to show that the fragments from a postulated RCP flywheel disintegration would be contained (GI-AP1000-SI-03.A2). In addition, Westinghouse provided an adequate demonstration to underpin the integrity of the SG vertical support and RCP casing (GI-AP1000-SI-06.A3). The Westinghouse listing of HSS welds was therefore not affected by the closure of the intra-structural integrity GDA Issues GI-AP1000-SI-03 and GI-AP1000-SI-06.

69. I asked Westinghouse to clarify the status of the structural integrity classification for non-welded regions (forgings, closure components, supports etc.). Westinghouse confirmed that the classification of non-welded regions is informed by component level classifications (Ref. 36). This is within the scope of AF-AP1000-SI-04 for licensing. However, I noted that although individual components (bolts or supports) were classified, multiple failures of bolts or supports were not assessed. The consequences of multiple failures of these redundant components may have significant consequences for vessels classified as HSS / HI. I consider that Westinghouse has appropriately classified individual components; however, I expect particular consideration in the safety case of multiple failures that could result in unacceptable consequences against which there is no protection. One such example is the failure of multiple bolts in an

RPV closure head. I consider that there exist suitable methods in design codes, such as that chosen by Westinghouse, to readily support resolution of this matter, which arose late in my assessment. I consider that this matter needs resolution early in licensing.

CP-AF-AP1000-SI-01 – The licensee shall consider modes of multiple failure of closures and supports for HSS and HI components and demonstrate that structural integrity provisions for closures and supports are adequate and commensurate with consequences of multiple failures.

70. Westinghouse retained the HSS classification for the dissimilar metal welds between the low alloy vessel nozzles and the austenitic stainless steel safe-ends on the RPV, PZR and SG. At Step 4 of GDA, ONR noted that the classification of these welds may be because Westinghouse cannot discount the possibility of weld defects threatening the integrity of the HSS parent vessel (Ref. 1). I view the decision to include these welds as part of each HSS vessel for the purposes of demonstrating that likelihood of gross failure in the vessel is so low that it can be discounted as cautious. My opinion is based on my understanding that Westinghouse is able to provide a consequence case for guillotine failure of these safe-end welds. I therefore consider that the basis for classification has not been fully explained, and note the following guidance of TAST/16:

"discounting gross failure should only be invoked if the consequences of failure are unacceptable, or it is not possible to demonstrate the consequences are acceptable."

71. The Westinghouse expert panel convened to undertake the structural integrity classification of components of the **AP1000** plant to meet UK expectations could not rule out the potential for damage to the In Containment Refuelling Water Storage Tank (IRWST) wall as a result of a pipe whip from postulated double-ended guillotine break (DEGB) of the PRHR HX return (outlet) line. Westinghouse confirmed that the combined loss of both the PRHR HX and the IRWST heat sinks may have unacceptable consequences (Ref. 39). Westinghouse subsequently assessed the consequences of a pipe whip of the PRHR HX outlet line in two submissions covering the integrity of the concrete IRWST wall and the PRHR HX mounting ring welds (Ref. 39).

72. Westinghouse claimed that consequences of an impact from a postulated pipe whip of the PRHR HX return line on the IRWST wall were not significant. An ONR civil engineering specialist reviewed the Westinghouse integrity claim for the IRWST wall (Ref. 39). and I subsequently raised RQ RQ-AP1000-1622 for Westinghouse to address questions covering the modelling approaches and assumptions used in the finite element analysis (FEA) to support its assessment. ONR considered the Westinghouse approach, described in Ref. (RQ-AP1000-1622 - Civil Engineering Comments on PRHR HX and IRWST Failure Mechanisms, 12 August 2016, TRIM Ref. 2016/323216) was consistent with SAPs ECE.12, ECE.13, ECE.14 and ECE.15 and I am content that a pipe whip from failure in the PRHR HX return line, impacting the IRWST wall and liner wall would not be detrimental to nuclear safety.

73. I also reviewed the Westinghouse companion integrity assessment of the mounting ring welds in the PRHR HX under as postulated DEGB of the PRHR HX return line (Ref. 39). My questions covered the consequences of a gross failure, the FEA model, the load cases and the results of the stress analyses (Ref. 39).

74. Westinghouse calculated the stresses in mounting ring welds and base metal using the 2013 edition of the ASME Section III Level D design limits. I observed that the weld stresses complied with the ASME Section III Level D design requirements with significant safety margins. However, for the base metal, the safety margin was lower and for one load case < 2%. I questioned whether this small margin was sensitive to

assumptions in the non-linear analysis, where an uncertainty in calculated stresses of the order of +/-10% may sometimes be expected.

75. Westinghouse updated its FEA model in Ref. 39. This included more accurate modelling of the pipe whip loading and revised material properties using the 1998 edition of the ASME Code through 2000 addenda claimed as the design reference point. Notably, the 1998 edition of the ASME Code included different methods for calculating the allowable design stresses and hence safety margin for Level D transients.

76. The results showed adequate safety margins for the mounting ring welds and that a safety margin of about 13% was now claimed for the base material. The change in the safety margin for the base material was dominated by invoking the 1998 edition of the ASME Code.

77. Although compliant with the design requirements of the nuclear code as agreed at the GDA design reference point, clearly, there is potential for non-compliance with code limits in the future. I am not satisfied with this position, particularly given the possible combined loss of safety functions delivered by the PRHR HX and IRWST. An adequate safety margin under these Level D loading conditions is not too demanding and I am confident that this matter can be resolved in the detailed design, for example by provision of restraints or modest design modifications to reinforce the connection. I have raised the following assessment finding to resolve this matter early in licensing.

CP-AF-AP1000-SI-02 - The licensee shall demonstrate the structural integrity of the PRHR HX outlet penetration in accordance with the current edition of the ASME Code, or shall implement alternative design measures to prevent the unacceptable consequences of a combined loss of safety functions.

Cross- Cutting GDA Matters

78. Westinghouse proposed to change the structural classifications of the Main Steam Line (MSL) from HSS and the welds from the Main Coolant Loop (MCL) to the Reactor Vessel safe-end from HI to Standard Class 1. The re-classification of the MCL and MSL were dependent on consequence assessments. For the MCL the direct consequences of a loss of coolant accident (LOCA) were within the design basis. The indirect consequences were assessed within the fuel design (GI-AP1000-FD-02) and internal hazards (GI-AP1000-IH-03 and GI-AP1000-IH-05) technical disciplines.

79. Westinghouse provided an adequate demonstration of limited core damage from the jet forces arising from a postulated guillotine failure of the reactor coolant loop pipework at the connection with the RPV. Detailed analysis of the effect of the depressurisation on vessel internals was completed. The loads are predicted to cause plasticity of some alignment plates and buckling of certain fuel assembly spacer grids immediately adjacent to the core barrel. In each case, the consequences are tolerable and coolable geometry is maintained (Ref. 40).

80. The final position in relation to the internal hazards aspects is reported in Ref. 41. ONR concluded that Westinghouse has developed revised processes and criteria to meet UK expectations. However, the completion of the indirect consequence analysis will be undertaken post GDA and is the subject of Assessment Finding CP-AF-AP1000-IH-06 of Ref. 41.

81. Similarly, the direct consequences of a postulated gross failure of the MSL were demonstrably within the design basis. The re-classification of the MSL therefore also centred on the internal hazards considerations. The final position in relation to the internal hazards aspects is reported in Ref 41. ONR concluded that Westinghouse has developed revised processes and criteria to meet UK expectations. Therefore,

Assessment Finding CP-AF-AP1000-IH-06 (Ref. 41) is also applicable to the justification of the MSL post GDA, ie to affirm classification, an assessment of the indirect consequences of MSL failure will be conducted in the site licensing phase.

82. A wider point concerned the Westinghouse position with respect to confirming the structural integrity classifications for all non-HSS pressure boundary components: including Standard Class 1, valve bodies, along with Class 2 and 3 components. Late in the closure phase, Westinghouse revised its pressure part failure case, described in (Ref. 41), which includes a statement implying that failure of the major pressure vessels of **AP1000** plant within the scope of pressure part failure is not deemed credible because the pressuriser is fitted with safety valves. Westinghouse reaffirmed this statement in the structural integrity classification document (Ref. 42): "Failure of the pressuriser within the scope of pressure part failure is not deemed credible because the pressuriser is fitted with safety valves." It also made this statement for the RCP, PRHR heat exchanger and Core Makeup Tank (CMT), and appears in the PCSR.

83. ONR's position from an internal hazards perspective is reported in Ref. 41. After identifying this statement to Westinghouse, it was clarified that this was included in error and the intention was not to deviate from other claims made in the internal hazards and structural integrity areas; Westinghouse opened a corrective action (CAPAL 100458138) to capture this issue to remove the statement, and document its resolution going forward.

84. The effects of indirect consequences of pressure part failure on the safety classification were also assessed within the Structural Integrity discipline during Step 4 of the GDA and AF-AP1000-SI-02 was raised:

"**AF-AP1000-SI-02** The licensee shall review the structural integrity classification scheme to remove the element of expert judgement in defining the HSS boundary by ensuring that the formalised assessments of the indirect consequences of failure of the Standard Class 1 and HI components / welds are fully reflected in the structural integrity classification scheme."

85. My expectation is that through AF-AP1000-SI-02 and the outcome of internal hazards assessment (Ref. 41) all potential indirect consequences of pressure part failure for HI, Standard Class 1 and lower classification components, as appropriate, shall be quantitatively analysed to meet UK expectations.

86. I was informed that valve bodies are included in the missile assessment. Internal missiles including valve bodies have been considered in the ONR's internal hazards assessment report (Ref. 41) but the matter needs further consideration as part of the closure of AF-AP1000-SI-02.

HSS Classifications Post GDA Step 4

87. The Westinghouse HSS classifications were for the purposes of the post GDA Step 4 fracture analyses, limited to the RPV, pressuriser, SG and its associated DMWs (Table 4).

88. Post GDA Step 4, there were developments within the Westinghouse structural integrity case along with work to progress the closure of several cross-cutting GDA issues which proceeded in parallel with the fracture avoidance work. Ways forward to meet UK expectations were developed, but the work could not be completed within the GDA timescale. I raised several assessment findings to progress the closure of work within the Westinghouse structural integrity case for the **AP1000** plant. Westinghouse also reported the final position on the cross-discipline GDA issues towards the end of the project. I raise additional assessment findings to progress the completion of this

work as part of the detailed design during licensing. My assessment findings are collated in Annex 1.

89. However, the uncertainty in the final structural integrity classifications did not unduly affect my assessment because the listing of HSS components included over six HSS welds. This was adequate for my sampling of the evidence for the Westinghouse fracture avoidance demonstration and more importantly Westinghouse's understanding of the UK expectations to underpin highest reliability claims.

Weld Ranking Process

90. At GDA Step 4, Westinghouse developed a weld ranking process to systematically rank welds to identify those that should be further analysed in terms of fracture mechanics calculations and technical justifications for the manufacturing inspections, identified in Ref. 1.

91. In preparation for updating its fracture mechanics calculations Westinghouse revised its weld ranking process. It updated the defect tolerance ranking to reflect the latest components design code stress and fatigue assessments as reflected in the design reference point (Ref. 43). However, it retained the Step 4 GDA NDT inspectability rankings. The updated weld ranking resulted in Westinghouse selecting the same welds at GDA Step 4, but there was a more quantitative basis to justify its selection.

92. The question of whether the lower shell barrel A to tubesheet weld bounded the SG channel head to tubesheet weld was raised in Ref. 1. Westinghouse provided further evidence to substantiate its view and that the lower shellbBarrel A to tubesheet weld was bounding and that defects of concern would be readily detected with the necessarily high level of confidence (Ref. 35). The Westinghouse position was supported by a fatigue usage factor for the lower shell barrel A to tubesheet weld being 3x the value for the SG channel head to tubesheet weld. I recognised that there is not a direct correlation between the fatigue usage factor and the amount of Fatigue Crack Growth (FCG), but on balance judged it was a reasonable indicator that the FCG rates would be less severe on the channel head side of the tubesheet. In addition, Westinghouse presented evidence to justify its view that defects of concern were readily detectable for either weld. While the stainless steel cladding on the inner surface of the channel head will impair the NDT performance to some extent, physical access for ultrasonic scanning is acceptable. Overall I believe that Westinghouse's statement regarding the NDT reliability for defects in the channel head to tubesheet weld is reasonable, provided that the effects of the cladding are considered.

93. Based on the explanation provided by Westinghouse, summarised in the previous paragraph, I am satisfied that for the GDA the lower shell barrel A to tubesheet weld is likely to bound the SG channel head to tubesheet weld. This notwithstanding, for licensing the channel head to tubesheet weld, among other locations, will be assessed during the licensing phase in response to the following assessment finding of Ref. 1.

AF-AP1000-SI-04: The licensee shall undertake fracture assessments on a wider range of weld locations on the HSS components in order to demonstrate that the limiting locations have been assessed. The licensee shall also undertake fracture assessments on the vulnerable areas of the parent forgings in order to demonstrate that the limiting locations have been assessed.

94. In summary, the Westinghouse weld rankings were unchanged from GDA Step 4. I am satisfied that Westinghouse had identified an adequate set of representative welds for the purposes of the fracture avoidance demonstration for GDA. I am content for Westinghouse to use the extant listing of HSS welds established early in the closure phase as a basis for updating its fracture calculations (Table 4).

Detailed Factors – Sampling and Selection of HSS Welds

95. Several detailed factors also informed my sampling strategy and the selection of HSS welds for my comparative fracture calculations:

- Addressing the main areas of uncertainty identified at GDA Step 4 that were not fully addressed in the Westinghouse Benchmarking report eg FCG.
- Assessing components / locations / types of welds (and defect orientations) which had not previously assessed either by EASL / ONR at GDA Step 4 or more recently in the Westinghouse commissioned independent calculations.

96. Clearly, various approaches could be adopted for the comparative studies, with the number of components / locations to be assessed being traded against the depth of investigation / level of independence. The HSS welds and defects selected for my comparative studies along with a brief explanation of my choice follows:

- PRZ manway to shell weld. The bounding location with an axial surface defect was assessed.
- RPV upper shell to lower shell weld. A circumferential surface defect at the bounding surface. (Note that although this location was considered previously by EASL, the most recent Westinghouse assessment employed a different approach and analysed a different location in the weld).
- ELLDS and full FCG assessment of the SG lower shell barrel to tubesheet weld, chosen due to the unexpectedly high FCG presented by Westinghouse at GDA Step 4.

