New Reactors Programme

GDA close-out for the AP1000 reactor

GI-AP1000-SI-03 – Reactor Coolant Pump – Pump Bowl Integrity and Flywheel Disintegration Case

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EXECUTIVE SUMMARY

Westinghouse Electric Company LLC (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), with 51 GDA issues attached to it. These issues require resolution prior to the 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 structural integrity discipline. Specifically, this report addresses GDA Issue GI-AP1000-SI-03 on Reactor Coolant Pump (RCP) integrity.

This GDA issue arose in Step 4 because:

- **Westinghouse changed the RCP bowl casing from martensitic stainless steel to clad ferritic material late in the process, so there was insufficient time to review the pump bowl integrity safety case.**
- **There were extant technical queries regarding the effects of postulated flywheel disintegration to support the safety case of the RCP.**

In its resolution plan, Westinghouse stated its approach to closing this structural integrity GDA issue:

- **Supply a technical report addressing the structural integrity considerations related to a clad ferritic pump bowl casing to support ONR's assessment of the pump bowl integrity case (GI-AP1000-SI-03.A1).**
- **Support the ongoing assessment of the flywheel disintegration safety case (GI-AP1000-SI-03.A2).**

I have reviewed and assessed the safety case, which addresses these structural integrity issues and my conclusions are as follows:

- **Westinghouse has supplied a technical report addressing the structural integrity considerations related to a clad ferritic pump bowl casing supporting the pump bowl integrity case.**
- **Westinghouse has tentatively demonstrated via revised calculations that the existing integrity analyses for the pump casing using martensitic steel could remain fit for purpose for the proposed clad ferritic steel.**
- **GDA Issue GI-AP1000-SI-03.A1 can be closed.**
- **An assessment finding has been raised to revisit the updated and full American Society of Mechanical Engineers (ASME) analyses and assessment of the RCP casing using revised material data at the licensing stage.**
- **Westinghouse has demonstrated that in the event of postulated disintegration of the flywheel, the fragments would be contained within the martensitic heat barrier maintaining the pressure boundary integrity of the RCP.**
- **GDA Issue GI-AP1000-SI-03-A2 can be closed.**

My judgement is based on the following factors:

- **The structural integrity assessments related to the clad ferritic pump bowl and the flywheel disintegration case follow codes of practice, thus reducing the risks to As Low As Reasonably Practicable (ALARP).**
- **I have taken cognisance of Safety Assessment Principles (SAPs) concerned with the integrity of metal components and structures, as well as other applicable SAPs.**

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 or decision:

- **The future licensee will be required to provide full evidence to substantiate design compliance with its chosen nuclear design code for the RCP casing with clad ferritic material properties.**

In summary, I am satisfied that GDA Issue GI-**AP1000**-SI-03 can be closed.

LIST OF ABBREVIATIONS

ALARP	As Low As Reasonably Practicable
ASME	American Society of Mechanical Engineers
ASME Code	ASME Boiler and Pressure Vessel Code
BMS	Business Management System
DAC	Design Acceptance Confirmation
IDAC	Interim Design Acceptance Confirmation
ISI	In-Service Inspection
ONR	Office for Nuclear Regulation
OPEX	Operational Experience
PCSR	Pre-Construction Safety Report
RCLP	Reactor Coolant Loop Piping
RCP	Reactor Coolant Pump
RGP	Relevant good practice
RPV	Reactor Pressure Vessel
RQ	Regulatory Query
SAP	Safety Assessment Principle
SG	Steam Generator
TAG	Technical Assessment Guide

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1 INTRODUCTION

1.1 Background

1. Westinghouse Electric Company LLC (Westinghouse) is the reactor 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), which had 51 GDA issues attached to it. These issues require resolution prior to the 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.

2. This report is the Office for Nuclear Regulation's (ONR's) assessment of Westinghouse's response to GDA Issue GI-**AP1000**-SI-03 – Reactor Coolant Pump – Pump Bowl Integrity and Flywheel Disintegration Case.

3. The GDA Step 4 structural integrity assessment of the Westinghouse **AP1000** reactor (Ref. 1) is published on ONR's website (www.onr.org.uk/new-reactors/ap1000/reports.htm) and describes the origin of this GDA issue. Further information on the GDA process in general is also available on the ONR website (www.onr.org.uk/new-reactors/index.htm).

4. Due to lack of assessment time available during the GDA Step 4 process, GI-**AP1000**-SI-03, relating to the Reactor Coolant Pump (RCP), raised requiring the following:

   - Supply a technical report addressing the structural integrity considerations related to a clad ferritic pump bowl casing to support ONR's assessment of the pump bowl integrity case.

   - Support the ongoing assessment of the flywheel disintegration safety case.

1.2 Scope

5. The scope of this assessment is described in the ONR assessment plan (Ref. 2) and is limited to submissions for GDA Issue GI-**AP1000**-SI-03.

6. Westinghouse stated its approach to closing GDA Issue GI-**AP1000**-SI- in its resolution plan (Ref. 3):

   - **GI-AP1000-SI.03.A1:** Supply a technical report addressing the structural integrity considerations related to a clad ferritic pump bowl casing to support ONR's assessment of the pump bowl integrity case.

   - **GI-AP1000-SI.03.A2:** Support the ongoing assessment of the flywheel disintegration safety case.

