

**New Reactors Programme**  
**GDA Close-out for the AP1000 Reactor**  
**GDA Issue GI-AP1000-RC-03 Revision 0 – Hydrogen Dosing System**

Assessment Report: ONR-NR-AR-16-046  
Revision 0  
March 2017

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Published 03/17

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## EXECUTIVE SUMMARY

Westinghouse Electric Company LLC (Westinghouse) is the reactor design company for the **AP1000**<sup>®</sup> reactor. Westinghouse completed Generic Design Assessment (GDA) Step 4 in 2011 and opted to pause the regulatory process. At that time, it had achieved an Interim Design Acceptance Confirmation (IDAC), which had 51 GDA Issues attached to it. These GDA 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 presents the assessment conducted as part of the close-out of the Office for Nuclear Regulation (ONR) GDA for the **AP1000** reactor design within the topic of Reactor Chemistry. This report specifically addresses GDA Issue GI-AP1000-RC-03 Revision 0, and associated GDA Issue Action related to the hydrogen dosing system.

GI-AP1000-RC-03 arose because the design of the hydrogen dosing system for the **AP1000** plant evolved throughout GDA and was the subject of a design change late in Step 4. While ONR welcomed this design change as a safety improvement, a number of concerns remained regarding the justification provided. Given the safety significance of controlling dissolved hydrogen, further substantiation and supporting evidence was considered necessary by ONR.

In response, WEC provided a single main submission which summarised its case regarding the adequacy of the hydrogen dosing system to safely support all modes of operation, including during faults. This was supported by a suite of documentation which contained further detailed evidence, including a description of the safety functions and safety design criteria, evidence that the hydrogen injection system design criteria have been met, an evaluation of the performance under abnormal events and a review of operating experience for high-pressure hydrogen injection systems, among others.

As a result of my assessment of these submissions, meetings and discussions with Westinghouse experts, and consultations with ONR colleagues in different technical areas, my conclusions are:

- WEC has identified the safety functions that the hydrogen dosing system in the **AP1000** design must provide and how these translate into specific dosing requirements during operations.
- I judge that the evidence provided by Westinghouse demonstrates that the system is capable of meeting these requirements. This is principally based on a series of calculations that demonstrate that the system will operate as intended. This has removed the concerns that led to the raising of the GDA Issue during Step 4, regarding insufficient evidence for this method of addition.
- Westinghouse has considered the likely faults associated with the system, including over- and underdosing and has demonstrated that, for the most part, these faults are relatively slow-acting and should be revealed by the controls in place. I am content that faster acting faults could be resolved through detailed design or operating procedures, so they do not fundamentally undermine the adequacy of the system.
- In response to this GDA Issue, Westinghouse has identified updates to the safety case. I reviewed these updates and am content that they accurately reflect the responses to the GDA Issue.

As a result of this assessment, I have identified three Assessment Findings. These relate to aspects of the detailed design and operating procedures for the system which will demonstrate that the risks are reduced so far as is reasonably practicable. These matters do not undermine the conclusions of the generic safety submission provided for GDA, and require licensee input and/or decisions to resolve.

Overall, on the basis of my assessment, I am satisfied that GDA Issue GI-AP1000-RC-03 can be closed.