Comparative Fracture Analyses and Calculations

97. Table 5 summarises the results from the Westinghouse fracture assessments, as presented in Ref. 28. I adopted a staged approach in my comparative work with the aim of progressively building confidence in Westinghouse methods and its application of the R6 procedure. The scope of my comparative work covered:

- review of the Westinghouse approach to capture the limiting transient/time point;
- high level review of AMEC Foster Wheeler comparative work commissioned by Westinghouse; and
- comparative calculations for selected HSS welds in the RPV, PRZ and SG.

Capture of the Limiting Transient / Time Point

98. I was aware that the need for a robust demonstration of the capture of the limiting transient / time point is the tenet of the following assessment finding of Ref. 1.

AF-AP1000-SI-06: The licensee shall use a robust methodology for identifying the limiting time steps for use in the more extensive fracture assessments that will be undertaken post GDA.

99. This notwithstanding, the validity of the ELLDS sizes derived for the sample of HSS welds also warranted underpinning with valid methods for GDA closure. With the support of Frazer-Nash (Ref. 30), I sought further evidence of the veracity of the Westinghouse methods for the capture of the limiting transient / time point by:

- reviewing the Westinghouse commissioned work; and

- undertaking an independent review for a HSS weld.

100. I compared the transient/time point combinations considered by both Westinghouse and AMEC Foster Wheeler giving rise to the ELLDS values for the PRZ upper to middle shell weld (PRZ2) and the RPV Direct Vessel Injection (DVI) nozzle to shell weld (RPV1).

101. For the PRZ2 weld, Westinghouse identified the limiting transient as the plant hydrotest. AMEC Foster Wheeler did not consider the plant hydrotest. AMEC Foster Wheeler identified the shop hydrotest as limiting, which occurs at a lower temperature for which the material properties of assessment are less favourable, hence predicted limiting defect sizes are understandably smaller.

102. Noting the identification of the shop hydrotest as the limiting transient, I consider it is important that a qualified inspection of the PRZ is conducted after the shop hydrotest. Westinghouse recognised this, and ONR will seek to confirm that this matter is captured in the relevant component specification as normal business in the licensing phase.

103. In the case of the RPV location RPV1, I observed some differences in the capture of the limiting transients / time points by Westinghouse and AMEC Foster Wheeler. I have discussed notable examples below.

104. For an outside axial defect, Westinghouse identified the large steam line break (Level D) transient as limiting, whereas AMEC Foster Wheeler identified the shop hydrostatic test as limiting.

105. Westinghouse contended that the shop hydrotest need not be included in the assessment, because qualified inspection follows this test to confirm the absence of significant defects. With the exclusion of the shop hydrotest, there was agreement between Westinghouse and AMEC Foster Wheeler that the large steam line break (Level D) transient was the limiting transient. Westinghouse recognised this but I viewed the need for a qualified inspection post the shop hydrotest as an important undertaking for the safety case of all HSS components. In common with my opinion expressed in paragraph 101, I consider this update as normal business to be conducted in the licensing phase

106. For a postulated inside circumferential defect, AMEC Foster Wheeler predicted the ELLDS for rod ejection (Level D) transient, whereas Westinghouse instead predicted the ELLDS for a large feedwater line break (Level D).

107. Westinghouse explained its rationale for its selection of the large feedwater break transient (Level D), (Ref. 35). This was consistent with the guidance in the extant Westinghouse R6 fracture mechanics methodology document. Westinghouse subsequently recalculated the ELLDS for an inner surface circumferential defect (6:1 aspect ratio (AR)) using the control rod ejection (CRE) transient and obtained results broadly consistent with AMEC Foster Wheeler.

108. The Westinghouse comparative work (Ref 18) offered a limited explanation for the differences in the limiting transient selection. Westinghouse subsequently attributed the differences to characteristic differences between the through-wall stress profiles. The salient point was that transients with high stress gradients at the surface eg thermal shock type transients with stresses that rapidly decline through-wall may obscure other transients with potentially lower surface stress magnitude / gradient, but with higher through-wall stresses that could result in a more limiting ELLDS. Westinghouse included further guidance in its R6 fracture mechanics methodology document (Ref. 12).

Capture of Limiting Transient / Time Point – ONR Commissioned Work

109. With the support of Frazer-Nash, I undertook a high-level review and tested the Westinghouse process for the capture of the limiting transient and time point for the ELLDS calculations (Ref. 30).

110. The Westinghouse process indicated that several variables should be examined for each transient to assist in determining the limiting time point: Lr, Kr and combinations of Lr and Kr (Ref. 12). This was a significant improvement in the approach used by Westinghouse at GDA Step 4 where the transient screening was limited to through-wall variation of the SIF. In principle, this addressed a concern raised by ONR at GDA Step 4, relating to the reliability of screening using the SIF parameter alone for the identification of the limiting transient / time point (Ref. 1).

111. I reviewed the implementation of the Westinghouse process for capturing the limiting transient / time point for a selection of HSS welds. I concluded that the intent of the Westinghouse process had been implemented.

112. I also commissioned Frazer-Nash to test the effectiveness of the Westinghouse process for capture of the limiting transient / time point by undertaking an independent evaluation. Westinghouse supplied stress, transient pressure and metal temperature data for all transients and time points for an inner circumferential defect at the SG lower shell A barrel to tubesheet weld (SG4), which allowed Frazer-Nash to independently select the bounding transient / time point for the ELLDS calculations. Using an engineering judgement based approach Frazer-Nash confirmed that Westinghouse had chosen the correct transient for its ELLDS.

113. In addition, often the welds joining the primary pipework to the major vessels include dissimilar metals. In addition, to mechanical loads, dissimilar metal welds invariably include high bending and shear stresses resulting from the mismatch in the material properties. Thus, if Westinghouse retained the HSS classification for the low alloy steel nozzle to safe-end welds in the RPV, PRZ and SG then the effects of these additional stresses warrant consideration in the capture of the limiting transients / time point. These aspects shall be addressed in licensing as part of the resolution of AF-AP1000-SI-06.

Westinghouse Commissioned Comparative ELLDS and FCG Calculations

114. Westinghouse commissioned independent fracture calculations for a sample of HSS welds. Westinghouse provided many of the input data which to some extent limited the level to which interpretation and engineering judgement were invoked. I viewed the use of engineering judgement as an important aspect of the R6 procedure, which unlike design code assessments, is not fully prescriptive. Westinghouse selected the following HSS welds: PRZ upper to middle shell weld (PRZ2); DVI nozzle to RPV shell weld (RPV1): and SG primary inlet nozzle to safe-end weld (SG3). I discuss the results of my high-level review of the Westinghouse commissioned comparative calculations below.

PRZ Upper to Middle Shell Weld (PRZ2)

115. A comparison report discussing the results of ELLDS calculations undertaken by Westinghouse and AMEC Foster Wheeler along with the specific calculations were available for my review (Ref. 19). The scope of the Westinghouse commissioned comparative work for PRZ weld PRZ2 was limited to ELLDS calculations. The limiting transient identified by both organisations was the shop hydrotest at 21°C. There was broad consistency in the approaches adopted by both organisations and ELLDS values were within 7%. I concluded there was very good agreement with the minor differences being attributed to material property assumptions. The results confirmed

that Westinghouse had undertaken an appropriate and conservative ELLDS calculation for PRZ weld (PRZ2).

RPV DVI Nozzle to Shell Weld (RPV1)

116. The Westinghouse ELLDS calculations along with independent calculations and a comparison report were available for my review (Ref. 18). The scope of the Westinghouse commissioned comparative work for DVI nozzle to RPV shell weld (RPV1) was limited to ELLDS calculations.

117. The comparison of ELLDS sizes (limiting defect depths) showed some differences between the Westinghouse and AMEC Foster Wheeler results. Westinghouse attributed the differences to several factors: eg choice of failure assessment and the classification of pipe stresses arising from thermal expansion. A further point was the accuracy of the curve fits to envelope stress distributions. However, in post-comparison calculations good agreement between the predicted ELLDS sizes were obtained for given inputs and assumptions.

118. I noted that the AMEC Foster Wheeler ELLDS calculations tended to give smaller ELLDS values. I attributed the difference mainly to the lower (off upper shelf) fracture toughness at 21°C used by AMEC Foster Wheeler. However, consideration of the shop hydrostatic test was not limiting because a qualified inspection will occur after the shop test. A better comparison was obtained with comparable material property assumptions.

119. Overall, I am satisfied there was a reasoned explanation for the different ELLDS values and that the Westinghouse calculations were appropriate and sufficiently conservative.

SG Primary Inlet Nozzle to Safe-End Weld (SG3)

120. A comparison report discussing the results of ELLDS and FCG calculations undertaken by Westinghouse and AMEC Foster Wheeler along with the specific calculations, were available for review (Ref. 20). The conclusions of the Westinghouse comparison work suggested that the ELLDS and FCG calculations were not fully reconciled. I undertook a high-level review to inform my understanding of the differences in the results.

121. Comparison of the ELLDS results showed that AMEC Foster Wheeler consistently predicted smaller sizes than Westinghouse. This was mainly due to AMEC Foster Wheeler using conservative lower bound yield stress values based on ASME for all its assessments, whereas Westinghouse used improved material specific tensile strength data to derive its yield stress values with lower bound values mainly used but alternatively with mean values for certain Level D transients. Westinghouse's use of mean values of yield stress for certain Level D transients accords with UK civil practice and with the guidance in the Westinghouse R6 fracture mechanics methodology document (Ref. 12). When it employed consistent material property assumptions, there was improved alignment between the ELLDS values predicted by Westinghouse and AMEC Foster Wheeler. I also note that Westinghouse ELLDS value of 27.43 mm is conservative because despite the low limiting transient frequency, Westinghouse retained the use of lower bound initiation toughness rather than invoke limited stable tearing (EMC.34). It should also be noted that UK civil nuclear practice would also allow use of mean initiation fracture toughness with mean yield stress for such Level D transients. I am therefore satisfied that the ELLDS value calculated by Westinghouse for weld SG3 is reasonable for the purposes of the GDA.

122. Generally, good agreement was found between the FCG predicted by Westinghouse and AMEC Foster Wheeler. However, significant differences in the FCG predictions

were observed at the dissimilar metal interfaces. The differences appeared to relate to the level of refinement in the stress inputs and how pipe loads were captured in the fatigue crack growth calculations. However, Westinghouse concluded that the differences in the predicted FCG were not fully understood and related to the conservatism of the input data provided and the assumptions then made, however, provided no additional information to elaborate (Ref. 20). I observed that based on the most conservative assumptions for FCG it may be challenging for Westinghouse to maintain a DSM of 2.0. I was unable to fully resolve this matter within the GDA timescale and have raised Assessment Finding CP-AF-AP1000-SI-07 (see paragraph 169) to ensure resolution during licensing.

123. On balance, and taking cognisance of the conservatism in the ELLDS values, I consider the QEDS values for dissimilar metal weld (SG3) as reasonable for the purposes of GDA. In consequence, I also judge the QEDS values for the other dissimilar metal welds between the low alloy vessel nozzles and the austenitic stainless steel safe-ends on the RPV and PRZ as reasonable for the purposes of the GDA. My regulatory judgement takes cognisance of the inherent conservatism in the Westinghouse decision not to invoke stable tearing in its ELLDS calculation under the limiting Level D transients. In addition, my judgement was informed by the Westinghouse decision to classify these welds as HSS and to consider as part of the vessel for the purposes of demonstrating that likelihood of gross failure in the vessel is so low that it can be discounted. I view this as a cautious decision, which goes beyond the position previously adopted in the UK civil nuclear practice.

Westinghouse v Frazer-Nash – Comparative ELLDS and FCG Calculations

124. I commissioned Frazer-Nash to undertake comparative studies for selected HSS welds in the PRZ, RPV and SG. These comparative studies were designed to further test the Westinghouse understanding and application of the R6 procedure. The HSS welds included: PRZ weld (PRZ3); RPV upper shell to lower shell weld (RPV2) weld and SG lower shell barrel to tubesheet weld (SG4), see Table 6.

125. Westinghouse provided input data for the calculations, but Frazer-Nash used engineering judgement and its R6 assessment experience to interpret certain inputs e.g. R-Code solutions, stress classification of mechanical loads, and residual stress assumptions. This arrangement allowed sufficient independence to inform a view on the adequacy of the Westinghouse calculations.

PRZ Manway to Shell Weld (PRZ3)

126. Frazer-Nash calculated an ELLDS (depth) calculated 59.7 mm, very close to the Westinghouse value of 59.5 mm. I concluded that Westinghouse had established an appropriate and conservative ELLDS value for PRZ weld (PRZ3) (see Table 6) for AR=2. Westinghouse predicted a total FCG of 7.52mm (depth) and examined the contribution of the most severe combinations of fatigue cycles to this value (6.83mm (depth)).

127. The Frazer-Nash sample FCG check was calculated as 10.33 mm and 6.37 mm (for assessments differing solely through using membrane weld residual stress of 170 MPa and 55 MPa, respectively. The lower FCG with 55 MPa is due to the lower value of the R ratio (R = ratio of the lowest and highest imposed SIF for a given stress cycle). The largest ΔKI in the Frazer-Nash calculation was always found at the major axis of the defect (the surface point).

128. Clearly, even with the small FCG sample, there is a significant difference between the results using membrane weld residual stress values of 170 MPa and 55 MPa. A sensitivity study by Frazer-Nash with a residual stress value of 170 MPa and growth governed by deepest point gave a FCG of 7.132 mm (depth). This agreed well with the

Westinghouse sample FCG of 6.83 mm. I therefore judged that the observed differences were dominated by Westinghouse not considering growth at the surface point and the high residual stress assumption of 170 MPa.

129. Westinghouse undertook a sensitivity study to show that its bounding ELLDS value was unlikely to be affected by any increase in FCG at the surface (Ref. 35). Westinghouse subsequently acknowledged that FCG must be considered at the surface point and that further guidance would feature in its R6 methodology document, (Ref. 34).

130. In contrast, I also noted that by adopting high residual stress values in its FCG calculations Westinghouse may introduce significant conservatism into its fracture analysis. I raised the point with Westinghouse in RQ-AP1000-1724 (Ref. 44) and in Ref. 35.