7. My assessment concentrated on the claims, arguments and evidence provided as part of the Pre-Construction Safety Report (PCSR) to address these issues.

8. In my opinion, the scope of the assessment was appropriate for the closure of GDA Issue GI-**AP1000**-SI-03 related to the RCP, which is an assembly of complex forgings. Westinghouse's classification and categorisation confirmed that the RCP is an ASME (American Society of Mechanical Engineers) Section III Class I component.

9. The scope of my assessment did not include matters that ONR found to be satisfactory in the GDA Step 4 report (Ref. 1).

1.3 Method

10. The assessments undertaken in this report comply with ONR guidance on the mechanics of assessment (Ref. 4) and with the requirements of the ONR Business Management System (BMS) document “Purpose and Scope of Permissioning” (Ref. 5), which defines the process of assessment within ONR.

1.3.1 Sampling strategy

11. It is rarely possible or necessary to assess an entire safety submission, so ONR adopts an assessment strategy of sampling. Ref. 5 explains the process for sampling safety case documents.

12. The sampling strategy for this assessment focused on aspects of the pump bowl design identified in the GDA Step 4 report (Ref. 1), which required further evidence to establish compliance with UK expectations of relevant good practice (RGP).

2 ASSESSMENT STRATEGY

2.1 Pre-Construction Safety Report

13. ONR's GDA guidance to requesting parties (Ref. 6) states that the information required for GDA may be in the form of a PCSR, and the Technical Assessment Guide (TAG) 051(Ref. 7) sets out regulatory expectations for a PCSR.

14. At the end of Step 4, ONR and the Environment Agency raised GDA Issue CC-02 (www.onr.org.uk/new-reactors/reports/step-four/Westinghouse-gda-issues/gi-ap1000-cc-02.pdf) requiring Westinghouse to submit a consolidated PCSR (Ref. 8) and associated references to provide the claims, arguments and evidence to substantiate the adequacy of the **AP1000** Design Reference Point.

15. A separate regulatory assessment report is provided to consider the adequacy of the PCSR and closure of GDA Issue CC-02. This report does not discuss the overall structural integrity issues covered in the PCSR, but is limited to those sections addressing GDA Issue GI-**AP1000**-SI-03.

2.2 Standards and Criteria

16. The standards and criteria adopted within this assessment are principally the Safety Assessment Principles (SAPs) (Ref. 9), internal TAGs, relevant standards and RGP informed by existing practices adopted on UK nuclear licensed sites.

17. The ASME Boiler and Pressure Vessel Code Section III is a well-recognised document for the design of nuclear components and ONR regards it as a good source of RGP. ONR is satisfied that, for the purpose of GDA, full compliance with the ASME Code Section III design requirements for the relevant components can be demonstrated.

2.2.1 Safety Assessment Principles

18. The key SAPs that have informed this assessment are listed in Table 1.

2.2.2 Technical Assessment Guides

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

2.2.3 National and International Standards and Guidance

20. Westinghouse has supplied Reference 10 to state the codes, standards and procedures used in the PCSR (Ref. 8). The following standards and procedures are used in this report:

- ASME Boiler and Pressure Vessel Code Section III (Ref. 11)
- R3 Impact Assessment Procedure (Ref. 12).

2.3 Use of Technical Support Contractors

21. ONR did not use Technical Support Contractors in support of this GI-**AP1000**-SI-03 assessment.

2.4 Integration with Other Assessment Topics

22. 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. In particular, ONR's internal

hazards discipline was kept informed of the developments throughout the assessments.

2.5 Out of Scope Items

23. This report does not consider any other structural integrity considerations of the PCSR (Ref. 8), which are covered by separate GDA issues.

3 REQUESTING PARTY'S SAFETY CASE

24. The latest full safety case for the **AP1000** reactor design and systems is detailed in the updated PCSR (Ref. 13). The central theme for this reactor design is the use of Class 1 passive safety systems, relying solely on natural phenomena such as natural cooling, gravity or the energy stored in pressurised pipes.

25. To address GDA Issue GI-**AP1000**-SI-03 on structural integrity, I have assessed the safety case for the RCP in Chapter 20F of the PCSR (Ref. 8). This includes the fault of postulated flywheel disintegration and the integrity of the RCP bowl casing.

3.1 Plant Description

26. The RCP is a vertical, single-stage centrifugal pump, which pumps reactor coolant at high temperature and pressure. It is designed so that the main impeller is attached to the rotor shaft of the driving motor. A detailed description and the functional requirements of the RCP are available in Appendix 20F of Reference 8.

27. The **AP1000** Reactor Coolant Loop has two Steam Generators (SGs) and each SG supports two RCP units (Figure 1). No additional supports for the RCPs are required.

28. Each RCP is also connected to the Reactor Pressure Vessel (RPV) via a pair of stainless steel pipes, which deliver the 'cold' reactor coolant from the SG to the RPV. The 'hot' reactor coolant is channelled from the RPV to the SG via another stainless steel pipe (Figure 1).

29. The main components of the **AP1000** RCP are described below.

3.1.1 Pressure Boundary

30. The pressure boundary consists of the pump bowl casing, heat barrier assembly and motor casing. These three units are clamped together using 24 high-strength closure bolts.