## LIST OF ABBREVIATIONS

ALARP	As Low As Reasonably Practicable
BWR	Boiling Water Reactor
CCS	Component Cooling water System
CVS	Chemical and Volume control System
DAC	Design Acceptance Confirmation
DCP	Design Change Proposal
EPRI	Electric Power Research Institute
FMEA	Failure Modes and Effects Analysis
GDA	Generic Design Assessment
IAEA	International Atomic Energy Agency
IDAC	Interim Design Acceptance Confirmation
LOCA	Loss Of Coolant Accident
ONR	Office for Nuclear Regulation
OpEx	operating experience
OR	Operating Rule
PCSR	Pre-Construction Safety Report
PGS	Plant Gas System
PRHR	Passive Residual Heat Removal
PSS	Primary Sampling System
PWR	Pressurised Water Reactor
RCP	Reactor Coolant Pump
RCS	Reactor Coolant System
RNS	Normal Residual Heat Removal System
RQ	Regulatory Query
SAP	Safety Assessment Principle
SCC	Stress Corrosion Cracking
STP	Standard Temperature and Pressure (0 °C and 101.3 KPa)
TAG	Technical Assessment Guide
TQ	Technical Query (see also RQ)
VCT	Volume Control Tank
Westinghouse	Westinghouse Electric Company LLC
WENRA	Western European Nuclear Regulators Association

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## 1 INTRODUCTION

### 1.1 Background

1. This report presents the assessment conducted as part of the close-out of the Office for Nuclear Regulation (ONR) Generic Design Assessment (GDA) for the Westinghouse Electric Company LLC (Westinghouse) **AP1000**<sup>®</sup> reactor design within the topic of Reactor Chemistry. The report specifically addresses the GDA Issue GI-AP1000-RC-03 Revision 0 and associated GDA Issue Action (Ref. 1) related to the hydrogen dosing system.
2. GDA follows a stepwise approach in a claims-argument-evidence hierarchy. In Step 2, the claims made by Westinghouse were examined and in Step 3 the arguments that underpin those claims were examined. The Step 4 assessment (Ref. 2) reviewed the safety aspects of the **AP1000** reactor in greater detail, by examining the evidence, supporting the claims and arguments made in the safety documentation. Westinghouse completed Step 4 in 2011 and then opted to pause the regulatory process. At that time, it had achieved an Interim Design Acceptance Confirmation (IDAC), which had 51 GDA Issues attached to it. These GDA Issues require resolution prior to the award of a Design Acceptance Confirmation (DAC) and before any nuclear safety-related construction of this reactor design can begin. Westinghouse re-entered the GDA process in 2014 to close the 51 GDA Issues.
3. The purpose of this report is therefore to provide the assessment that underpins the judgement made in closing GDA Issue GI-AP1000-RC-03. This assessment is focused on the deliverables identified within the Westinghouse resolution plan (Ref. 3) published in response to the GDA Issue, and on further assessment that was undertaken of those deliverables.
4. The related GDA Step 4 report (Ref. 2) is published on the ONR website ([www.onr.org.uk/new-reactors/ap1000/reports.htm](http://www.onr.org.uk/new-reactors/ap1000/reports.htm)), and this provides the assessment underpinning GI-AP1000-RC-03. Further information on the GDA process in general is also available on the ONR website ([www.onr.org.uk/new-reactors/index.htm](http://www.onr.org.uk/new-reactors/index.htm)).

### 1.2 Scope

5. The scope of this assessment is detailed in the assessment plan (Ref. 4). Consistent with this plan, the assessment is restricted to considering whether the Westinghouse submissions to ONR for GI-AP1000-RC-03 provide an adequate response sufficient to justify closure of the GDA Issue. Importantly, it is not within the scope of this assessment to re-visit areas already found by ONR to be satisfactory unless, during my assessment, important safety issues emerged that required the expansion of my assessment scope.
6. As such, this report only presents the assessment undertaken as part of the resolution of GI-AP1000-RC-03 and it is recommended that this report be read in conjunction with the Step 4 Reactor Chemistry assessment of the **AP1000** reactor (Ref. 2) in order to appreciate the totality of the assessment undertaken as part of the GDA process.
7. This assessment focused on the justification for the hydrogen dosing system, which controls the addition of dissolved hydrogen to the primary coolant. Hydrogen is added to minimise corrosion of the structural materials and fuel, and to minimise radioactivity within the plant. Due to the design of the **AP1000** plant, the approach for adding this hydrogen is novel, and due to a late design change within Step 4, was not fully reflected within the safety case. GI-AP1000-RC-03 was raised to ensure that an adequate safety case is provided for the hydrogen dosing system. The scope of assessment here is therefore to ensure that the **AP1000** system design is adequate,

including during potential faults, and is capable of meeting the functional requirements of the plant. This also needs to be reflected appropriately within the safety case.