131. Westinghouse explained that the FCG calculations were undertaken in advance of updating its methodology document (Ref. 44). Westinghouse acknowledged the inconsistency and gave a further commitment to use consistent membrane weld residual stress values in its ELLDS and FCG evaluations in future assessments. The commitment was captured in an update to the methodology document (Ref. 12).

132. Overall, I am satisfied that the ELLDS calculation was conservative and that the FCG calculations were appropriate for the purposes of the GDA.

RPV Upper Shell to Lower Shell Weld (RPV2)

133. The comparative work included ELLDS and FCG checks for a sample of the highest transient combinations. An inner surface defect with AR 6:1 was chosen for comparative assessment due to the relatively high FCG predicted by Westinghouse ie 7.4 mm for the full fatigue spectra over a 60-year design life from an initial flaw depth of 25.0 mm (Ref. 30). Westinghouse also estimated a sample FCG of 3.78 mm (depth) for the three most severe combinations of fatigue cycles for a 6:1 AR starting from depth 25.0 mm over the 60-year design life.

134. For CMT Recirculation and Heated Drain-down Test, Frazer-Nash calculated a ELLDS (depth) of 62.62 mm using hoop collapse with Lr = 0.51. In comparison, the Westinghouse ELLDS was 69.5 mm (the Westinghouse assessment used hoop collapse with Lr = 0.42). In a sensitivity study setting Lr = 0.42, the Frazer-Nash calculated an ELLDS of 69.71mm ie very similar to Westinghouse. The difference between the Frazer-Nash and Westinghouse calculations therefore centred on the Lr used for hoop collapse.

135. Westinghouse explained its Lr value of 0.42 was based on a limit load solution for a thin-walled cylinder with circumferential cracks under combined internal pressure, axial tension and bending. The solution was generated using a Von Mises yield criterion, whereas the Frazer-Nash Lr value was based on the hoop stress portion of the Connors Eq 60 using the more conservative Tresca yield criterion. I am satisfied with the Westinghouse explanation. This was because the difference in limit loads between Tresca and Von Mises is commonly found and that the Von Mises solution is widely accepted.

136. A sample FCG (depth) over 60 years was calculated by Frazer-Nash was 3.700mm. The largest ΔKI in the Frazer-Nash calculation was always found at the minor axis (deepest point). In comparison, the sample FCG (depth) predicted by Westinghouse was 3.780 mm. There was therefore excellent correlation between the two results.

137. I concluded that Westinghouse ELLDS and FCG calculations for RPV weld (RPV2) were conservative and appropriate.

Steam Generator Lower Shell to Tubesheet Weld (SG4)

138. The SG lower shell to tubesheet weld (SG4) was chosen for assessment due to the high FCG predicted by Westinghouse at this location at GDA Step 4 (Ref. 1). In addition, ONR had not previously commissioned any comparative assessments for the SG. A circumferential semi-elliptic defect (AR 6:1) aligned with the weld and located on the inner surface was chosen for comparative assessment due to this defect having a high FCG of 5.590 mm (depth) over 60-years from a starting depth of 15 mm (Ref. 30). The relevant ELLDS predicted by Westinghouse was 53.47 mm (depth), obtained for the Inadvertent Opening of the ADS Valves – Service Level C at 1,200 seconds (Ref. 30).

139. The ELLDS (depth) calculated by Frazer-Nash with pressure bending stresses treated as secondary was 49.42 mm. In contrast to the Westinghouse value above. A separate Frazer-Nash assessment which treated all pressure stresses as primary (consistent with Westinghouse), but retaining Connors 60 plastic collapse solution, gave an ELLDS of 53.54 mm ie very similar to the Westinghouse ELLDS value. Note that these ELLDSs were calculated using SIF values at the surface point.

140. I attributed the small disparity to differences between the pressure bending stress classification and its effects on the V factor (a correction factor applied to the SIF in R6 to account for the interactions between primary and secondary stresses). There also appeared to be inconsistencies in the Westinghouse assumptions relating to its SIF and plastic collapse calculations.

141. In the response to RQ-AP1000-1726, Westinghouse recognised it was inconsistent to classify the pressure bending stresses as primary in the SIF calculation, while using an internal pressure (membrane only) plastic collapse solution (Ref. 45). However, for location SG4, the more conservative value of 49.42mm calculated by Frazer-Nash still affords a DSM in excess of 2.0. I also noted that the large pressure bending stresses in the vessel wall at SG4 are mainly the result of the displacement incompatibility between the SG lower shell and the flanged tubesheet when subjected to the pressure loading. Large pressure bending stresses are not present in the other HSS component ELLDS shell locations (eg PRZ, RPV).

142. To ensure conservative ELLDSs are calculated in the future, Westinghouse added explicit guidance to its fracture mechanics methodology document, (Ref. 12). This will highlight the importance of consistent pressure bending stress classification (ie primary or secondary) in the plastic collapse solutions and SIF solutions; and include advice on the use of appropriate plastic collapse solutions for primary bending stress. I note the commitment from Westinghouse, but consider that the non-conservative assumption could have been established through sensitivity studies. Indeed, the use of sensitivity studies to establish conservatism along with the robustness of margins is an important means of informing the engineering judgements required in the R6 defect assessment procedure.

143. In preparing the input data for the comparative FCG work Westinghouse confirmed that peaks and troughs within each transient are considered. However, it was unclear from the Westinghouse methodology whether there was provision for cross-combining of peaks and troughs among different transients. It was therefore uncertain whether the Westinghouse approach was appropriate in terms of covering interactions between different transients.

144. I sought clarification in RQ-AP1000-1726, in which Westinghouse confirmed that its approach includes limited transient interactions, but not all, and that future assessments would provide more clarity on how the transients are considered when performing the FCG evaluations (Ref. 45). This question and response must be seen in the context that cross-combining transients (known as rainflow or reservoir cycle

counting) is undoubtedly conservative when calculating FCG, but that the Westinghouse approach of simply summing the growth from the individual transients is potentially non-conservative. The balance depends on the nature of the transients being considered. Westinghouse also grouped similar transients and base the FCG on the worst one from the group; this adds considerable conservatism. I proposed that Westinghouse should consider a sensitivity study to confirm that the method it has chosen to accumulate FCG from the various transients is appropriate and conservative. This matter is subject to my Assessment Finding CP-AF-AP1000-SI-07, see Annex 1.

145. Frazer-Nash calculated a FCG (depth) of 4.850 mm, which correlated reasonably well with the Westinghouse prediction of 5.590 mm.

146. I established that the high FCG predicted by Westinghouse at this location at GDA Step 4, was obtained using the more onerous FCG rate calculation method for light-water reactor environments from ASME XI Appendix A Subarticle A4300(b)(2), identified in Ref. 30. However, in its updated fracture calculations for weld SG4, Westinghouse invoked a significant reduction in FCG based on ASME Code Case N-643-2.

147. ASME Code Case N-643-2 provides a more realistic procedure for computing fatigue crack growth rates than the existing fatigue crack growth rate curves in Appendix A to Section XI of the ASME Code when non-EAC behaviour exists. Susceptibility to EAC during fatigue cycling is determined by checks against metallurgical factors such as material chemistry and environmental factors. An important material chemistry factor is the sulphur content of the steel. Confirmation that the specified sulphur content is achieved in the as-built components would feature as part of the response to Assessment Finding AF-AP1000-SI-29, raised in Ref. 1 at Step 4 of GDA. This requires the future licensee to ensure that the safety case for the structural integrity of components on the individual site reflects the actual build and operation on that site.

148. Overall, I am satisfied that Westinghouse had undertaken suitably conservative and appropriate ELLDS and FCG calculations for weld (SG4).

QEDS and Reconciliation

149. I raised RQs aimed at establishing whether QEDS values would provide a reasonable basis for reconciliation with the NDT inspection plans. The Westinghouse reconciliation document (Ref. 35) arrived late in the closure phase of the work. Westinghouse chose not to re-evaluate the defect size margins to take cognisance of my RQs, instead it offered engineering judgements supported by some scoping estimates as a means of justifying its QEDS values. The main topics discussed were as follows.

Limiting Transient / Time Point

150. I asked Westinghouse to confirm the limiting ELLDS size for all defect orientations at RPV location RPV1, and to establish the effects, if any, for reconciliation with the NDT inspection plans. Westinghouse acknowledged that the CRE transient resulted in a smaller ELLDS (71.8mm) for an inside circumferential surface defect of 6:1 AR (Ref. 35). However, the overall limiting ELLDS based on the DSM for a 6:1 AR defect was unchanged (i.e. an outside circumferential flaw for the CRE at 3880.7 seconds with an ELLDS (depth) of 63.1mm. Additionally, the limiting ELLDS based on the bounding DSM of 2.1 remained 73.2mm for an inside axial 6:1 AR defect. I concluded that Westinghouse had demonstrated that the limiting ELLDS value for RPV location RPV1 remained valid for the purposes of the GDA. Westinghouse committed to remove this potential source of non-conservatism in future fracture assessments.

Surface Tip Assessment

151. The identification of the limiting location on the defect for FCG i.e. the surface or deepest point was raised in relation to PRZ weld PRZ3 (Refs. 35 and 44). Westinghouse confirmed that for a 2:1 AR defect there could be cases where flaws can have higher FCG at the surface tip compared to the deepest point. In most cases, the sampled HSS welds related to ELLDS values for 6:1 AR defects with the deepest point limiting (Ref. 35).

152. However, HSS welds PRZ1 and RPV2 indicated similar DSM values for defect ARs of 2:1/3:1 and 6:1 (Table 5). Westinghouse performed a sensitivity study to show that even if the estimated FCG was doubled a DSM of > 2.0 would be maintained against the inspection plan target QEDS values of 10 x20mm and 25 x 50mm for welds PRZ1 and RPV2 respectively. Note that Westinghouse reclassified weld SG1 as Standard Class 1 and so was not considered. I was satisfied that Westinghouse had demonstrated that the limiting ELLDS values were unlikely to be significantly affected by higher FCG at the surface for the purpose of the GDA.

153. Westinghouse committed to remove this potential source of non-conservatism in future fracture assessments. I reviewed the revised guidance in the Westinghouse R6 fracture mechanics methodology document. I was not convinced that the Westinghouse guidance mandates consideration of the surface point in the baseline FCG assessments. However, its proposed FCG sensitivity studies would reveal when growth at the surface point is more onerous and therefore when growth at the surface point should also be considered by Westinghouse in its baseline FCG assessments.

Residual Stress Values in FCG Calculations

154. For PRZ weld PRZ1 and PRZ3 (and other HSS vessel shell welds not involving significant material dissimilarities) the Westinghouse retention of a membrane residual stress value of 170 MPa in its FCG calculations introduced further conservatism (Ref. 44). This was because effective PWHT to established nuclear codes is expected to lower membrane residual stress values in shell welds to circa 55 MPa. I therefore concluded that the Westinghouse FCG predictions for PRZ shell welds (PRZ1 to PRZ3) and other FCG calculations for welds subject to proven effective PWHT procedures would be conservative if the high residual stress value of 170 MPa was used.

Treatment of Ductile Tearing in Level C/D Transients

155. Westinghouse presented fracture assessments were based on the use of lower bound initiation toughness, and this included the more severe, faulted and accident, Level C/D transients. In UK civil nuclear practice, SAP EMC.34 allows for a limited degree of stable tearing to be invoked for the severe faulted and accident transients providing valid fracture toughness data is available. UK civil nuclear practice also allows use of mean yield stress and mean initiation fracture toughness for these lower frequency events. The Westinghouse approach therefore introduced an additional degree of conservatism in the assessment of Level C/D transients.

156. I raised RQ-AP1000-1771. Westinghouse acknowledged that its use of material properties for the purposes of the GDA differed from UK practice, but chose to retain the additional conservatism by not invoking ductile tearing for Level C/D transients in its fracture assessments (Ref. 35). I note the Westinghouse position and that its approach introduces additional conservatism when Level C/D transients limit the ELLDS values.

157. Overall, I am satisfied that Westinghouse had provided adequate responses to my RQs.

4.3.1.3 Summary

Benchmarking and Methodology

158. In advance of updating its R6 fracture mechanics calculations for a sample of HSS welds, Westinghouse undertook informative benchmarking evaluations to understand the difference between ELLDS sizes calculated by Westinghouse and EASL for the PRZ and RPV at GDA Step 4. I concluded from my initial review that Westinghouse offered plausible explanations for the observed differences and that it had taken initiatives to reduce the likelihood of a recurrence of the oversights / errors identified at GDA Step 4.

159. A more detailed review of the Westinghouse benchmarking and methodology documents resulted in a large number of commitments from Westinghouse to update its R6 fracture mechanics approaches to meet UK expectations. I attribute this not to a lack of technical competence, but a reflection of the different nuclear regulatory regimes. In particular, application of the R6 procedure relies more on engineering judgements, interpretation and experience to achieve a conservative result than code-based prescriptive fracture assessment approaches.

160. The Westinghouse level of verification and validation of its R6 fracture mechanics calculations met its company-wide procedure for design analyses, but fell short of UK expectations for highest reliability components in some areas e.g. the need to use alternative methods to verify the reliability of the R-Code software. This was rectified by Westinghouse updating its R6 fracture mechanics methodology document.

161. Several points arising from GDA Step 4 required significant work to close-out; for example, the treatment of through-wall bending stresses; improved visibility of the limitations of the WESTEMS software in evaluating thermal stresses under severe thermal transients; the accuracy of third order polynomial stress fits and the need to assess both the crack depth and tip positions in ELLDS and FCG calculations. These points were resolved with Westinghouse updating its R6 fracture methodology document, but not without multiple regulatory interventions.

162. I acknowledged that Westinghouse had made significant progress in its understanding and application of the R6 defect assessment procedure post GDA Step 4. However, my confidence in its proficiency in the application and interpretation of the R6 procedure is tempered by the many commitments Westinghouse invoked in response to my RQs and influence. These commitments, while welcome and reflective of the learning gained, were nonetheless necessary, despite the Westinghouse initiatives, notably the engagement and access to a UK contractor experienced in the application of the R6 procedure.

163. I identified shortfalls in the veracity of the Westinghouse verification and validation arrangements to underpin its fracture analyses for HSS components. These do not undermine my confidence in the validity of the Westinghouse methods to progress the GDA closure, but I raise the following assessment finding to support licensing.