31. In the currently proposed design, the RCP casing is made of ferritic steel forging (SA-508 Grade 3) with austenitic cladding in the regions exposed to reactor coolant. This is a change in design from the original martensitic steel forging to clad ferritic forging. Westinghouse submitted this design change late in the process and so it could not be assessed during GDA Step 4. As a result, GDA Issue GI-**AP1000**-SI-03.A1 was raised. The heat barrier and motor casing are made of high-strength martensitic stainless steel forging (SA 182 . F6NM) and there is no change to their designs.

32. In Reference 8, it is stated that the pressure boundary components are designed to meet the requirements of the ASME Code Section III Division 1 (Ref. 11).

3.1.2 Impeller / Diffuser

33. In the pump and motor unit, a semi-axial impeller / diffuser combination is mounted within a one-piece casing. Westinghouse claims this very high hydraulically efficient design is based on proven hydraulics that have been used for over 30 years.

3.1.3 Flywheel

34. The flywheel is placed between the impeller and the motor. It consists of a one-piece forged stainless steel cylinder, with several smaller heavy metal (tungsten) cylinders inside. These cylinders minimise the size of the flywheel, reducing the drag and associated heat generation, and provide the necessary rotational inertia to deliver sufficient the reactor coolant for the flow coastdown. Westinghouse has claimed that this design is advantageous over available alternatives.

35. The flywheel is encased within the heat barrier martensitic forging, which is part of the pressure boundary and provides containment for the flywheel only. Cooling provided for this component maintains a homogeneous temperature distribution around the flywheel, reduces the frictional losses of the flywheel and protects the rotating components from the adverse operating conditions.

36. During GDA Step 4, Westinghouse submitted justifications for the postulated flywheel disintegration case. However, these arrived too late for detailed assessment of the extant technical issues. Consequently, Step 4 GDA raised the GDA Issue GI-**AP1000**-SI-03.A2 to complete the assessment of Westinghouse's submissions.

3.1.4 Other Components

37. The RCP consists of motor and electrical components, which provide the means to transmit the driving torque via the motor shaft.

3.2 Resolution Plan for GI-AP1000-SI-03 – Reactor Coolant Pump

38. The scope of this report covers the claims, arguments and evidence from Westinghouse, exclusively addressing GDA Issue GI-**AP1000**-SI-03.

39. The Westinghouse resolution plan for GDA Issue GI-**AP1000**-SI-03 (Ref. 3) states that technical justification addressing the structural integrity of the clad ferritic pump bowl and the supporting assessment of the flywheel disintegration case will be provided. Westinghouse provided these justifications in Reference 8.

40. In Reference 8, Westinghouse has proposed a change of material for the RCP bowl casing forging from martensitic to clad ferritic steel and has claimed that the existing ASME analyses and assessments with martensitic forging would remain fit for purpose for the clad ferritic casing. The safety case for the integrity of the RCP in Reference 8 is based on claims, arguments and evidence to address GDA Issue GI-**AP1000**-SI-03.A1.

41. To address GDA Issue GI-**AP1000**-SI-03.A2, Westinghouse claimed in Reference 8 that in the event of a postulated disintegration of the flywheel, the broken components would be contained within the heat barrier forging without challenging the overall pressure boundary for the RCP. This is important because broken components with substantial energy could create subsequent hazard to other safety systems or personnel in the vicinity. Westinghouse provided supporting evidence in support of those claims and arguments.

42. Westinghouse has provided evidence in Reference 8 to support its claim that the change of material for the RCP bowl casing and postulated disintegration of the flywheel would not challenge the ASME Code Section III Class 1 (Ref. 11) design requirements for the pump (see Subsection 3.1.1 above).

4 ONR ASSESSMENT OF GDA ISSUE GI-AP1000-SI-03

4.1 Scope of Assessment Undertaken

43. Consistent with the two actions of GDA Issue GI-**AP1000**-SI-03, the scope of my assessment considered the following:

- A1 – Structural integrity considerations related to the clad ferritic pump bowl casing
- A2 – Flywheel disintegration assessment

44. To progress closure of GDA Issue GI-**AP1000**-SI-03, I assessed the Westinghouse PCSR, Chapter 20 Appendix F (Ref. 8). I raised several questions through a Regulatory Query (RQ), RQ-**AP1000**-1772 (Ref. 14), and my subsequent assessment considered Westinghouse's responses to these queries.

45. In Reference 14, I queried Westinghouse's ALARP (As Low As Reasonably Practicable) and fit-for-purpose justification for the selection of clad ferritic casing over martensitic forging, the associated and supporting Operational Experience (OPEX), degradation mechanisms, etc.

46. I held level 4 technical engagements with Westinghouse where I discussed:

- my regulatory expectations based on RGP; and
- technical and safety aspects of each of Westinghouse's submissions.

47. My interest was to establish whether Westinghouse's safety case submissions adequately considered UK RGP for the RCP bowl safety case, and were supported by the necessary evidence to validate the claims in the safety case.

48. I finally considered whether risks associated with the proposed RCP design are reduced to ALARP, such that GDA Issue GI-**AP1000**-SI-03 can be closed.