8. Further details of the scope of assessment can be found in Section 2.1 of my report.
9. Due to this scope, the structure of this report differs from that adopted for previous reports produced within GDA, most notably from the Step 4 Reactor Chemistry assessment (Ref. 2). This is because this report details the assessment of GI-AP1000-RC-03 only, rather than close-out of all GDA Issues associated with Reactor Chemistry. This allows closure of GDA Issues as the work is completed rather than waiting for the resolution of all work in this technical topic.

### **1.3 Methodology**

10. The methodology for the assessment follows HOW2 Guidance on Mechanics of Assessment within the Office for Nuclear Regulation (ONR) (Ref. 5).
11. I have sampled all of the submissions made in response to GI-AP1000-RC-03, to various degrees of breadth and depth. I chose to focus my assessment on those aspects that I judged to have the greatest safety significance, or where the hazards appeared least well controlled. My assessment has also been influenced by the claims made on the hydrogen dosing system, my previous experience of similar systems for reactors and other nuclear facilities, and the specific gaps in the original submissions made by Westinghouse that led to the GDA Issue.
12. The Safety Assessment Principles (SAPs) (Ref. 6), alongside the relevant Technical Assessment Guides (TAGs) (Ref. 7), have been used as the basis for this assessment.



## 2 ASSESSMENT STRATEGY

13. The intended assessment strategy for resolution of GI-AP1000-RC-03 is set out in this section. This identifies the scope of the assessment and the standards and criteria that have been applied.

### 2.1 Assessment Scope

14. This report presents only the assessment undertaken for resolution of Reactor Chemistry GDA Issue GI-AP1000-RC-03, related to the hydrogen dosing system (Ref. 1). This report does not represent the complete assessment of the **AP1000** design in the Reactor Chemistry topic area for GDA, or even the complete assessment of the hydrogen dosing system. It is recommended that this report be read in conjunction with the Step 3 and Step 4 Reactor Chemistry assessments of the Westinghouse **AP1000** reactor (Refs 8 and 2) in order to appreciate the totality of the assessment undertaken as part of the GDA process. Section 3 of this report provides a brief overview of the background to GI-AP1000-RC-03.
15. This assessment does not revisit aspects of the safety case already accepted as being adequate during previous stages of GDA. However, where the assessment of the Westinghouse responses highlight shortfalls not previously identified during Step 4, or cast doubt on previously accepted arguments, these were assessed within this report.
16. The focus for this assessment was on the adequacy of the justifications provided for the design of the hydrogen dosing system. This system controls the concentration of dissolved hydrogen within the primary coolant, which can affect the likelihood and significance of a number of hazards. This assessment was particularly focused on whether the **AP1000** system design is suitable and capable, including during potential faults and transients, of meeting the functional requirements of the plant for all modes of operation. This needs to be reflected appropriately within the safety case, including any limits or conditions that result. This scope of assessment is appropriate for GDA because the **AP1000** design is novel in this regard, and sufficient evidence needs to be provided that the design is appropriate, otherwise it is possible that major design changes would be necessary.
17. Annex 1 of this report contains the full text of the GDA Issue and Action (Ref. 1). The Westinghouse resolution plan, which details the methods by which the requesting party intended to resolve this GDA Issue via identified timescales and deliverables, is contained in Ref. 3 and discussed further in Section 3.