CP-AF-AP1000-SI-04 – The licensee shall ensure that robust verification and validation arrangements, incorporating adequate independent review, are developed and implemented to underpin the fracture assessments for HSS and HI components.

164. I have observed that the plant hydrostatic test constitutes the limiting transient in two fracture analyses of PRZ welds. I consider that this identifies the potential for such tests to result in defect growth, and note that these tests are necessarily conducted after In-service Inspection (ISI) has taken place during an outage. While hydrostatic testing is a requirement of the reference edition of the ASME Code, I am aware that the more recent ASME Code Case N-498 allows for the periodic hydrostatic test to be replaced with a leak test; this change has been accepted by the United States Nuclear Regulatory Commission. Leak testing is conducted at higher temperature than the

hydrostatic test, hence the potential for brittle failure is somewhat reduced. Furthermore, should a through-wall flaw be present at the time of testing, the leak rate at operating pressure would be lower than that associated with hydrostatic test pressure. I therefore raised the following assessment finding to require that arrangements for in-service pressure testing of systems accord with current good practice at the time of site licensing.

CP-AF-AP1000-SI-05 – The licensee shall justify that any periodic hydro-tests proposed for HSS and HI components comply with relevant good practice.

Comparative Work and QEDS Values

165. Westinghouse has improved its process for the capture of the limiting transient / time point for the ELLDS calculations. My review work confirmed that in general there was good agreement between the Westinghouse capture of the limiting transient / time point and those undertaken in either the Westinghouse or the ONR commissioned comparative work. There were some differences for one HSS weld (RPV1) in the Westinghouse commissioned work, but these were explained through further work. I drew confidence from the results from the ONR commissioned independent review work. My view is that engineering judgement with input from other specialism disciplines is a very important part of the process in the capture of the limiting transient/time point. I gained sufficient confidence that Westinghouse had adopted adequate methods for the purposes of the GDA.

166. I have identified that Assessment Finding AF-AP1000-SI-06 of Ref. 1 requires that a robust method is applied during site licensing to identify the limiting time steps used in future fracture analyses (see paragraph 98). In this assessment, I have identified several points of detail relating to this matter, as follows:

- My sampling of the Westinghouse fracture analysis for HSS welds for the GDA close-out was largely based on weld types where mechanical loads tend not to contribute significantly to the imposed stress. Therefore, if stresses from mechanical loads are significant, additional engineering judgment will be needed to provide confidence that the bounding transient / time point are identified.
- Dissimilar metal welds with significant differences in material properties invariably induce high bending and shear stresses. Thus, if Westinghouse retain the HSS classification for these welds then the effects of these additional stresses also warrant consideration in the capture of the limiting transients / time point.
- It is important that a conservative approach to the capture of the limiting transient / time point is adopted and so resolution of AF-AP1000-SI-06 is important for licensing. I consider that the licensee will also need to ensure the adequacy of independent challenge in the approach to capture of the limiting transient / time point.

To complement AF-AP1000-SI-06 I have raised the following assessment finding to ensure that these aspects are addressed in the licensing phase.

CP-AF-AP1000-SI-06 – To promote resolution of assessment finding AF-AP1000-SI-06, the licensee shall take account of stresses due to mechanical loads and stresses in dissimilar metal welds when determining the limiting transient / time point for fracture analysis. These fracture analyses shall be subject to thorough and independent validation.

167. A comparison of the Westinghouse commissioned comparative R6 fracture analyses for a sample of HSS welds showed the Westinghouse ELLDS values were in general conservative and appropriate in the majority of cases. In post comparison review work Westinghouse offered plausible explanations for the differences.

168. I note that for the SG primary inlet nozzle to safe-end weld (SG3) the ELLDS and FCG calculations were not fully explained in the Westinghouse comparative work. On balance, and taking cognisance of the conservatism in the ELLDS values, I consider the QEDS values for dissimilar metal weld (SG3) as reasonable for the purposes of the GDA. In consequence, I also judged the QEDS values for the other dissimilar metal welds between the low alloy vessel nozzles and the austenitic stainless steel safe-ends on the RPV and PRZ as reasonable for the purposes of the GDA.

169. I have earlier noted my opinion that HSS classification of safe-end welds appears a cautious decision by Westinghouse (see paragraph 70). However, I was unable to fully resolve this matter with Westinghouse within the GDA timescale and so have raised the following assessment finding to ensure resolution during licensing.

CP-AF-AP1000-SI-07 – The licensee shall justify the classification of dissimilar metal welds between the low alloy vessel nozzles and the austenitic stainless steel safe-ends on the RPV, PRZ and SG. The justification shall clarify the basis for classification and explain how resultant requirements for the demonstration of structural integrity are balanced against demands on inspection capability, particularly if highest reliability is claimed.

170. A companion series of ONR commissioned comparative ELLDS and FCG calculations for a further set of HSS welds showed areas of good agreement and difference between the Westinghouse and ONR commissioned calculations. The reasons for the differences were identified and understood. Westinghouse enacted several updates to its R6 fracture mechanics methodology document. I note the commitments from Westinghouse, but consider that the potential for non-conservative assumptions could have been established through adequately scoped sensitivity studies. The use of sensitivity studies to establish the robustness of margins eg on defect size or fracture toughness is a fundamental tenet of the R6 defect assessment procedure.

171. The goal setting UK nuclear safety regime combined with the non-mandatory requirements of the R6 defect assessment procedure place additional responsibilities on the user to invoke engineering judgements in its fracture avoidance demonstrations. This can cause difficulties for Requesting Parties who are most familiar with code-based prescriptive methods. I appreciated that Westinghouse has gained considerable knowledge from the regulatory engagement during GDA, but to support future licensing consider that the following assessment finding is warranted.

CP-AF-AP1000-SI-08 – The licensee shall ensure that sensitivity studies are undertaken to underpin the margins in its fracture avoidance demonstrations for HSS and HI components.

172. I was not convinced that the Westinghouse R6 fracture mechanics methodology guidance mandates consideration of the surface point in the baseline FCG assessments. However, its proposed FCG sensitivity studies would reveal when growth at the surface point is more onerous and therefore when growth at the surface point should also be considered by Westinghouse in its baseline FCG assessments. This aspect shall be addressed by the licensee as part of Assessment Finding CP-AF-AP1000-SI-07.

173. Westinghouse decided to retain the use of lower bound initiation toughness in all its fracture assessments. UK civil nuclear practice allows for a limited degree of stable tearing to be invoked for severe faulted and accident conditions (Level C/D transients). UK civil nuclear practice also allows for mean initiation toughness and mean yield stress to be used for such lower frequency events. The Westinghouse approach therefore introduces additional conservatism into ELLDS calculations if the limiting transient is governed by a Level C/D transient.

174. ONR’s expectation is that a conservative fracture assessment is undertaken for highest reliability components. However, to achieve a highest reliability demonstration it is also important that reasonable demands are placed on the licensee’s requirements for qualified inspection. This is because the aim of the qualified inspection is to screen out defects of structural concern using highly reliable inspection systems (ie conventional readily proven techniques, procedures and operators). On balance, and taking cognisance of the results of the Westinghouse and ONR commissioned comparative work along with the adequacy of the responses to my RQs I am satisfied that the QEDS values provide a reasonable basis for reconciliation with the NDT inspection plans for the purposes of GDA.

175. The final QEDS values for HSS welds and non-welded regions shall be confirmed by the future licensee taking cognisance of the assessment findings raised in this assessment report, see Annex 1, and extant findings AF-AP1000-SI-04 to AF-AP1000-SI-06 and AF-AP1000-SI-29, raised in Ref. 1 at Step 4 of GDA.

4.3.2 Inspection Qualification

176. The following assessment deals firstly with some generic issues and then separately with each of the actions and then draws overall conclusions with regard to the issue.

177. The Step 4 report accepted that it was not necessary to provide a detailed treatment for all of the HSS components in relation to the avoidance of fracture claims. Westinghouse’s approach was to rank welds using a combination of defect tolerance ranking and inspectability ranking to generate 12 locations for which it would present a more detailed treatment. As some bounding cases were identified, this number was reduced to seven locations for NDT analysis as follows:

- RPV lower shell to upper shell
- RPV DVI nozzle to upper shell
- RPV Inlet nozzle to safe-end (dissimilar metal weld)
- PRZ upper head to upper shell
- PRZ manway to shell
- PRZ surge nozzle to safe-end (dissimilar metal weld)
- SG main steam nozzle to MSL pipe

178. The expectation for GDA is for Westinghouse to demonstrate that high reliability NDT can be performed during the manufacture of HSS components and that this reliability can be demonstrated through a formal process of inspection qualification. In practice, this entails applying NDT methods that are based upon sound physical principles and are widely used in industry.

179. The approach to the assessment is twofold:

- Establish that the design of HSS components enables high reliability NDT to be applied.
- Review the effectiveness of Westinghouse’s proposed NDT techniques based upon the evidence presented in its IPs.

180. Westinghouse has agreed that the manufacturing inspections for the HSS components will be qualified in accordance with the ENIQ methodology (Ref. 23).

181. The main requirements of the ENIQ methodology are:

- The qualification of the NDT procedure and the NDT personnel are separated.
- NDT procedures are qualified through a combination of written technical justification and practical demonstration. The technical justification brings together the physical basis of the NDT techniques with experimental and theoretical evidence to support the ability of the NDT to meet the predefined inspection objectives.
- The qualification body (a body of experts acting independently of the inspection organisation and licensee) assess the technical justification and the results from the practical trials. If the qualification body judges that the outcome is satisfactory, it will issue a qualification certificate or equivalent statement.

4.3.2.1 Westinghouse Approach for Qualified Inspections During GDA

182. Westinghouse chose to submit the evidence that manufacturing NDT is able to deliver the required capability in the form of IPs. These documents were shortened versions of the technical justifications that would be needed for a full qualification and included a summary of: the inspection objectives; an overview of the proposed inspection techniques and available evidence to support the capability of the NDT. Westinghouse sought an independent review of the IPs for which it used the services of the IVC acting as a quasi-qualification body. The conclusion of this independent review was an IVC statement confirming its judgement that the proposed inspections, when fully developed, were likely to meet the required capability.

183. While Westinghouse’s approach could be inferred from the activities that it was undertaking in GDA, it was important to understand whether the same process was being applied consistently. To this end I raised RQ-AP1000-1351 and RQ-AP1000-1471, to which Westinghouse responded with the procedure given in Ref. 46. I found this procedure helpful in describing the roles and responsibilities and the steps taken to arrive at a final GDA IP. The process also included a summary of which sections of a full ENIQ style technical justification were included in the GDA IPs.

184. An important input to the IPs is the QEDS derived from a R6 fracture mechanics calculation. Westinghouse proceeded with the IPs based upon on initial values of the QEDS; derivations of final QEDS values were proceeding in parallel with the production of the IPs. A final reconciliation process was then performed to ensure that adequate margins remained between the size of defect that could be reliably rejected by NDT and the fracture mechanics limiting defect size. Westinghouse included this reconciliation process in its procedure (Ref. 46) for producing IPs. The overall process included:

    - the drafting of the IPs;
    - the independent review by the IVC;
    - resolution of the IVC comments through an iterative process to generate the final version of the IP;
    - the issue of an IVC statement summarising its conclusions regarding the likely capability of the NDT techniques. Where relevant, this statement included caveats of any potential limitations; and
    - the reconciliation process for comparing the final QEDS values and the assumed working values used for the production of the IPs.

185. The IPs for the RPV upper shell to lower shell weld and the RPV DVI nozzle –shell welds were assessed during Step 4 and consequently have not been reviewed under GI-AP1000-SI-01.

186. My approach to the assessment reported here has been to combine a full assessment of a sample of IPs supplemented by a targeted review of others. This approach has been informed by Westinghouse's process for the production of IPs, which has included the independent review by the IVC.

187. Below I have presented my general conclusions on the IPs followed by more specific assessments of individual assessment plans.

4.3.2.2 Inspection Plans: Generic Comments

188. The IPs propose the deployment of ultrasonic probes using a motorised scanner combined with digital data collection and display. This approach provides good control of the probe scanning, the ability to analyse the data offline and a permanent record of the inspection that can be viewed at a later stage.

189. From my review, I am satisfied that Westinghouse has applied an effective process for the production of IPs. The content of the IPs, combined with the review by a quasi-qualification body, has demonstrated a clear understanding of the ENIQ methodology for inspection qualification.

190. I considered that the IPs are well constructed and are aligned with the ENIQ recommended practice (Ref. 23) that provides guidance for the production of technical justifications. Consequently, I believed that Westinghouse's IPs provide a good basis for developing into complete technical justifications that will be needed for the actual qualification.

191. A common theme that arose from my review of the IPs was whether the 'design for inspectability' concept had been adequately embraced. Consequently, many of the questions I raised were aimed at establishing whether, when balanced against other factors, there was any significant benefit to the inspection by implementing design changes. In the examples presented in the IPs these changes would be either to improve the surface finish or to change the shape to improve the scanning access for ultrasonic probes. NDT of HSS items performed during manufacture and in-service are an integral part of the safety case and consequently the design for inspectability of each component must be considered to an extent that exceeds code requirements.

4.3.2.3 Inspection Plan for RPV DVI Nozzle to Safe-End Weld

192. The IP for the RPV DVI nozzle to safe-end weld was issued at Revision 0 late in Step 4 of the GDA, and was subsequently updated to Revision 1 to address comments from the IVC.

193. In this instance, I targeted my assessment at Westinghouse's process for the production of the IPs produced during GDA rather than conducting a full assessment of the IP. I noted that there have been significant modifications between Revision 1 and Revision 0 and that these changes have been made largely as a result of comments raised by the IVC. Having viewed the IVC comments sheet and Westinghouse's response to these comments, I am satisfied that the challenge raised by the independent review has been an effective exercise.

4.3.2.4 Inspection Plan for RPV Inlet Nozzle to Safe-End Weld

194. An austenitic stainless steel forged safe-end ring is joined to the ferritic steel forged RPV inlet nozzle by an alloy-690 weld; the inner surface of the nozzle forging is clad with austenitic stainless steel weld material and the ferritic steel fusion face is first buttered with alloy-690 weld metal. The dissimilar nature of the joint, along with the coarse grain anisotropic welds, present particular difficulties for ultrasonic inspection and careful selection of techniques is required. I noted that coarse grain anisotropic

welds are also present in other areas, notably the main coolant line and that Westinghouse has selected the RPV inlet nozzle to safe-end weld as the bounding case.