4.2 Assessment

49. This part of the report is divided into two subsections (4.2.1 and 4.2.2), describing in turn my assessment of the following structural integrity issues:

- flywheel disintegration
- structural integrity considerations of the clad ferritic pump bowl casing

4.2.1 Flywheel Disintegration (GI-AP1000-SI-03.A2)

50. The RCP flywheel is encased by the heat barrier forging, which forms part of the RCP pressure boundary. GDA Step 4 raised questions for the **AP1000** reactor (Ref. 1), questions as to whether the heat barrier forging would be able to contain the fragments from a postulated failure of the flywheel. Although Westinghouse provided a technical justification, this could not be progressed further due to lack of available assessment time and so was captured under GDA Issue GI-**AP1000**-SI-03.A2.

51. RQ-**AP1000**-1354 (Ref. 15) raised further technical queries via after the restart of the GDA process. Westinghouse responded to those queries by providing the evidence for the safety claims and arguments supporting the disintegration safety case.

52. The queries in Reference 15 were mainly concentrated on the postulated flywheel disintegration analysis and assessment that used the traditional analytical / semi-

empirical Hagg and Sankey procedure based on a small range of burst discs and containment shell geometries. The Hagg and Sankey methodology prescribes a two-stage process as described below (see also Figure 2):

- Stage 1 – localised perforation failure of the containment shell on initial impact by the burst disc fragments. It is assumed that the perforation failure occurs when the energy transfer during impact, as measured by the energy loss of the burst fragment, exceeds the maximum compression and shear strain energy that the contact zone of the containment shell is capable of absorbing.
- Stage 2 – if the localised perforation does not occur, it is assumed that the residual energy is dissipated in the form of tensile strain throughout an extended volume of the containment shell material. Failure occurs when the residual energy exceeds the allowable strain energy of the extended volume.

53. I assessed (Ref. 16) the postulated disintegration report from the pump manufacturer KSB (Ref. 17) and, after consideration of the claims, arguments and evidence provided in Westinghouse's response to RQ-**AP1000**-1354 (Ref. 15), concluded that Westinghouse has adequately demonstrated the following:

- The underlying assumptions for judging the size of a simplified fragment are credible, conservative and bounding for the failure mechanisms related to the flywheel design.
- The differences in geometry and material properties of the RCP flywheel and containment do not change the underlying basis and assumptions made by the Hagg and Sankey methodology.
- The method of calculating the area of impact by the simplified fragment mass is conservative. The assumption that the impacting mass is equal to the fragment mass is realistic and conservative despite the narrow annulus between the flywheel and heat barrier.
- Neglecting the effects of water surrounding the flywheel is conservative.

54. The Hagg and Sankey methodology is a well-established, traditional method for assessing spun discs and casings. It is recognised in the turbomachinery industry as a reliable and simple method for assessing disc failure and casing integrity. It is also stated in the R3 Impact Assessment Procedure (Ref. 12) as a reliable methodology for assessing containment of missiles. The R3 procedure is a well-recognised RGP within the UK nuclear industry for undertaking impact assessments following simplified methodologies.

55. The details of my assessment are available in Reference 16, which describes the rationale and evidence substantiating the abovementioned conclusions.

56. My assessment of the postulated flywheel disintegration safety case was informed by the ONR SAPs: EMC.32 to EMC.33, EHA.1 to EHA.7 and EHA.14.

57. From the claims, arguments and evidence provided in response to RQ-**AP1000**-1354 (Ref. 15), I can conclude that:

- RQ-**AP1000**-1354 can be closed; and
- GDA Issue GI-**AP1000**-SI-03.A2 has been adequately justified and can be closed.

4.2.2 Clad Ferritic Pump Bowl Casing (GI-AP1000-SI-03.A1)

58. As part of my assessment of the structural integrity considerations for the clad ferritic pump bowl casing, I have considered the three safety claims made by Westinghouse in Reference 8:

- Claim 1: High quality will be achieved during manufacture.
- Claim 2: Good design is achieved through compliance with ASME.
- Claim 3: In-service degradation is managed.

4.2.2.1 Claim 1: High Quality Will Be Achieved During Manufacture

4.2.2.1.1 Fabrication

59. The structural integrity safety case (Ref.12) states that the Class I parts of the RCP pressure boundary will be fabricated according to the ASME Code Section III Subsection NB, Article NB-4000. The associated heat exchanger support will be fabricated according to the ASME Code Section III Subsection NF, Article NF-4000. I have sampled ASME Subsection NB, which is concerned with ASME Class I components and I judge that fabrication of this component in accordance with the code requirements is adequate.

4.2.2.1.2 Material Specification

60. The material used for the construction of the RCP bowl casing is a single forging that complies with ASME Code Section II. The material chosen is SA-508 Grade 3. This material has been used in existing and operating nuclear power plants for a variety of different components, including the RCP, SG and RPV.

61. I asked Westinghouse if it had considered unintended consequences, such as the need for dissimilar metal welds, when considering its material choices. Westinghouse responded (Ref. 14) that the material selection for the RCP was done such that the interfacing components were taken into consideration. Westinghouse presented the aspects considered in its optioneering process as part of its response to my question regarding unintended consequences of material choice such as dissimilar metal welds. The use of casting to manufacture this component was discounted on the grounds of its susceptibility to internal flaws and possible need for weld repairs. The use of austenitic stainless steels was discounted due to the need for a dissimilar metal weld combination between the SG channel head and the pump casing, which is the larger of the two interfaces in the design. The use of martensitic material was also discounted as it would have led to two dissimilar metal weld combinations between the SG channel head and the Reactor Coolant Loop Piping (RCLP). The balance between higher strength and lower thermal conductivity as well as the lack of OPEX for this material in this application was considered as a disadvantage, which led to discounting martensitic material for the manufacture of the RCP casing.