### 2.2 Related GDA Issues

18. ONR's GDA Guidance to Requesting Parties (Ref. 9) states that the information required for GDA may be in the form of a Pre-Construction Safety Report (PCSR). ONR guidance (NS-TAST-GD-051: The purpose, scope, and content of nuclear safety cases, Ref. 7) sets out regulatory expectations for a PCSR. The PCSR is the highest-level summary of the safety case and provides the links to the detailed arguments and evidence that may reside in a suite of supporting documentation.
19. At the end of Step 4, ONR and the Environment Agency raised GDA Issue GI-AP1000-CC-02 (Ref. 10), requiring Westinghouse to submit a consolidated PCSR and associated references to provide the claims, arguments and evidence to substantiate the adequacy of the **AP1000** design reference point. A separate assessment report has been prepared to consider the adequacy of the PCSR and closure of GDA Issue GI-AP1000-CC-02. Therefore, this report does not discuss the overall adequacy of the

Reactor Chemistry aspects of the PCSR. However, this assessment does consider the specific aspects related to GI-AP1000-RC-03 and the hydrogen dosing system.

20. An important output from the safety case is the identification of any limits or conditions necessary in the interests of safety (also known as Operating Rules, OR). ONR guidance (NS-TAST-GD-035: The limits and conditions for nuclear plant safety, Ref. 7) sets out regulatory expectations.
21. At the end of Step 4, ONR and the Environment Agency raised GDA Issue GI-AP1000-CC-01 (Ref. 11) requiring Westinghouse to demonstrate its arrangements to identify ORs and key safety requirements and to document these within the PCSR. A separate assessment report has been prepared to consider the adequacy of the responses and closure of GDA Issue GI-AP1000-CC-01. Therefore, this report does not discuss the overall adequacy of the Reactor Chemistry-related ORs. However, this assessment does consider the specific aspects related to GI-AP1000-RC-03 and the hydrogen dosing system.

### **2.3 Assessment Approach**

22. The assessment was undertaken by examining the evidence provided by Westinghouse in response to GI-AP1000-RC-03. This was assessed against the expectations and requirements of the SAPs and other guidance considered appropriate. Forming the basis of the assessment undertaken to prepare this report were:
  - submissions made to ONR in accordance with the resolution plan;
  - consideration of internal and international standards and guidance, international experience, operational feedback and expertise and assessments performed by other regulators, especially their findings;
  - interaction with other relevant technical areas (where appropriate);
  - raising and issuing of Regulatory Queries (RQs) as appropriate, followed by assessment of Westinghouse responses; and
  - holding technical meetings to progress the identified lines of enquiry.
23. The following subsections provide an overview of the outcome from each of the information exchange mechanisms in further detail.

#### **2.3.1 Regulatory Queries**

24. A total of four RQs were raised with Westinghouse for the assessment of GI-AP1000-RC-03. The responses to the RQs were assessed as part of this assessment. Commentary on the most important and relevant RQ responses is included in the assessment section later in this report as appropriate. The responses provided further evidence to support resolution of the GDA Issue.

#### **2.3.2 Technical Meetings**

25. A number of technical meetings with Westinghouse were held during assessment of the GI-AP1000-RC-03 responses. The principal focus of these meetings was to discuss progress and responses, to facilitate technical exchanges and to hold discussions with Westinghouse technical experts on emergent issues.

### **2.4 Standards and Criteria**

26. This assessment has been undertaken in line with the requirements of NS-PER-GD-014 (Ref. 12). The standards and criteria adopted within this assessment are principally the SAPs (Ref. 6), internal TAGs (Ref. 7), relevant national and international standards and relevant good practice informed from existing practices adopted on UK nuclear licensed sites. Further details are provided below.

### **2.4.1 Safety Assessment Principles**

27. The key SAPs applied within this assessment are included within Table 1.
28. As the SAPs (Ref. 6) constitute the regulatory principles against which duty holders' safety cases are judged, they are therefore the basis for ONR's nuclear safety assessment. It is worth noting that the 2014 Edition (Revision 0) of the SAPs was used when performing the assessment described in this report, whereas the original Step 4 assessment used the 2006 Edition. From a Reactor Chemistry perspective, the main change is that the current edition includes specific SAPs relating to chemistry (ECH.1 to 4).