195. Westinghouse's IP (Ref. 24) proposes techniques for defects aligned in the welding direction (circumferential defects) and defects aligned perpendicular to the welding direction (transverse defects).

196. Westinghouse presented experimental evidence for the capability of the inspection techniques that was largely derived from exercises used to qualify the in-service inspection of similar welds. While in-service inspection is targeted at surface breaking defects (or near surface breaking defects), the evidence is relevant for a relatively large scope of the manufacturing inspection.

197. The inspection described in the IP makes use of all available inspection surfaces for applying probes. I judged that careful thought had been given to the selection of probe parameters (wave mode, frequency, size and focus configurations) and that the 'physical reasoning' for this selection was well described. The large number of scans described are expected to provide an effective inspection for the detection and rejection of circumferential defects.

198. The detection of embedded transverse defects is particularly difficult as the ultrasonic beam is passing entirely through coarse grain anisotropic weld material. Characterisation and sizing are even more difficult as these rely on analysing lower amplitude signals. In my opinion, the evidence presented for the reliable detection and rejection of transverse defects was not compelling, an opinion that was shared by the IVC in its review of the IP. I noted that the IP did not provide a clear definition of the inspection requirements for transverse defects and that they were not included in the discussion on worst-case defects. As a consequence, I raised RQ-AP1000-1472 which asked Westinghouse to clarify the safety case requirements for an NDT capability for embedded transverse defects. Westinghouse responded by stating first that embedded transverse defects were highly unlikely to occur in practice and, if present, would be of a size that could not threaten structural integrity (Ref. 25). Westinghouse subsequently claimed that high reliability inspection techniques for embedded transverse flaws are not required to support the structural integrity safety case. I believe that this is a reasonable position to take for manufacturing inspections (it will be necessary to revisit this argument in relation to in-service inspection), noting that Westinghouse has retained surface breaking transverse defects within the scope of the high reliability manufacturing NDT.

199. While the detection of embedded transverse defects is particularly difficult in this case due to the coarse grain structure in the weld, Westinghouse extended this requirement for transverse defects to all of the HSS welds.

200. In RQ-AP1000-1352, I raised a question relating to the surface finish of the cladding at the inner surface of the RPV. The IP indicated that the cladding would be left in the as-clad state, leaving the potential for small steps at cladding interfaces that could interfere with ultrasonic inspection. Westinghouse stated that the surface finish requirements were ultimately dictated by the inspection procedure that would specify a requirement on roughness to be better than 3.2 µm Ra (Roughness Average) and maximum probe gap to surface of 0.5 mm in line with BS EN ISO 16827:2014. In my opinion there may be significant benefits to ultrasonic inspection through improving the surface condition and that adhering to the requirements of a standard may not be an ALARP (As Low As Reasonably Practicable) position. In particular, the reliable evaluation of indications may necessitate an improved surface. I expect this to be considered when addressing AF-AP1000-SI-31, AF-AP1000-SI-32 (Ref. 1) and CP-AF-AP1000-SI-08 (see Section 4.3.2.7).

201. Dissimilar metal welds of the type used to join the RPV nozzle to safe-end present particular challenges for ultrasonic inspection due to the coarse grain anisotropic structure of the weld, cladding and buttering and the presence of several interfaces. Consequently, it is important to optimise the overall inspection conditions to achieve an acceptable inspection capability. Westinghouse confirmed that it performs a supplemental ultrasonic inspection of the nozzle-buttering interface before the weld is made, thereby enhancing the capability for detecting defects in this region and which are aligned with the interface. While this inspection stage is not qualified, it will provide a valuable opportunity to detect any manufacturing defects associated with laying down the buttering.

202. The IP states that the inspection from the end face of the safe-end provides an effective means of detecting defects but I noted that the presence of the weld preparation (for the subsequent safe-end to pipe weld) restricted coverage significantly. In RQ-AP1000-1352, I asked whether, in the context of a design for inspectability philosophy, it was possible to machine this weld preparation after the safe-end weld inspection had been completed, thereby providing an end face that was flat and perpendicular to the nozzle / safe-end axis. In response, Westinghouse confirmed that this was possible and because of the significant improvement that this would provide for the inspection capability, it is my expectation that this will be taken forward for the UK **AP1000** reactor; see Assessment Finding CP-AF-AP1000-SI-08, paragraph 219.

4.3.2.5 Inspection Plan for PRZ Upper Head to Upper Shell Weld and Manway to Shell Weld

203. Westinghouse provided a single IP for the PRZ upper head to shell and manway to shell welds (Ref. 26). I am satisfied that, due to the change in section, the PRZ upper head to shell weld represents a more challenging case than the PRZ shell to shell welds.

204. Westinghouse's IP proposed techniques for defects aligned in the welding direction (circumferential defects) and defects aligned perpendicular to the welding direction (transverse defects).

205. Westinghouse presented experimental evidence for the capability of the inspection techniques that was largely derived from exercises used to qualify the in-service inspection of similar welds. While in-service inspection is targeted at surface breaking defects (or near surface breaking defects), the evidence is relevant for a relatively large scope of the manufacturing inspection.

206. The geometry of both welds presents specific challenges to the inspection:

- The outside diameter of the PRZ upper shell reduces near the weld and the cylindrical shell is welded to a head with spherical geometry.
- The manway to shell weld is a set-through nozzle configuration with access restrictions for applying ultrasonic probes.

207. In addition, the PRZ inner surface is clad with austenitic stainless steel which can interfere with ultrasonic inspection.

208. These challenges require particular attention to the selection of scans and ultrasonic probe parameters and wherever possible the condition of the inspection surfaces should be considered.

209. The IP defines ultrasonic scans to be applied from the external surface only for both welds and I raised RQ-AP1000-1451 to question the feasibility of deploying scans from the inner surface. In response, Westinghouse argued that such scans were

problematic as this required man-access to a confined space and that the evidence presented in the IP demonstrated that the required inspection capability could be achieved from external scans alone. The IVC, in its independent assessment, also judged that the inspection objectives could be met with external scans alone. Westinghouse did state, however, that scans from the inner surface would be applied if the actual qualification exercise deemed it necessary to deliver the defined inspection objectives.

210. I note the difficulty in applying probes from the inner surface and the need to consider human factors and conventional safety as a result of confined space working. However, I consider that suitably designed scanning equipment could be deployed to deliver inner surface scans if necessary. Consequently, I would not expect any compromises to be made in the ability to meet the inspection objectives as a result of constraining the inspection to only the outer surfaces. Similarly, I do not expect any reduction in the defect size margin resulting from a relaxation of the inspection objectives.

211. The IP was unclear regarding the ultimate inspection objective for transverse defects and therefore I sought clarification on this matter in RQ-AP1000-1451. In responding to a similar matter for the RPV inlet nozzle to safe-end welds, Westinghouse provided a generic statement on the requirement for transverse defects that removed the claim for high reliability NDT for embedded transverse defects. This was done on the basis that such defects were highly unlikely to occur and in any case could not be of a size that would threaten structural integrity. The inspection for such defects would still be retained but without the claim for high reliability. The high reliability claim for transverse defects would therefore be for surface breaking, or near-surface breaking defects. I consider that this is a reasonable position to take noting that this argument is only for the manufacturing inspection; the position with regard to in-service inspection will need to be reconsidered at a later stage.

212. Initially, the IP stated that the cladding would be left in the as-clad condition as long as the surface finish was adequate for ultrasonic inspection. In response to a question raised in RQ-AP1000-1451, Westinghouse clarified that the IP was incorrect in this respect and the manufacturing specifications require that the clad surface is manually ground and will meet the surface finish and error of form requirements for ultrasonic inspection. I am satisfied with this response to my query.

4.3.2.6 Inspection Plan for PRZ Surge Nozzle to Safe-End Weld

213. A 316 stainless steel forged safe-end is joined to the SA508 ferritic steel surge nozzle by a dissimilar metal weld made from alloy 690. The inner surface of the ferritic nozzle is clad with 308L/309L stainless steel. The anisotropic coarse grain structure of the weld, buttering and cladding presents difficulties for ultrasonic inspection similar to those for the RPV inlet nozzle to safe-end weld discussed in Section 4.3.2.4; here the difficulties are less severe than for the RPV case due to the significantly small section thickness.

214. Westinghouse's IP (Ref. 27) proposes techniques for defects aligned in the welding direction (circumferential defects) and defects aligned perpendicular to the welding direction (transverse defects).

215. I judged from my full assessment of other IPs and of Westinghouse's process for its production, that it was unnecessary to undertake a complete assessment of all IPs. Instead I targeted my review of this IP to the issue of design for inspectability, a common theme in the questions that I raised from my review of other IPs.

216. While I accepted that inspectability had been considered in the weld design, I raised RQ-AP1000-1634 to aid my judgement as to whether any further improvements could

be made. In particular, I questioned whether the taper design on the surge nozzle could be modified to improve the access for scanning ultrasonic probes on the nozzle side of the weld. In response, Westinghouse stated that the weld design had combined a consideration of both inspectability and the need to minimise fatigue stresses. It also confirmed that a design for inspectability assessment for in-service inspection had been undertaken. Noting that the manufacturing NDT applies ultrasonic probes from both inner and outer surfaces (in-service inspection applies probes from the outer surface only) I am satisfied that the benefit to ultrasonic inspection of changing the weld design is relatively small compared to the potential uncertainty introduced in other structural integrity areas.

4.3.2.7 Inspection Plan for MSL: SG Main Steam Nozzle to Pipe

217. The SG main steam nozzle to main steam pipe weld was initially classed as HSS but later reclassified as a Class 1 item and as such it would no longer be included in the scope of GI-AP1000-SI-01. My initial assessment, undertaken while it was still classified as HSS, raised an important issue relating to the design for inspectability that is worth mentioning here.

218. Ultrasonic inspection relied on scans from the external surface as there was no access to the inner surface. The initial design for the weld included a change of section, from the SG outlet nozzle to the smaller diameter steam pipe and this change of section was taken up by manually shaping the outer surface of the weld. In my opinion this manual profiling of the weld surface could impair the inspection performance and opportunities exist for improving the design of the transition to promote ultrasonic inspection. In response, Westinghouse modified the design to move the transition away from the weld, thereby improving the ability to scan ultrasonic probes over the weld surface. It is important to note that this modification benefits both the manufacturing and the in-service inspections.

219. This specific issue of design for inspectability arose as a result of assessing the IP for the SG outlet nozzle to steam pipe weld while it was still classified as HSS. Potentially, there may be other instances where an improvement in design and/or manufacturing process could lead to significant enhancements in the inspection performance. I noted that the Step 4 structural integrity assessment raised two assessment findings, AF-AP1000-SI-31 and AF-AP1000-SI-32, relating to the design for inspectability for the **AP1000** reactor. Both of these were in the context of in-service inspection and referred to the implementation of actions identified in Westinghouse's design for inspectability documents, Ref. 47 and 48. The Step 4 assessment looked at the general requirements document (Ref. 47) and then sampled the implementation of these requirements for the RPV as specified in Ref. 48. The equivalent document for other HSS and Class 1 items was not reviewed in GDA. To supplement these findings, I have raised a further assessment finding.

CP-AF-AP1000-SI-09 - The licensee shall ensure the design and manufacture of Class 1 and HSS welds facilitates reliable inspection of components during manufacture and in-service.

4.3.2.8 Qualified Inspections Summary

220. I am satisfied that Westinghouse hasprovided the IPs in line with the requirements of GI-AP1000-SI-01. These IPs have been produced to a good standard and have sufficient detail for me to conclude that it will be possible to undertake high reliability NDT at manufacture of HSS components and that qualification of the NDT system will confirm that defects of structural concern (derived from fracture mechanics) will be detected and rejected.

221. Westinghouse applied a process in GDA whereby it employed the services of a quasi-qualification body to undertake an independent assessment of the IPs. I am satisfied that this process was effective and, in some cases, resulted in an improved IP. Because of this process I targeted my assessment at the more technically complex areas and on those aspects where design considerations were important.

222. The format and content of the IPs followed the ENIQ recommended practice for technical justifications and will provide a good basis for completing the qualification at a later stage.

4.3.3 Material Properties Testing

223. Lower bound materials toughness properties are required as input to the fracture analyses of HSS components. At Step 4 of GDA it was accepted that Westinghouse had provided adequate lower bound toughness data and other materials data for use in the GDA fracture assessments. However, Ref. 1 identified that materials toughness properties will, in future, need to be underpinned by additional fracture toughness testing on parent material and representative welds. Consequently Ref. 1 included Assessment Finding AF-AP1000-SI-11 as follows:

AF-AP1000-SI-11*: The licensee shall produce a comprehensive material data set for the HSS, High Integrity (HI), Standard Class 1 and Class 2 components for use during the design and assessment process and also to support through life operation. This will need to cover all relevant data including the basic design data and the confirmatory batch and weld specific test data from the additional fracture toughness testing programme. It will need to be clearly presented such that the initial pedigree of the data can be traced following the literature trail with comparison to other international data sets where possible.*

224. At Step 4 of GDA the fracture toughness testing proposals were judged sufficiently developed for award of an IDAC but not, at that stage, considered adequate to fully establish the required principles for additional testing within GDA.

225. Accordingly, GDA Issue Action GI-AP1000-SI-01.A3 required Westinghouse to submit proposals for additional materials testing to underpin the fracture toughness values used in the fracture analyses. Westinghouse acknowledged the need to perform this additional material testing for HSS components in its resolution plan (Ref. 5).

226. Westinghouse submitted initial proposals for fracture toughness testing early in my assessment. I found these did not clearly establish how the fracture toughness tests support the safety case, in particular the fracture analyses. Also, it was unclear whether the proposed fracture toughness testing accorded with RGP in the UK.

227. In response to my queries of Ref. 49, Westinghouse revised its proposal for fracture toughness, submitted as Ref. 21. I found this updated proposal more closely matched my expectations. Ref. 21 explicitly addressed the needs of the safety case with direct links to the use of this testing to underpin the fracture analyses, and to the classification of components. The proposed number and location of samples were clarified and the standards to be applied were identified.

228. Ref. 21 includes proposals for testing of forged and weld materials of HSS components, including the dissimilar metal welds at the RPV inlet nozzle to safe-end, SG inlet nozzle to safe-end and PRZ surge nozzle to safe-end connections. Westinghouse proposed fracture toughness testing of compact tension specimens for each of the limiting low alloy steel locations, as determined from Charpy impact curves, for the HSS components. I consider this approach satisfactory for identifying the limiting material of a particular HSS component.