62. I accept Westinghouse's assessment that a ferritic forging with internal cladding represents an ALARP design. This material choice allows for similar base material between the RCP casing and the SG channel head. This weld has not been considered as part of the assessment for the closure of GDA Issue GI-**AP1000**-SI-03 as it has been considered in the SG section of the safety submission. This material choice does result in a dissimilar metal weld in the casing–RCLP interface. However, this is the smaller and thinner of the two interfaces. This addresses the point raised on the consideration of dissimilar metal welds during GDA Step 4.

63. Westinghouse's structural integrity submission also considers the material selection of the cladding. It states that low-alloy steel components in contact with the primary

coolant – that is, the pump casing – will be cladded. The cladding will be multi-layered with type 309L weld metal as the first layer, followed by type 308L weld metal for the other layers. The cladding process will be weld overlay. I consider the extensive use and OPEX of the materials, as well as the corrosion resistance properties of the cladding material, to be suitable and sufficient considerations as part of the material selection.

64. I have considered Westinghouse's material selection for the RCP bowl, the internal cladding and process as part of my assessment. I found that the material selection process takes into consideration point (e) from paragraph 295 of the SAPs, and considers the use of proven materials for this application. Therefore, I judge Westinghouse's submission for material selection to be adequate.

4.2.2.1.3 Welding

65. Westinghouse's structural integrity safety case states that the external pressure boundary welds are limited to the interfaces connecting the components to the casing. The pressure boundary components are single-piece forgings. Where welding is required, the process will be conducted in accordance with ASME Code Section III and Section IX. I consider the management of welding processes according to an established nuclear code to be adequate. I have based my judgement against paragraph 301 of the SAPs, which states that: "Components and structures important to safety should be designed, manufactured, installed, examined and inspected using codes, specifications and standards commensurate with their safety classification in accordance with Principle ECS.3".

4.2.2.1.4 Non-Destructive Testing

66. The structural integrity safety case states that Non-Destructive Testing will be conducted by personnel qualified and certified to ASME Code Section III, NB-5000. The inspections will be conducted according to ASME Code Section III, NB-2000, NB-5000 and Section V, Article 5. I have sampled ASME Subsection NB, which is concerned with ASME Class I components and I judge that inspections of this component in accordance with the code requirements as a basis may be adequate. I have based my judgement against paragraph 301 of the SAPs, which states that: "Components and structures important to safety should be designed, manufactured, installed, examined and inspected using codes, specifications and standards commensurate with their safety classification in accordance with Principle ECS.3".

4.2.2.2 Claim 2: Good Design Achieved by Compliance with ASME

4.2.2.2.1 Pressure Boundary Stress Analysis (Pump Bowl Casing)

67. The pump bowl casing forging, which forms part of the RCP pressure boundary (Subsection 3.1.1 above), was originally made of martensitic stainless steel (SA 182 F6NM). However, later in the design that material was changed to ferritic steel clad with austenitic stainless steel for the wetted surface. Materials for all other RCP components remain unchanged. Westinghouse has claimed in Chapter 20F of the PCSR (Ref. 8) that the effects of this material change for the casing of the pump bowl on the current safety case is minimal. That is based on a study by KSB, concluding that the martensitic and ferritic steel forging material properties used in the RCP are fairly comparable (ferritic steel is mechanically weaker than martensitic steel).

68. Westinghouse has further claimed in Reference 8 that all the conclusions from the existing ASME analyses for the pump casing using the martensitic steel properties remain valid for the revised ferritic material. Westinghouse added that the effect on the

maximum stresses for the ASME Code Section III level A to D conditions would not be affected significantly and would still remain compliant with the allowable limits.

69. In Reference 8, Westinghouse has highlighted a few mechanical and design factors that could potentially mitigate the effects of reduced material strength for the proposed ferritic steel for the casing in place of the martensitic forging.

70. Westinghouse informed me that the revised analyses results with actual material data would be available at the procurement stage and Westinghouse is committed to take appropriate measures to ensure compliance with ASME design requirements.

71. I reviewed these claims and arguments from Westinghouse on the change of material for the RCP pump casing and requested (Ref. 14) Westinghouse to provide the evidence supporting the claim that any effect due to change of material for the pump casing on the integrity assessment would be minimal.

72. I discussed this issue with Westinghouse (Ref. 19) and in response Westinghouse provided the KSB report (Ref. 20), which includes the comparative study on material properties. I reviewed the KSB report and was generally content with the claims, arguments and evidence provided for the RCP design.

73. However, in Table 5-1 of Section 5.1.2 of Reference 20, the comparison of material properties between martensitic, ferritic and austenitic (comparison purposes only) clearly shows that following ASME Code III Section II D requirements, the tensile properties of the ferritic steel is weaker than the martensitic steel by 31% to 45%, while the calculated allowable stresses based on ASME III Section II could be lower by 22% to 31% (dependent on temperature).

74. Notwithstanding the substantial differences in the material tensile properties, Westinghouse reaffirmed, based on the available margins on the allowable stresses, that the conclusions from the existing ASME analyses results would still remain valid and be fit for purpose.