### **2.4.2 Technical Assessment Guides**

29. The TAGs (Ref. 7) that have been used as part of this assessment are set out in Table 2.

### **2.4.3 National and international standards and guidance**

30. There are both International Atomic Energy Agency (IAEA) standards (Ref. 13) and Western European Nuclear Regulators Association (WENRA) reference levels (Ref. 14) of relevance. However, they are not specific to hydrogen dosing and therefore the SAPs were the foremost standard considered. It should be noted that the latest version of the SAPs (Ref. 6) has been benchmarked against both IAEA and WENRA guidance.

### **2.5 Use of Technical Support Contractors**

31. No technical support work was undertaken to support this assessment.

### **2.6 Integration with Other Assessment Topics**

32. 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. To assess the adequacy of the submissions provided by Westinghouse for GI-AP1000-RC-03, I have required only limited input from other technical disciplines and the assessment reported here is consistent with this. As described in Section 2.2, this assessment was integrated with the wider requirements of GI-AP1000-CC-01 (limits and conditions) and GI-AP1000-CC-02 (PCSR) respectively.

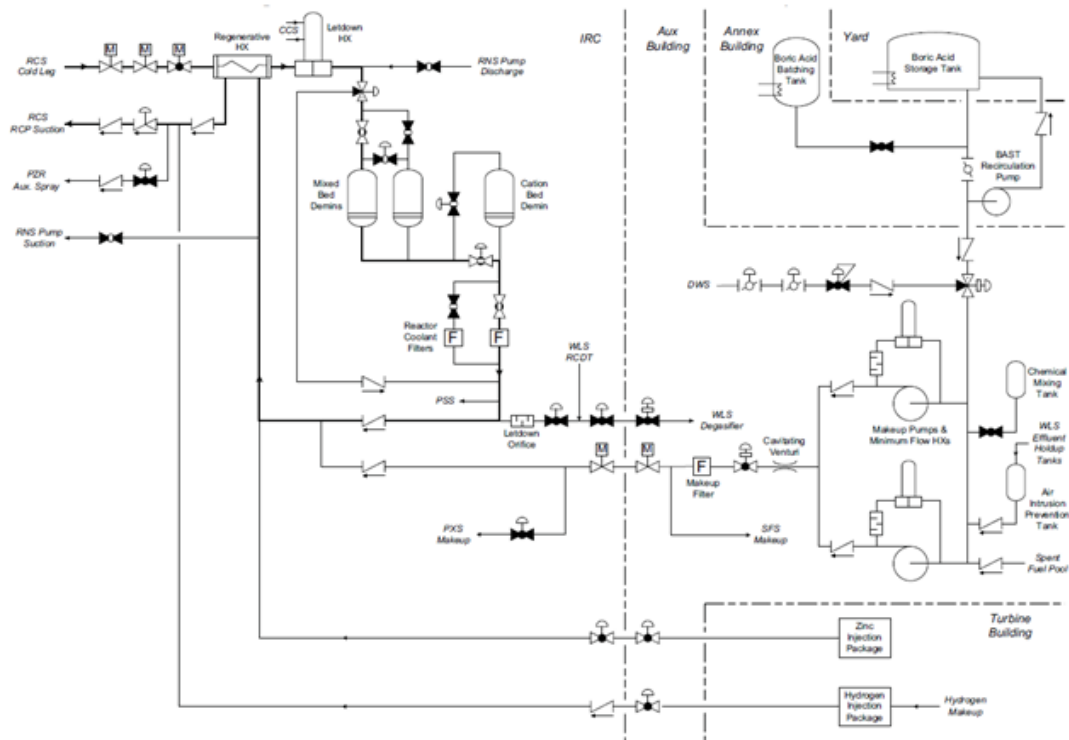
### **2.7 Out of Scope Items**

33. This assessment report for GI-AP1000-RC-03 focuses solely on the hydrogen dosing system. No specific items within the remit of this GDA Issue have been identified as out of scope.