229. Ref. 21 asserts that sufficient representative material of forgings and welds will be available to complete the proposed testing, with archive material for additional testing if required in future. I am content that the archiving of HSS materials is established in principle within GDA and will seek more detailed evidence of adequate archiving arrangements during the site licensing phase.

230. Assessing the claim of sufficient representation, I examined the proposed scope of testing. Ref. 21 groups limiting HSS components and welds into like materials to identify those to undergo fracture toughness testing. Content that Westinghouse has proposed dedicated testing of the limiting RPV material, I observed that the SG and PRZ are grouped for supplemental testing selection. I enquired whether Westinghouse proposed testing of limiting material from each of these HSS components.

231. Westinghouse clarified its intent, which is that supplemental fracture toughness testing is performed on one set of material only, an approach it justifies on the basis that the SG and PRZ will be of the same grade and class of material. Charpy results of the material from these forgings is proposed to identify the most limiting, which will undergo additional fracture toughness testing.

232. I do not accept that the proposed arrangement provides adequate assurance of the true representation of fracture toughness, which I considered vitally necessary for the highest reliability components. The SG and PRZ may, for example, have different supply chains, forging patterns and reduction ratios. This could result in variation of materials properties between these components that may credibly remain unrevealed by the proposed testing arrangements. I accept that the use of Charpy testing provides an adequate screening method for fracture toughness testing within an individual component, but I do not accept this approach for different components even where these are of the same grade. I considered that good practice in the UK is for individual fracture toughness testing of material from each component of the highest reliability. I regard this to be an important principle for testing of HSS material and so raised the following assessment finding.

CP-AF-AP1000-SI-10: The licensee shall undertake sufficient fracture toughness testing of the limiting forged material for each HSS component to validate assumptions of the fracture analysis for that component.

233. To account for variability between batches of welding consumables, Ref. 21 proposes testing of all weld wire heats for all dissimilar metal, stainless steel, and chrome-molybdenum weld wires associated with HSS welds. This represents an increased scope of testing, as compared with that initially proposed by Westinghouse, and I am satisfied that it is sufficiently comprehensive for testing of welding consumables.

234. Westinghouse did not propose fracture toughness testing of the low alloy HAZ. It justified this decision based on the outcome of a study of the USA operating fleet RPV beltline HAZ specimen tests. Westinghouse identified that this study showed that the irradiated Charpy transition temperature of the base metal bounds the irradiated Charpy transition temperature of the HAZ, typically by a large margin. Incorporating this operating experience, and noting that HAZ toughness data is highly scattered, often not providing meaningful results, Westinghouse identified that the American Society for Testing and Materials (ASTM) committee removed the requirement to include HAZ material in RPV surveillance programmes. I am satisfied that valid characterisation of HAZ material fracture toughness is impracticable in this instance and content that Westinghouse has adequately justified its proposal in this respect.

235. In Ref. 50 I questioned the orientation of fracture toughness specimens to be extracted from HSS forgings. In response Westinghouse updated its fracture toughness testing document (Ref. 21) to explain how its sampling direction is both conservative, with samples oriented in the weakest toughness direction, and consistent with the fracture

analysis for test crack propagation. I am satisfied that the directions chosen for sampling of fracture toughness properties are acceptable for both parent and weld locations.

236. In addition to HSS material, Ref. 21 proposes testing materials of the main coolant loop stainless steel weld and the SG main steam nozzle to MSL pipe weld. These are not presently classified as HSS components, but were included because work to classify these components was incomplete at the time Ref. 21 was issued. I consider that the scope and manner of testing is broadly equivalent to that proposed for HSS components, and noted that the matter of classification is the subject of a separate GDA issue, GI-AP1000-SI-06.

237. In my assessment, I examined evidence of good practice. Ref. 21 identifies that mechanical tests will be conducted according to the following standards:

- Charpy impact tests – ASME SA-370 "Test Methods and Definitions for Mechanical Testing of Steel Products"
- Drop Weight Nil Ductility Tests– ASTM E208 "Standard Test Method for Conduction Drop-Weight Tests to Determine Nil-Ductility Transition Temperature of Ferritic Steels"
- Fracture toughness testing in the transition regime – ASTM E1921 "Standard Test Method for Determination of Reference Temperature, T0, for Ferritic Steels in the Transition Range"
- Fracture toughness testing on the upper shelf – ASTM E1820 "Standard Test Method for Measurement of Fracture Toughness"
- The Reference Nil Ductility Temperature shall be determined from the Charpy and drop weight tests in accordance with the provisions of ASME III NB-2000

238. Ref. 21 further specifies that the supplier to Westinghouse shall maintain a quality assurance programme that meets the following requirements:

- 10 CFR 50 Appendix B – "Quality Assurance Criteria for Nuclear Power Plants and Fuel Reprocessing Plants"
- U.S. Nuclear Regulatory Commission, Regulatory Guide 1.28, "Quality Assurance Program Requirements (Design and Construction)," Revision 3, August 1985
- ASME NQA-1-1994, "Quality Assurance Requirements for Nuclear Facility Applications"

239. The standards and requirements proposed by Westinghouse are familiar to me. I consider these well established and internationally recognised as suitable for mechanical testing of nuclear grade materials. I am satisfied that these standards and requirements, if adequately applied, are suitably rigorous for application to components of the highest reliability. I am content that Ref. 21 broadly accords with my expectations in relation to current standards, guidance and RGP.

240. Based on the foregoing discussion (paragraphs 223 to 239) and noting the requirement of CP-AF-AP1000-SI-09 for comprehensive testing of forged HSS material, I am content that Westinghouse proposals for materials properties testing are adequately defined in GDA for award of a DAC.

241. To promote lifelong integrity, Ref. 21 describes a RPV surveillance programme following the guidance of ASTM E185. This is intended to account for the effects of irradiation embrittlement by periodic affirmation of acceptable materials properties through life. As noted in Ref. 1, detailed implementation of the surveillance scheme is

outside the scope of GDA and the matter is subject to the following assessment finding.

AF-AP1000-SI-22: *The licensee shall demonstrate that the damage correlation used to determine the shift in the reference temperature for nil ductility transition is suitable for the RPV materials. This needs to reflect on the current understanding of dose damage correlations and should be kept under review over the life of the plant as new data becomes available from surveillance specimens and from worldwide data.*

242. I am satisfied that the principles of the surveillance scheme are adequately defined in Ref. 21 for the purposes of GDA. As reflected in Ref. 1, detailed implementation of the RPV surveillance programme will be addressed in the site licensing phase.

243. Since completion of Step 4 of GDA certain issues have arisen in the international supply chain for large forgings. These include events at Doel 3, where hydrogen flaking was identified, and at Flamanville 3, where areas of chemical segregation were identified. For **AP1000** plant, the RPV head is a single piece forging with an integral flange, and thus is a significantly larger forging than some earlier PWR head designs, which have a dome forging and separate flange forging. A similar concern may also apply to the SG channel heads of **AP1000** plant, which are also larger than some earlier PWR designs. Whilst my concerns have not arisen due to any shortcoming in Westinghouse's GDA submissions, I consider that this important experience should be acknowledged in my assessment. I consider that careful control to ensure adequate material homogeneity is particularly important for manufacturing large forgings of the highest reliability components. Indeed, should similar phenomena occur in production of components of the UK **AP1000** plant, evidence for the avoidance of fracture could be infringed, by increased defect occurrence and unacceptable variation of materials properties respectively. To guard against this risk I have raised the following assessment finding.

CP-AF-AP1000-SI-11: The licensee shall require that its supplier of HSS forgings provides verified and validated evidence of the absence of manufacturing defects and the achievement of acceptable material properties.

4.3.4 Key Assessment Considerations and Regulatory Judgements

244. Westinghouse identified three HSS components, the RPV, PRZ and SG. For the purposes of my assessment I regard these as equivalent to the highest reliability components described in the SAPs (Ref. 11). Therefore, I consider that the stringent principles EMC.1 to EMC.3 apply to this issue.

245. The themes of my assessment described thus far have been fracture analysis, inspection qualification and materials properties testing. This section describes my assessment of how Westinghouse has reconciled evidence relating to these topics in its safety case for HSS components, as reported in Ref. 28.

246. For each HSS component, Westinghouse has developed a safety case that integrates qualified inspection with limiting defects sizes, determined by analyses that apply conservative material properties. The objective is to show that limiting defect sizes are larger than those that can be reliably detected and characterised. Westinghouse used the term DSM to describe the margin between these parameters. Ref. 1 identifies the objective is to demonstrate a minimum DSM value of 2.0.

247. My assessment of the fracture analyses conducted by Westinghouse for HSS welds is described in Section 4.3.1, where I have expressed satisfaction that the outcome of those analyses provides an acceptable basis for reconciliation with the demonstration of inspection capability in GDA. In Section 4.3.2 I have concluded that it will be possible to undertake high reliability manufacturing inspection of HSS components and

that qualification of the inspection system will confirm that defects of structural concern, identified by fracture mechanics, will be detected and rejected. I am therefore satisfied that the data identified by Westinghouse to establish DSMs are valid.

248. It was noted at Step 4 of GDA that the target of a minimum DSM of 2.0 accords with approaches previously adopted in the UK (Ref. 1). Ref. 28 concludes that a minimum DSM of 2.0 has been demonstrated for all the limiting design locations evaluated in GDA; the outcome is summarised in Table 5.

249. I am therefore content that Westinghouse has provided adequate demonstration of fracture avoidance for the sample of HSS welds considered in GDA. I consider that Westinghouse has applied a suitably demanding method for fracture analysis and a sufficiently robust method to show that inspections can be qualified. In conjunction, these establish an acceptable margin between limiting defect sizes and the defect sizes that can reliably be detected.

250. Consistent with UK good practice for treatment of the highest reliability components, Westinghouse has applied the R6 assessment method to determine limiting defect sizes for the set of HSS welds considered in GDA. Over the course of my assessment, Westinghouse has updated its procedure for defect evaluation (Ref. 12) to address queries I have raised.

251. I have previously noted that the R6 method is generally less prescriptive than the methods of the ASME Code. Application of R6 sometimes requires expert interpretation and judgement to confidently establish a valid result for which the degree of conservatism is well understood.

252. I consider that the current revision of Ref. 12 reflects how the Westinghouse methodology has matured over the course of my assessment. It is my opinion that this will be of significant benefit when undertaking assessment of the increased number of HSS locations to be considered in future for site licensing. In particular, I consider that this will promote resolution of the following assessment finding of Ref. 1:

AF-AP1000-SI-04: *The licensee shall undertake fracture assessments on a wider range of weld locations on the HSS components in order to demonstrate that the limiting locations have been assessed. The licensee shall also undertake fracture assessments on the vulnerable areas of the parent forgings in order to demonstrate that the limiting locations have been assessed.*

253. I have raised 10 assessment findings in this assessment. These matters do not undermine my judgements regarding the generic safety submission and generally relate to the future development of the site-specific safety case. My assessment findings are collated in Annex 1 and its basis is summarised in the following paragraphs.

254. In Section 4.3.1.2, I have raised two assessment findings relating to developments in the structural integrity safety case that have arisen during my assessment:

255. CP-AF-AP1000-SI-01 requires additional consideration of multiple failure of bolted closures and supports for HSS and HI components. For example, I judged that it will be necessary to consider multiple bolt failures at the RPV closure. Westinghouse classifies these bolts as Standard Class 1, which I consider acceptable for the purposes of GDA because individual bolt failure will not result in unacceptable consequences. However, I consider that the site licensing safety case should be developed further to acknowledge that multiple bolt failures, beyond a certain critical number, could credibly result in unacceptable consequences. I acknowledge that a beneficial degree of redundancy exists in the closure design, and consider that design codes, such as that chosen by Westinghouse, include suitable methods to readily support resolution of this matter.

256. CP-AF-AP1000-SI-02 requires further effort to demonstrate the structural integrity of the PRHR HX outlet penetration. While I acknowledge that Westinghouse has established compliance with the requirements of the nuclear code agreed at the GDA design reference point, I consider there is potential for non-compliance with code limits in future editions of that code. I am content that this matter can be resolved in considering the detailed design at the licensing phase, for example either by revised analysis, the provision of restraints or modest design modifications to reinforce welds.

257. In Section 4.3.1.3, I have raised five assessment findings on the subject of fracture analysis:

- Assessment Finding CP-AF-AP1000-SI-03 requires robust verification and validation, incorporating independent review, for fracture analyses of the highest reliability components in future. The origin of this assessment finding is described in Section 4.3.1.3; for example, I identified my expectation that alternative methods should be applied to verify the reliability of software used for fracture analysis. Westinghouse has updated its R6 methodology document (Ref. 12) to promote future compliance with the requirements of this assessment finding.
- Assessment Finding CP-AF-AP1000-SI-04 requires the licensee to justify that any periodic hydrostatic tests proposed for HSS and HI components comply with current good practice.
- Assessment Finding CP-AF-AP1000-SI-05 requires a detailed account of stresses due to mechanical loads and stresses in dissimilar metal welds when determining the limiting transient / time point for fracture analysis. It is also required that these fracture analyses shall be subject to thorough and independent validatory review.
- In Section 4.3.1.2 I noted that Westinghouse classifies the dissimilar metal welds between the vessel nozzles and the safe-ends on the RPV, PRZ and SG as HSS. Consistent with the opinion given by ONR at Step 4 of GDA (Ref. 1) I regard this classification to be a cautious decision by Westinghouse. I also consider that the QEDS for these welds is small compared to other HSS locations, and so appears more difficult to screen out by inspection. In Section 4.3.2.4, I noted that the dissimilar nature of the RPV inlet nozzle to safe-end weld and the coarse grain anisotropic welds presents particular difficulties for ultrasonic inspection. Assessment Finding CP-AF-AP1000-SI-06 requires that the classification of dissimilar metal welds between the low alloy vessel nozzles and the austenitic stainless steel safe-ends on the RPV, PRZ and SG is justified. The justification shall clarify the basis for classification and explain how resultant requirements for the demonstration of structural integrity are balanced against demands on inspection capability, particularly if highest reliability is claimed.
- Assessment Finding CP-AF-AP1000-SI-07 requires that sufficient sensitivity studies are conducted for the fracture analyses of the highest reliability components in future. I consider this is necessary to confidently establish that the analyses are valid and reasonably conservative. Westinghouse has updated its R6 methodology document (Ref. 12) to promote future compliance with the requirement of this assessment finding.