75. I further requested Westinghouse to justify its integrity claim and in response (Ref. 21), Westinghouse provided a tentative calculation, demonstrating a potential margin of [redacted] under the design conditions of operation, considering clad ferritic steel properties for the pump bowl casing.

76. I have checked the data in Table 3-1 of Reference 20 and it states that, based on ASME III Division 1 (Ref. 11) design requirements for the martensitic steel casing, 30 mm thickness is sufficient from 'pressure' considerations, whereas that required for the weaker clad ferritic steel is 39 mm. However, Reference 21 states that the casing thickness to be provided 'as-built' in the **AP1000** RCLP is [redacted]. Thus by comparing the design with as-built thicknesses, I could judge that the safety margin [redacted] based on pressure-only considerations (that is, section thickness) is still reasonably acceptable.

77. Westinghouse also stated in the PCSR (Ref. 12) that for the martensitic stainless steel RCP bowl casing forging, the fatigue usage factors for the locations with maximum stress intensity ranges, following ASME Code Section III design requirements, are so low that no further considerations were needed. It is my judgement that although the clad ferritic stainless steel forging is mechanically weaker than the martensitic forging, given the reasonable margin on the as-built section thickness for the RCP bowl casing, the fatigue damage would still remain low enough so as not to cause any concern.

78. Full ASME Code Section III design compliance for a component requires consideration of pressure, shakedown and fatigue loadings using relevant material properties. Although Westinghouse could not provide full ASME Code Section III compliance for

the clad ferritic RCP casing, in my opinion, the reasonable safety margin available with the as-built casing thickness of [redacted] (irrespective of martensitic or clad ferritic stainless steel) would be sufficient to reduce the risks from the extant shakedown and fatigue assessments to ALARP.

79. My above judgement has been informed by the following SAPs: EMC.3, EMC.7, EMC.11, EMC.13 and EMC.22 (Ref. 9, see also Table 1).

80. Westinghouse has already stated in References 8 and 14 that, at the procurement stage, revised ASME analyses and assessments for the RCP using relevant materials properties will be provided.

81. As explained above, the tentative calculations (Refs 20 and 21), in place of updated and full ASME analyses for the RCP pump casing, provide a basis for judging that an adequate full demonstration is achievable and they do not undermine the RCP safety case in general. However, further substantiation work by Westinghouse is necessary to fully address the integrity of the RCP using revised material for the pump bowl casing. Consequently, I recommend closing this GDA assessment issue and I have raised an assessment finding to be progressed further at the licensing stage.

82. Overall, I am generally satisfied with the safety case for the RCP and recommend closing GDA Issue GI-**AP1000**-SI03.A1 (Ref. 1).

4.2.2.3 Claim 3: Mitigation and Management of In-Service Degradation

4.2.2.3.1 Compatibility with the Environment

83. The structural integrity safety case (Ref. 8) indicates that the selection of the pressure boundary materials has taken cognisance of potential through-life degradation mechanisms, which could threaten the integrity of the pressure boundary. I asked Westinghouse to provide information on the degradation mechanisms and the mitigations in place to counter through-life degradation.

84. Westinghouse’s response (Ref. 14) revealed that it has considered seven degradation mechanisms: material defects, corrosion, fatigue, stress corrosion cracking, primary water stress corrosion cracking, underclad cracking and irradiation embrittlement. The list of degradation mechanisms considered as part of the design is suitable for the component and environmental considerations.

85. The degradation mechanisms are primarily mitigated during the design stage by careful consideration of material selection. Westinghouse has also considered the material degradation mechanisms applicable to the materials selected for the manufacture of RCP components. I have sampled the degradation mechanisms as part of my assessment. I consider the inclusion of degradation mechanisms as part of the design considerations to be a significant improvement in the safety submission compared with the previous submission. Previously, the material degradation was not considered. I have considered the management of the degradation mechanisms as part of the design considerations for material selection and have taken cognisance of SAPs EAD. 1 and EAD.2. I judge that the considerations of material degradation in a primary coolant environment to be adequate.

4.2.2.3.2 In-Service Inspection

86. The structural integrity safety case (Ref. 8) states that In-Service Inspection (ISI) will be conducted according to Section XI of the ASME Code. It also states that the design has considered access for ISI of the component, in order to minimise locations difficult to inspect (Ref. 19). ISI is not considered within the scope of GDA and is an aspect to

be addressed by the future licensee. As such, I have not considered these proposals as part of the GDA issue closure assessment.

4.2.2.3.3 Comparison with Standards, Guidance and Relevant Good Practice

87. Subsection 2.2 of this report identifies the standards, guidance and RGP that have informed my assessment. In particular, my assessment has been guided by ONR's SAPs (Table 1) and TAGs (Table 2). A notable example of RGP adopted by Westinghouse is its application of the ASME Code for RCP design and ISI.

4.3 Assessment Finding

88. Westinghouse has provided preliminary evidence (Ref. 21) to substantiate integrity that the change of material for the pump casing from martensitic to clad ferritic steel would still ensure compliance with the design requirements of ASME Code Section III Division 1. This evidence supports the safety case, but more evidence is needed to substantiate this claim.

89. The future licensee will be required to provide full and detailed evidence to substantiate design compliance with its chosen nuclear code of practice for the RCP casing with clad ferritic material properties. This has been captured as an assessment finding in Annex 1.