### 3 REQUESTING PARTY'S SAFETY CASE

#### 3.1 Overview of the Westinghouse Safety Case for the Hydrogen Dosing System

34. In the **AP1000** design, as with every other Pressurised Water Reactor (PWR), there is a safety requirement to maintain a small amount of dissolved hydrogen within the primary coolant when the plant is operating. As the water coolant passes through the core, radiolysis occurs, the net effect of which is to produce a range of oxidising species. If left unchecked, this would result in higher corrosion rates of structural materials, enhanced oxidation of fuel cladding and increased generation and transport of radioactivity around the plant systems. The small additions of hydrogen are sufficient to remove the oxidising species and mitigate these effects.
35. The system responsible for controlling the primary coolant chemistry in the **AP1000** design is the Chemical and Volume Control System (CVS). The hydrogen dosing system is a subsystem of the CVS. The CVS was assessed extensively during Step 4 of GDA and is reported in Ref. 2. However, the design of the CVS has a number of differences from other PWRs and directly influences how hydrogen is controlled. The CVS is shown in Figure 1 and the main points of relevance to GI-AP1000-RC-03 are described below.



**Figure 1: AP1000 Chemical and Volume Control System (CVS)**

36. In normal operation a flow of coolant is taken from one of the cold leg lines (1B), cooled via regenerative and non-regenerative heat exchangers and subjected to chemical treatment (such as clean-up and dosing) before being heated and returned to the suction of both pumps on steam generator 1. All of this main piping is located within the containment. Various other functions and routings are possible but are not relevant to hydrogen dosing so are not discussed in detail here (see Ref. 2 for more details). The driving force for this flow is provided by the pressure difference across the Reactor Coolant Pumps (RCPs) in normal operations or the Normal Residual Heat Removal System (RNS) pumps during shutdowns. This means that the CVS in the **AP1000** design operates at full primary circuit pressure (around 15 MPa), whereas in most PWRs the coolant pressure is reduced (to around 1 MPa).

37. The **AP1000** CVS design has therefore removed a number of components commonly found in comparable PWR systems, including the Volume Control Tank (VCT), which is important in the context of GI-AP1000-RC-03. The VCT is a large volume tank where the depressurised coolant collects before being returned to the RCS. The cover gas above the coolant in this tank is used to control the concentration of dissolved hydrogen by varying the coolant temperature or pressure, or concentration of hydrogen in the cover gas. This is a simple and reliable system, but it requires a large volume of hydrogen and produces large amounts of off-gas which must be treated by the gaseous radwaste systems. As the **AP1000** CVS is high pressure and does not include a VCT, Westinghouse opted for an in-line hydrogen addition system, injecting hydrogen gas directly into the pipework of the CVS with the intention of dissolving it quickly in the coolant flowing past and certainly before any undissolved gas reaches safety equipment. This is a significantly safer solution for a high-pressure CVS, avoiding the use of a high-pressure hydrogen gas-filled vessel.
38. The fundamental claim made by Westinghouse regarding the hydrogen dosing system in the **AP1000** safety case is that it is suitable and sufficient to meet the functional requirements placed upon it, including the control of dissolved hydrogen.