258. I consider that satisfactory resolution of assessment finding CP-AF-AP1000-SI-07 will also promote resolution of the following assessment finding of Ref. 1:

AF-AP1000-SI-05: *The licensee shall undertake fracture assessments to show that a postulated defect with a 10:1 AR defect would not lead to an unacceptably large reduction in the DSM in the overall demonstration of fracture ie the licensee shall demonstrate that a 10:1 AR would not lead to a 'cliff edge' effect on the DSM.*

259. In Section 4.3.2 I have raised one assessment finding on the subject of inspection qualification:

- Assessment Finding CP-AF-AP1000-SI-08 requires that the design and manufacture of Class 1 and HSS welds facilitates reliable inspection of components during manufacture and in-service. This assessment finding originated due to my observation regarding the profile of the SG main steam nozzle to pipe weld, noted in Section 4.3.2.7. In response, Westinghouse approved Design Change Proposal APP-GW-GEE-5360 to modify the design of this feature to the benefit of both manufacturing and in-service inspections. My opinion is that similar beneficial modifications may be warranted elsewhere, for example at locations not sampled by ONR in GDA.

260. In my assessment of proposals by Westinghouse for materials properties testing (Section 4.3.3) I have raised two assessment findings:

- Assessment Finding CP-AF-AP1000-SI-09 requires fracture toughness testing of the limiting forged material for each HSS component. I consider that the highest standards are required at every stage of life for components of the highest reliability. Therefore, it is my opinion that dedicated testing of material from each HSS component is necessary to validate assumptions of the corresponding fracture analysis with sufficient high confidence.
- Assessment Finding CP-AF-AP1000-SI-10 requires the evidence of the absence of manufacturing defects and the achievement of acceptable material properties for the HSS forgings. This assessment finding originated due to issues reported in the international supply chain for such components (see paragraph 243) rather than any shortcoming in submissions provided by Westinghouse.

4.4 Comparison with Standards, Guidance and RGP

261. Section 2.2 of this report identifies standards, guidance and RGP that have informed my assessment, which is described in Section 42. In particular, my assessment has been guided by ONR's SAPs, see Table 1, and TAGs, see Table 2. Notable example of RGP adopted by Westinghouse include application of the R6 procedure for fracture analysis and application of the ENIQ methodology to confidently establish that NDT can be qualified in future.

4.5 Assessment Findings

262. During my assessment 10 items were identified for a future licensee to take forward in its site-specific safety submissions. These are collated in Annex 1. These matters do not undermine the generic safety submission and are primarily concerned with the provision of site-specific safety case evidence, which will usually become available as the project progresses through the detailed design, construction and commissioning stages. These items are captured as assessment findings.

263. Residual matters are recorded as assessment findings if one or more of the following apply:

- site-specific information is required to resolve this matter;
- the way to resolve this matter depends on licensee design choices;
- the matter raised is related to operator-specific features / aspects / choices;
- the resolution of this matter requires licensee choices on organisational matters;

- to resolve this matter the plant needs to be at some stage of construction / commissioning.

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5 CONCLUSIONS

264. This report presents the findings of the assessment of GDA Issue GI-AP1000-SI-01 Avoidance of Fracture, relating to the **AP1000** GDA closure phase. To conclude:

- I am satisfied that Westinghouse has provided adequate demonstration of fracture avoidance for the sample of HSS welds considered in GDA.

265. My judgement is based upon the following factors:

- Westinghouse has applied the suitably demanding R6 procedure for fracture analysis of the HSS welds.
- Westinghouse has applied the sufficiently robust ENIQ methodology to show that inspections of the HSS welds can be qualified.
- In conjunction, these establish an acceptable margin between limiting defect sizes and the defect sizes that can reliably be detected.

266. I have raised 10 assessment findings in my assessment. These identify evidence that will be required to support the site-specific safety case and are collated in Annex 1.

267. I consider that, from a structural integrity perspective, the **AP1000** design is suitable for construction in the UK.

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31. R-Code Version 5.1 Assessment of the Integrity of Structures containing Defects using the R5 and R6 Procedures. EdF Energy Nuclear Generation Ltd.

32. Westinghouse Document, 'EASL Benchmark Reports Comment Reconciliation', WEC REG-0163N Enclosure 1, 30 June 2015, TRIM 2015/243630.

33. RQ-AP1000-1353 AP1000 GI-AP1000-SI-01 Fracture Assessment: Comparative Studies Aspects of TSC Benchmarking WEC-REG-0273N 21 August 2015, TRIM Ref. 2015/315283.

34. RQ-AP1000-1632, SI01 Action 1 – Fracture Assessment Benchmarking & Methodology, TRIM Ref. 2016/365953.

35. WEC-REG-1485N, Letter from Westinghouse, Transmittal of GI-AP1000-SI-01 Deliverables, 16 December 2016, TRIM Ref. 2016/494560.

36. RQ-AP1000-1789 - UK Structural Integrity Classification James Caul13 January 2017

Full Response, TRIM Ref. 2017/18388.

37. ONR-NR-AR-16-005 **AP1000** Assessment Report - GI-AP1000-SI-03 - Reactor Coolant Pump Rev. 0, TRIM Ref. 2017/31112.

38. ONR-NR-AR-16-013, **AP1000** Assessment Report , GDA close-out for the **AP1000** reactor GDA Issue GI-AP1000-SI-06 – Structural Integrity Categorisation and Classification, Rev. 0, TRIM Ref 2017/67167.

39. RQ-AP1000-1616 **AP1000** UK Structural Integrity Classification - PRHR HX Mounting Ring Welds Evaluation for PRHA Loads on Outlet Nozzle - James Caul and Anindya Sen - 19 August 2016 - Full Response, TRIM Ref. 2016/331733.

40. ONR-NR-AR-16-007 - **AP1000** Assessment Report Fuel Design GI-AP1000-FD-02 - Tolerability of Depressurisation Forces in LBLOCA Revision 0 20 February 2017, TRIM Ref. 2016/274994.

41. ONR-NR-AR-16-020, “GDA close-out for the AP1000 reactor Internal Hazards GDA issues GI-AP1000-IH-01 to IH-06” Revision A, TRIM Ref. 2016/275001 2017/87944

42. WEC-REG-1540N Enclosure 1 UKP-GW-GLR-004 Revision 3 **AP1000** UK Structural Integrity Classification, 19 January 2017, TRIM Ref. 2017/27086.

43. UKP-MV01-Z0R-100, “Results of Weld Ranking Process for Reactor Vessel, Steam Generator, Pressurizer, Main Steam Line and Main Coolant Loop Piping Defect Tolerance,” Rev. 3, TRIM Ref. 2016/343413.

44. RQ-AP1000-1724 **AP1000** GDA Issue SI01 - Comparative Fracture Calculations for a Sample of HSS Welds - Pressuriser & Reactor Pressure Vessel - James Caul – 14 November, TRIM Ref. 2016/443999.

45. RQ-AP1000-1726 **AP1000** GDA Issue SI01 Comparative Fracture Calculations for a Sample of HSS Welds Steam Generator James Caul 14 November 2016 Full Response, TRIM Ref. 2016/444007.

46. Westinghouse Process for the Development of **AP1000** related Manufacturing Non-Destructive Testing Inspection Plans as WDI-PJF-2405360-TCR-003 Revision 2, TRIM Ref. 2016/91514.

47. **AP1000** Design for Inspectability Program: ISI Requirements for Class 1 Components. APP-GW-VW-001 Revision 0, April 2006, TRIM Ref. 2011/81451.

48. **AP1000** Component ISI Inspectability Assessment: Reactor Pressure Vessel and Reactor Pressure Vessel Head. APP-MV01-VMR-001 Revision A. Westinghouse Electric Company, March 2008, TRIM Ref. 2011/81478.

49. RQ-AP1000-1450 **AP1000** GI-AP1000-SI-01 Fracture Toughness Testing Proposals James Caul 05 April 2016 Full Response, TRIM Ref. 2016/144710.

50. RQ-AP1000-1623 AP1000 GI-AP1000-SI-01 Fracture Toughness Testing Proposals James Caul and Gareth Hopkin 19 August 2016 Full Response, TRIM Ref. 2016/331783.

Table 1

Relevant Safety Assessment Principles Considered in the Assessment

SAP No	SAP Title	Description
SC.4	The regulatory assessment of safety cases Safety case characteristics	A safety case should be accurate, objective and demonstrably complete for its intended purpose.
EMT.2	Engineering principles: maintenance, inspection and testing frequency	Structures, systems and components should receive regular and systematic examination, inspection, maintenance and testing as defined in the safety case.
EMT.5	Engineering principles: maintenance, inspection and testing procedures	Commissioning and in-service inspection and test procedures should be adopted that ensure initial and continuing quality and reliability.
ECS.2	Safety classification of structures, systems and components	Structures, systems and components that have to deliver safety functions should be identified and classified on the basis of those functions and its significance to safety.
ECS.3.	Engineering principles: safety classification and standards codes and standards	Structures, systems and components that are important to safety should be designed, manufactured, constructed, installed, commissioned, quality assured, maintained, tested and inspected to the appropriate codes and standards.
ECS.5	Engineering principles: safety classification and standards use of experience, tests or analysis	In the absence of applicable or relevant codes and standards, the results of experience, tests, analysis, or a combination thereof, should be applied to demonstrate that the structure, system or component will perform its safety function(s) to a level commensurate with its classification.
EMC.1	Engineering principles: integrity of metal components and structures: highest reliability components and structures	The safety case should be especially robust and the corresponding assessment suitably demanding, in order that a properly informed engineering judgement can be made that: (a) the metal component or structure is as defect-free as possible; and (b) the metal component or structure is tolerant of defects.
EMC.2	Engineering principles: integrity of metal components and structures: highest reliability components and structures	The safety case and its assessment should include a comprehensive examination of relevant scientific and technical issues, taking account of precedent when available.
EMC.3	Engineering principles: integrity of metal components and structures: highest reliability components and structures	Evidence should be provided to demonstrate that the necessary level of integrity has been achieved for the most demanding situations identified in the safety case.
EMC.4	Engineering principles: integrity of metal components and structures: general procedural control	Design, manufacture and installation activities should be subject to procedural control.
EMC.5	Engineering principles: integrity of metal components and structures: general defects	It should be demonstrated that components and structures important to safety are both free from significant defects and are tolerant of defects.
EMC.6	Engineering principles: integrity of metal components and structures: general defects	During manufacture and throughout the full lifetime of the facility, there should be means to establish the existence of defects of concern.

SAP No	SAP Title	Description
EMC.7	Engineering principles: integrity of metal components and structures: design loadings	The schedule of design loadings (including combinations of loadings) for components and structures, together with conservative estimates of its frequency of occurrence should be used as the basis for design against normal operation, fault and accident conditions. This should include plant transients and tests together with internal and external hazards.
EMC.8	Engineering principles: integrity of metal components and structures: design providing for examination	Geometry and access arrangements should have regard to the need for examination.
EMC.9	Engineering principles: integrity of metal components and structures: design product form	The choice of product form of metal components or its constituent parts should have regard to enabling examination and to minimising the number and length of welds in the component.
EMC.10	Engineering principles: integrity of metal components and structures: design weld positions	The positioning of welds should have regard to high-stress locations and adverse environments.
EMC.11	Engineering principles: integrity of metal components and structures: design failure modes	Failure modes should be gradual and predictable.
EMC.12	Engineering principles: integrity of metal components and structures: design brittle behaviour	Designs in which components of a metal pressure boundary could exhibit brittle behaviour should be avoided.
EMC.13	Engineering principles: integrity of metal components and structures: manufacture and installation materials	Materials employed in manufacture and installation should be shown to be suitable for the purpose of enabling an adequate design to be manufactured, operated, examined and maintained throughout the life of the facility.
EMC.14	Engineering principles: integrity of metal components and structures: manufacture and installation techniques and procedures	Manufacture and installation should use proven techniques and approved procedures to minimise the occurrence of defects that might affect the integrity of components or structures.
EMC.15	Engineering principles: integrity of metal components and structures: manufacture and installation control of materials	Materials identification, storage and issue should be closely controlled.
EMC.16	Engineering principles: integrity of metal components and structures: manufacture and installation contamination	The potential for contamination of materials during manufacture and installation should be controlled to ensure the integrity of components and structures is not compromised.
EMC.18	Engineering principles: integrity of metal components and structures: manufacture and installation third-party inspection	Manufacture and installation should be subject to appropriate third-party independent inspection to confirm that processes and procedures are being followed.
EMC.19	Engineering principles: integrity of metal components and structures: manufacture and installation non-conformities	Where non-conformities with procedures are judged to have a detrimental effect on integrity or significant defects are found and remedial work is necessary, the remedial work should be carried out to an approved procedure and should apply the same standards as originally intended.
EMC.20	Engineering principles: integrity of metal components and structures: manufacture and installation records	Detailed records of manufacturing, installation and testing activities should be made and be retained in such a way as to allow review at any time during subsequent operation.