5 CONCLUSIONS

90. This report presents the assessment of the claims, arguments and evidence contained in the technical justifications from Westinghouse, addressing GDA Issue GI-**AP1000**-SI-03 on the RCP, relating to the **AP1000** GDA closure phase.

91. To conclude:

- Westinghouse has supplied a technical report addressing the structural integrity considerations related to a clad ferritic pump bowl casing and supported the ongoing assessment of the pump bowl integrity case.
- Westinghouse has tentatively demonstrated, via preliminary calculations, that there are adequate margins available to compensate for the change of material for the pump casing and that the existing integrity analyses for the pump casing using martensitic steel could remain fit for purpose for the proposed clad ferritic steel casing.
- GDA Issue GI-**AP1000**-SI-03.A1 can be closed.
- An assessment finding has been raised in Annex 1 to revisit the updated and full ASME analyses and assessment of the RCP casing using revised material data at the licensing stage.
- Westinghouse has demonstrated that, in the event of a postulated disintegration of the flywheel, the fragments would be contained within the martensitic heat barrier maintaining the pressure boundary of the RCP.
- GDA Issue GI-**AP1000**-SI-03-A2 can be closed.

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

6 REFERENCES

1.	Step 4 Structural Integrity Assessment of the Westinghouse **AP1000** Reactor, ONR-GDA-AR-11-011 Revision 0, 14 November 2011, TRIM 2010/581520
2.	UK **AP1000** Assessment Plan for Closure of GDA Structural Integrity Issues 1 to 6, Revision 0, March 2015, TRIM 2015/149240
3.	WEC-REG-0872N, Enclosure 4, Resolution Plan for GI-**AP1000**-SI-03: Reactor Coolant Pump, Revision 3, 13 April 2016, TRIM 2016/157079
4.	Guidance on Mechanics of Assessment, TRIM 2013/204124
5.	Purpose and Scope of Permissioning, NS-PER-GD-014 Revision 5, TRIM 2015/304735
6.	GDA Guidance to Requesting Parties, www.onr.org.uk/new-reactors/ngn03.pdf
7.	www.onr.org.uk/operational/tech_asst_guides/ns-tast-gd-051.pdf)
8.	UK **AP1000** Pre-Construction Safety Report UKP-GW-GL-793 Chapter 20F Revision 0C, Westinghouse Electric Company LLC, September 2010, TRIM 2017/24563
9.	Safety Assessment Principles for Nuclear Facilities, 2014 Edition Revision 0, ONR, November 2014, ,
10.	**AP1000** Design Reference Point for UK GDA, September 2010, TRIM 2011/353689
11.	American Society of Mechanical Engineers Boiler and Pressure Vessel Code, Section III, “Rules for Construction of Nuclear Facility Components,” 1998 Edition through 2000 Addenda
12.	R3 Impact Assessment Procedure, EDF Energy Nuclear Generation Limited
13.	UK **AP1000** Pre-Construction Safety Report UKP-GW-GL-793 Revision 1, Westinghouse Electric Company LLC. January 2017, TRIM 2017/43700
14.	RQ-**AP1000**-1772, **AP1000** GI-**AP1000**-SI-03 Reactor Coolant Pump – Pump Bowl Integrity Case and Flywheel Disintegration Case, TRIM 2016/498282
15.	Westinghouse Electric Company Response to RQ-AP-1000-1354, TRIM 2015/459547
16.	Westinghouse Electric Company – Assessment of Missile Analysis from Postulated Failure of **AP1000** Reactor Coolant Pump Flywheel, ONR-**AP1000**-AR-15-001 Revision 0, TRIM 2017/24753
17.	Missile Analysis of Flywheel with Tungsten Alloy Inserts, KSB Document H23-07-P-033, TRIM 2011/82525
18.	Peer Review of ONR-**AP1000**-AR-15-001 Revision 0,TRIM 2017/27011
19.	ONR-NR-CR-16-864 – Discussion with Westinghouse on 16 January 2017, TRIM 2017/22873

20.	Information Package for Final Design Review Reactor Coolant Pump Type RUV for Westinghouse Reactor **AP1000** – KSB Document UA4 38793 (TRIM (2017/24583)
21.	WEC – **AP1000** – SI03 and RQ-1772 – Email – Response to Further Queries from A Sen, TRIM 2017/29324

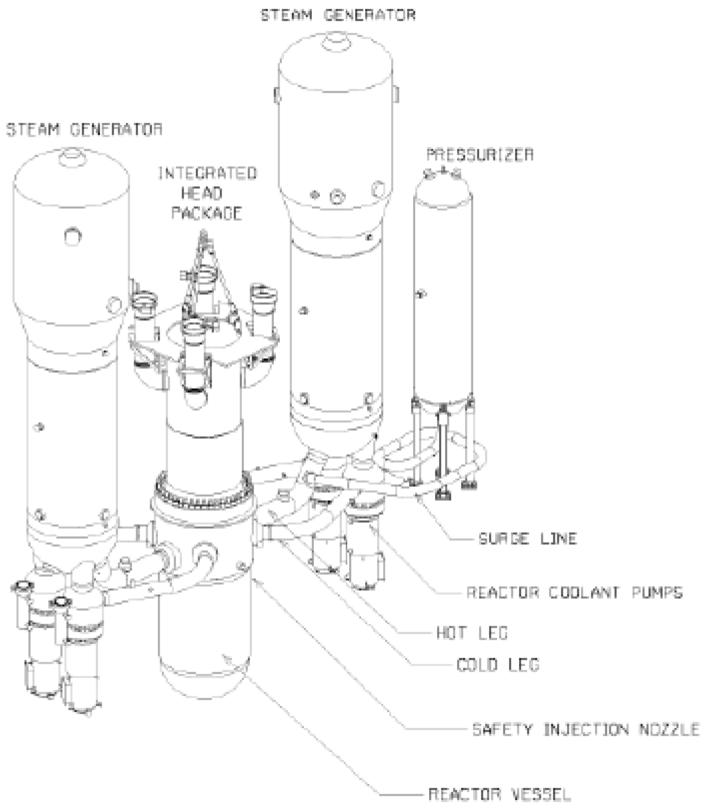

Figure 1: AP1000 Reactor Coolant Loop

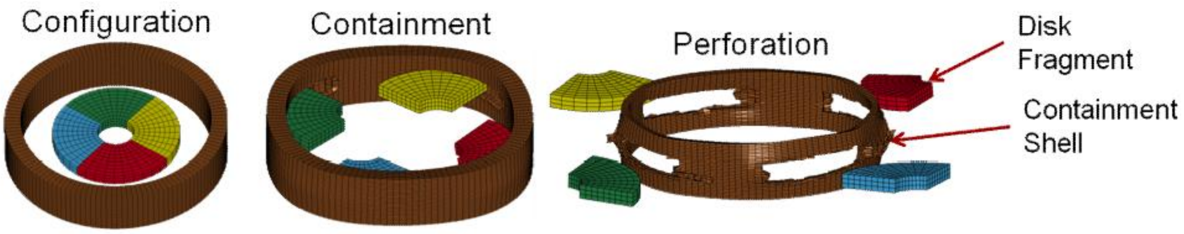

Figure 2: Hagg and Sankey principle

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.
EAD.1	Engineering principles: ageing and degradation	Safe working life
EAD.2	Engineering principles: ageing and degradation	Lifetime margins
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.3	Engineering principles: maintenance, inspection and testing	Type-testing
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 their 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.3	Engineering principles: integrity of metal components and structures: highest reliability components and structures	Evidence
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.
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 their 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

SAP No	SAP Title	Description
		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 their constituent parts should have regard to enabling examination and to minimising the number and length of welds in the component.
EMC.11	Engineering principles: integrity of metal components and structures: design	Failure modes
EMC.13	Engineering principles: integrity of metal components and structures: manufacture and installation	Materials
EMC.22	Engineering principles: integrity of metal components and structures: operation	Material compatibility
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.32	Engineering principles: integrity of metal components and structures: analysis	Stress analysis
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 their contribution to the safety case.
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.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.
EHA.1	Engineering principles: external and internal hazards: identification and characterisation	An effective process should be applied to identify and characterise all external and internal hazards that could affect the safety of the facility.
EHA.2	Engineering principles: external and internal hazards: data sources	For each type of external hazard either site-specific or, if this is not appropriate, best available relevant data should be used to determine the relationship between event magnitudes and their frequencies.
EHA.3	Engineering principles: external and internal hazards: design basis events	For each internal or external hazard which cannot be excluded on the basis of low frequency or insignificant consequence (see Principle EHA.19), a design basis event should be derived.
EHA.4	Engineering principles: external and internal hazards: frequency of initiating event	For natural external hazards, characterised by frequency of exceedance hazard curves and internal hazards, the design basis event for an internal or external hazard should be derived to have a predicted frequency of exceedance

SAP No	SAP Title	Description
		that accords with Fault Analysis Principle FA.5. The thresholds set in Principle FA.5 for design basis events are 1 in 10 000 years for external hazards and 1 in 100 000 years for man-made external hazards and all internal hazards (see also paragraph 629).
EHA.5	Engineering principles: external and internal hazards: design basis event operating states	Analysis of design basis events should assume the event occurs simultaneously with the facility's most adverse permitted operating state (see paragraph 631 c) and d)).
EHA.6	Engineering principles: external and internal hazards: analysis	The effects of internal and external hazards that could affect the safety of the facility should be analysed. The analysis should take into account hazard combinations, simultaneous effects, common cause failures, defence-in-depth and consequential effects.
EHA.7	Engineering principles: external and internal hazards: 'cliff-edge' effects	A small change in design basis fault or event assumptions should not lead to a disproportionate increase in radiological consequences.
EHA.14	Engineering principles: external and internal hazards: fire, explosion, missiles, toxic gases etc. – sources of harm	Sources that could give rise to fire, explosion, missiles, toxic gas release, collapsing or falling loads, pipe failure effects, or internal and external flooding should be identified, quantified and analysed within the safety case.

Table 2

Technical Assessment Guides considered in the assessment

Technical Assessment Guide No	Description
NS-TAST-GD-005	Guidance on the Demonstration of ALARP (As Low As Reasonably Practicable)
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

Annex 1

Assessment Findings – GI-AP1000-SI-03: AP1000 Reactor Coolant Pump

Number	Assessment Finding	Report Section
CP-AF-AP1000-SI-11	The future licensee will be required to provide full and detailed evidence to substantiate design compliance with its chosen nuclear code of practice for the RCP casing with clad ferritic material properties	4.3