SAP No	SAP Title	Description
EMC.21	Engineering principles: integrity of metal components and structures: operation safe operating envelope	Throughout its operating life, components and structures should be operated and controlled within defined limits and conditions (operating rules) derived from the safety case.
EMC.22	Engineering principles: integrity of metal components and structures: operation material compatibility	Materials compatibility for components should be considered for any operational or maintenance activity.
EMC.23	Engineering principles: integrity of metal components and structures: operation ductile behaviour	For metal pressure vessels and circuits, particularly ferritic steel items, the operating regime should ensure that they display ductile behaviour when significantly stressed.
EMC.24	Engineering principles: integrity of metal components and structures: monitoring operation	Facility operations should be monitored and recorded to demonstrate compliance with, and to allow review against, the safe operating envelope defined in the safety case (operating rules).
EMC.25	Engineering principles: integrity of metal components and structures: monitoring leakage	Means should be available to detect, locate, monitor and manage leakages that could indicate the potential for an unsafe condition to develop or give rise to significant radiological consequences.
EMC.26	Engineering principles: integrity of metal components and structures: monitoring forewarning of failure	Detailed assessment should be carried out where monitoring is claimed to provide forewarning of significant failure.
EMC.27	Engineering principles: integrity of metal components and structures: pre- and in-service examination and testing examination	Provision should be made for examination that is capable of demonstrating with suitable reliability that the component or structure has been manufactured to an appropriate standard and will be fit for purpose at all times during future operations.
EMC.28	Engineering principles: integrity of metal components and structures: pre- and in-service examination and testing margins .	An adequate margin should exist between the nature of defects of concern and the capability of the examination to detect and characterise a defect.
EMC.29	Engineering principles: integrity of metal components and structures: pre- and in-service examination and testing redundancy and diversity	Methods of examination of components and structures should be sufficiently redundant and diverse.
EMC.30	Engineering principles: integrity of metal components and structures: pre- and in-service examination and testing qualification	Personnel, equipment and procedures should be qualified to an extent consistent with the overall safety case and the contribution of examination to structural integrity aspects of the safety case.
EMC.31	Engineering principles: integrity of metal components and structures: in-service repairs and modifications repairs and modifications	In-service repairs and modifications should be carefully controlled through a formal procedure for change.
EMC.32	Engineering principles: integrity of metal components and structures: analysis stress analysis	Stress analysis (including when displacements are the limiting parameter) should be carried out as necessary to support substantiation of the design and should demonstrate the component has an adequate life, taking into account time-dependent degradation processes.
EMC.33	Engineering principles: integrity of metal components and structures: analysis use of data	The data used in analyses and acceptance criteria should be clearly conservative, taking account of uncertainties in the data and its contribution to the safety case.

SAP No	SAP Title	Description
EMC.34	Engineering principles: integrity of metal components and structures: analysis defect sizes	Where high reliability is needed for components and structures and where otherwise appropriate, the sizes of crack-like defects of structural concern should be calculated using verified and validated fracture mechanics methods with verified application.
EAD.1	Engineering principles: ageing and degradation safe working life	The safe working life of structures, systems and components that are important to safety should be evaluated and defined at the design stage.
EAD.2	Engineering principles: ageing and degradation lifetime margins	Adequate margins should exist throughout the life of a facility to allow for the effects of materials ageing and degradation processes on structures, systems and components.
EAD.3	Engineering principles: ageing and degradation periodic measurement of material properties	Where material properties could change with time and affect safety, provision should be made for periodic measurement of the properties.

Table 2

Technical Assessment Guides Considered in the Assessment

Technical Assessment Guide No	Description
NS-TAST-GD-005	Guidance on the Demonstration of ALARP
NS-TAST-GD-006	Deterministic Safety Analysis and The Use of Engineering Principles in Safety Assessment
NS-TAST-GD-016	Integrity of Metal Components and Structures
NS-TAST-GD-009	Examination, Inspection, Maintenance and Testing of Items Important to Safety
NS-TAST-GD-051	The purpose, scope, and content of safety cases
NS-TAST-GD-094	Categorisation of safety functions and classification of structures, systems and components

Table 3

Standards and Guidance Considered in the Assessment

ASME Boiler and Pressure Vessel Code	1998 Edition, through 2000 Addenda
IAEA Assessment and Management of Ageing of Major Nuclear Power Plant Components Important to Safety - Primary Piping in PWRs	IAEA-TECDOC-1361, July 2003
R6 Assessment of the Integrity of Structures containing Defects. British Energy Generation Ltd	Revision 4 April 2001
European Methodology for Qualification of Non-Destructive Testing	3rd Issue ENIQ 31 EUR 22906 EN August 2007 ISSN 1018-5593

Table 4
HSS Welds Selected for the Assessment

Component	Post Step 4 GDA Welds	Type*	Comments
RPV	Inlet Nozzle to Safe-End [V1, V2, H1, H2] (Cuts 1-8, *RPV3*)	DMW	IP covered by SG DM weld
	Upper Shell to Lower Shell [ASN12] (RPV2)	S-S	IP covered by PRZ S-S weld. Frazer-Nash independent ELLDS and sample FCG calculations (RPV2).
	DVI Nozzle to Upper Shell [ASN10, ASN11] (RPV1)	N-S	AMEC Foster Wheeler independent ELLDS calculations (RPV1)
PRZ	Upper Shell to Middle Shell [PRZ2] (PRZ2)	S-S	AMEC Foster Wheeler independent ELLDS calculations (PRZ2)
	Manway to Shell [PRZ3] (PRZ3)	N-S	IP covered by RPV N-S weld. Frazer-Nash independent ELLDS and sample FCG calculations (PRZ3).
	Upper Head to Upper Shell [PRZ1] (PRZ1)	H-S	IP covered by PRZ S-S weld
	Surge Nozzle to Safe-End [PRZ4] (PRZ4)	DMW	IP covered by SG DM weld
SG	Primary Inlet Nozzle to Safe-End [SGw3] (SG3)	DMW	AMEC Foster Wheeler independent ELLDS & FCG calculations (SG3)
	Lower Shell Barrel A to Tubesheet [SGw4] (SG4)	H-S	IP covered by PRZ S-S weld. Frazer-Nash independent ELLDS and full FCG calculations (SG4)
	Main Feedwater Nozzle to Shell [SGw5] (SG5)	N-S	IP covered by RPV N-S weld

* Note

DMW = Dissimilar Metal Weld
S-S = Shell to Shell Weld
N-S = Head to Shell Weld
H-S = Head to Shell Weld

At GDA Step 4, MSL and MCL were classified as HSS. Post GDA Step 4, Westinghouse proposed to change the structural classification from HSS to Standard Class 1. MSL and MCL therefore not shown in Table above.

HSS location definitions: [] brackets relate to Step 4 GDA, () brackets relate to post Step 4 GDA.

Table 5

Reconciliation of Critical Defect Sizes and Inspection Capability [Ref. 28]

Component Weld	AR = 2 or AR = 3				AR = 6			
	QEDS (mm)	LFCG (mm)	ELLDS (mm)	DSM (mm)	QEDS (mm)	LFCG (mm)	ELLDS (mm)	DSM
PRZ1	14.5 x 29	2.11	33.75	2.0	10 x 60	5.92	32.36	2.0
PRZ2	15 x 30	3.10	76.23	4.2	15 x 90	4.49	45.71	2.3
PRZ3	15 x 30	7.52	59.53	2.6	12 x 72	5.14	36.33	2.1
PRZ4	5 x 10	0.02	13.98	2.78	5 x 30	1.34	13.63	2.15
RPV 1	25 x 50	1.9	74.0	2.8	25 x 150	11.7	73.9	2.0
RPV 2	25 x 50	1.7	57.1	2.1	25 x 150	7.4	69.5	2.1
RPV3	6 x18	0.8	18.7	2.7	6 x 36	1.7	15.5	2.0
SG1	Not applicable based on revised SI classification							
SG2	6 x 18	0.424	17.46	2.72	6 x 36	0.424	13.6	2.12
SG3	6 x 18	7.54	39.54	2.92	6 x 36	7.54	27.43	2.03
SG4	15 x 30	1.120	53.771	3.336	15 x 90	5.59	53.472	2.597
SG5	15 x 30	2.162	56.58	3.30	10 x 60	6.44	33.82	2.06

Notes:

PRZ1	Upper head to upper shell	RPV3	Inlet nozzle to safe-end weld
PRZ2	Middle shell to upper shell	SG1	Steam outlet nozzle to pipe
PRZ3	Manway to shell	SG2	Inlet nozzle safe-end to pipe
PRZ4	Surge line	SG3	Inlet nozzle to safe-end
RPV1	DVI nozzle to RPV shell	SG4	Lower shell to tubesheet
RPV2	Upper shell to lower shell	SG5	Main feedwater nozzle to shell

Table 6

Comparative ELLDS and FCG Calculations Performed Post GDA Step 4.

Location & Postulated Defect	Westinghouse ELLDS (mm) & Load Case / Timepoint	Westinghouse FCG (mm) & QEDS (mm)	AMEC Foster Wheeler ELLDS (mm) & Load Case / Timepoint	AMEC Foster Wheeler FCG (mm) & QEDS (mm)
PRZ2 Inside axial semi-elliptic surface defect AR=6.	45.71 (Plant Hydrotest)	4.49 (15 x 90)	25.60 (Shop Hydrotest)	Not calculated
RPV1 Inside axial semi-elliptic surface defect AR=6.	73.9 (Transient Group 5 (Loss of Load, Offsite Power and Partial Loss of RCS Flow), 14s, Level C & D)	11.7 (25 x 150)	36.31 (Shop Hydrotest at 21°C)	Not calculated
SG3 Inside axial semi-elliptic surface defect AR=6.	27.43 (100% Normal Operating Power with D4 Piping Loads; Cut ASN2 (mid-weld)) (Level C & D)	7.54 (6 x 36) (Cut ASN2)	7.30 (Level C & D Transient, 2700s; Cut ASN11 (weld / safe-end))	6.97 (6 x 36) (Cut ASN11)
Location & Postulated Defect	**Westinghouse ELLDS (mm) & Load Case / Time Point**	**Westinghouse FCG (mm) & QEDS (mm)**	**Frazer-Nash ELLDS (mm) & Load Case / Time Point**	**Frazer-Nash FCG (mm) & QEDS (mm)**
PRZ3 Inside axial semi-circular surface defect AR=2.	59.53 (Plant Hydrotest, 49°C)	7.52 [6.83] (15 x 30)	59.70 (i) 66.67 (ii) (Plant Hydrotest, 49°C)	[10.330 (iii)] [7.132 (iv)] (15 x 30)
RPV 2 Inside circumferential semi-elliptic surface defect AR=6.	69.5 (Core Makeup Tank (CMT) Recirculation and Heated Drain-down Test, 2521s)	7.4 [3.780] (25 x 150)	62.62 (v) 69.71 (vi) (CMT Recirculation and Heated Drain-down Test, 2521s)	[3.700] (25x 150)
SG4 Inside circumferential semi-elliptic surface defect AR=6.	53.472 (Inadvertent Opening of the ADS Valves – Service Level C, 1200s)	5.590 (15 x 90)	49.42 (vii) 53.54 (viii) (Inadvertent Opening of the ADS Valves – Service Level C, 1200s)	4.850 (15 x 90)

Notes

- AR = aspect ratio (ie total length divided by depth).
- FCG starts from QEDS shown.
- FCG in [ ] brackets indicates 'sample' FCG based on a few significant cycles (with no [ ] brackets the full FCG (all cycles) is shown).
- PRZ3 assessments by Frazer-Nash: (i) indicates all stresses due to pressure and manway access bolt pre-load treated as primary (consistent with Westinghouse); (ii) indicates all non-membrane stresses due to pressure and manway access bolt pre-load treated as secondary; (iii) FCG considers more onerous of surface and deepest point; (iv) FCG considers deepest point only (consistent with Westinghouse and non-conservative).
- RPV2 assessments by Frazer-Nash: (v) indicates Tresca criterion used for hoop collapse; (vi) indicates Von Mises criterion used for hoop collapse (consistent with Westinghouse).
- SG4 assessments by Frazer-Nash: (vii) indicates pressure bending stress treated as secondary; (viii) indicates pressure bending stress treated as primary in SIF calculation but pressure (membrane stress) plastic collapse solution retained (consistent with Westinghouse approach).
- Table populated, in general, on basis of the postulated defect giving the bounding Westinghouse DSM for the location (taking consideration of defects with AR=2 and AR=6 but excluding

Westinghouse results for shop hydrotest as assessed at 21°C); the sole exception is PRZ3, which was chosen due to its high predicted FCG. AMEC Foster Wheeler and Frazer-Nash ELLDS results populated for the same postulated defect and AR as for Westinghouse ELLDS; AMEC Foster Wheeler (SG3 only) and Frazer-Nash FCG results populated for same postulated defect and starting QEDS as for Westinghouse FCG.

- The shop hydrotest was not included in final Westinghouse results for PRZ2 and RPV1 as qualified inspection will be performed following the respective shop hydrotest demonstrating that the PZR and RV enter service free from significant defects.

Annex 1

Assessment Findings – GI-AP1000-SI-01: Avoidance of Fracture

Number	Assessment Finding	Report Section
CP-AF-AP1000-SI-01	The licensee shall consider modes of multiple failure of closures and supports for HSS and HI components and demonstrate the structural integrity provisions for closures and supports are adequate and commensurate with consequences of multiple failures.	4.3.1.2
CP-AF-AP1000-SI-02	The licensee shall demonstrate the structural integrity of the PRHR HX outlet penetration in accordance with the current edition of the ASME Code, or shall implement alternative design measures to prevent the unacceptable consequences of a combined loss of safety functions.	4.3.1.2
CP-AF-AP1000-SI-03	The licensee shall ensure that robust verification and validation arrangements, incorporating adequate independent review are developed and implemented to underpin the fracture assessments for HSS and HI components.	
CP-AF-AP1000-SI-04	The licensee shall justify that any periodic hydro-tests proposed for HSS and HI components complies with relevant good practice.	4.3.1.3
CP-AF-AP1000-SI-05	To promote resolution of Assessment Finding AF-AP1000-SI-06, the licensee shall take account of stresses due to mechanical loads and stresses in dissimilar metal welds when determining the limiting transient and time point for fracture analysis. These fracture analyses shall be subject to thorough and independent validation.	4.3.1.3
CP-AF-AP1000-SI-06	The licensee shall justify the classification of dissimilar metal welds between the low alloy vessel nozzles and the austenitic stainless steel safe-ends on the RPV, PRZ and SG. The justification shall clarify the basis for classification and explain how resultant requirements for the demonstration of structural integrity are balanced against demands on inspection capability, particularly if highest reliability is claimed.	4.3.1.3
CP-AF-AP1000-SI-07	The licensee shall ensure that sensitivity studies are undertaken to underpin the margins in its fracture avoidance demonstrations for HSS and HI components.	4.3.1.3
CP-AF-AP1000-SI-08	The licensee shall ensure the design and manufacture of Class 1 and HSS welds facilitates reliable inspection of components during manufacture and in-service.its	4.3.1.3
CP-AF-AP1000-SI-09	The licensee shall undertake fracture toughness testing of the limiting forged material for each HSS component to validate assumptions of the fracture analysis for that component.	4.3.2.7
CP-AF-AP1000-SI-10	The licensee shall require that its supplier of HSS forgings provides verified and validated evidence of the absence of manufacturing defects and the achievement of acceptable material properties.	4.3.3