### 3.2 Assessment during GDA Step 4

39. As discussed more fully in Ref. 2, the design of the hydrogen dosing system for the **AP1000** design evolved throughout Step 4. The original design was one whereby the hydrogen was added intermittently along with the depleted zinc solution (for dose reduction) through a single line. Adding a liquid and gaseous additive together would create safety challenges and problems in achieving adequate control. In response to ONR concerns, a Design Change Proposal (DCP) for a new hydrogenation and zinc injection system, APP-GW-GEE-1766 (Ref. 15), was submitted in November 2010. It was given the highest UK Level 1 categorisation by Westinghouse following the categorisation scheme operating in GDA. The change was intended to be standard for all **AP1000** plants, worldwide. In summary, the single hydrogen and zinc injection line was separated to add zinc before and hydrogen after the regenerative heat exchanger, as shown in Figure 1.
40. While ONR welcomed this design change as a safety improvement, a number of concerns remained regarding the justifications provided in the DCP. Further information for the new design was requested in TQ-AP1000-1184 and 1230 (Ref. 16), the latter asking specifically for evidence that the proposed system would work as intended. Note that during Step 4 RQs were known as Technical Queries (TQs), but otherwise are the same. Neither response to these TQs fully justified the design of the revised hydrogen injection system, nor provided the expected level of evidence.
41. Given the safety significance of controlling dissolved hydrogen, often found within the highest level of limits and conditions, ONR expected a higher degree of substantiation and supporting evidence than was provided by Westinghouse during Step 4. On the basis of Ref. 15, and the responses to TQ-AP1000-1184 and 1230 (Ref. 16), the conclusion of the Step 4 assessment was that insufficient evidence had been provided that the new system would work as required for a Category 1 safety change. Due to the importance of this parameter and associated control system, and it was considered important to resolve this before acceptance of the design, GDA Issue GI-AP1000-RC-03 was raised.

### 3.3 Summary of the GDA Issue and Action

42. The full text of GI-AP1000-RC-03 (Ref. 1) and the associated one Action is in Annex 1.

43. The overall requirement in the GDA Issue was to provide a consistent and structured safety case which demonstrates that the hydrogen dosing system is adequate. Specifically, this included:
- evidence to support the dosing system during all operating modes;
  - demonstration of the impact of anticipated transient conditions; and
  - fault analysis and controls.
44. While not explicitly mentioned in the GDA Issue, it was implicit in the expectation of producing a consistent safety case that matters such as limits and conditions, categorisation and classification and redundancy and diversity would be considered as necessary by Westinghouse.

### 3.4 Westinghouse Deliverables in Response to the GDA Issue and Action

45. The Westinghouse resolution plan for this GDA Issue is given in Ref. 3. This provides details of the deliverables Westinghouse intended to provide to respond to the Action. The following section contains a brief description of the submitted deliverables that formed the basis of the assessment.
46. According to Ref. 3, to resolve GI-AP1000-RC-03, Westinghouse intended to provide sufficient evidence to support the **AP1000** hydrogen dosing system design. The evidence was provided in two separate documents (Refs 17 and 18) which considered all modes of plant operation and anticipated transient conditions. The evidence provided in these two documents, along with existing evidentiary documents (referenced later in my assessment as appropriate), would themselves be references to a UK-specific summary document that provided the coherent safety case for the hydrogen dosing system, **AP1000** Hydrogen Injection System – Safety Demonstration, UKP-GW-GL-100 (Ref. 19).
47. Ref. 19 included a description of the safety functions, and safety design criteria, a description of the **AP1000** hydrogen injection system, demonstration that the **AP1000** hydrogen injection system design criteria are met, performance under abnormal events, a Failure Modes and Effects Analysis (FMEA) and a review of operating experience for high-pressure hydrogen injection systems. Ref. 19 therefore formed the basis of my assessment.
48. In addition to the submissions detailed above, which formed the basis for Westinghouse's resolution plan, responses to the various RQs also informed my assessment. These are referenced throughout Section 4.
49. Finally, Westinghouse provided an update to the PCSR to identify how the resolution of this GDA Issue would be reflected in the overall **AP1000** safety case. This is discussed further in Section 4.

#### 4 ONR ASSESSMENT OF GDA ISSUE GI-AP1000-RC-03

50. This assessment has been carried out in accordance with Purpose and Scope of Permissioning, NS-PER-GD-014, (Ref. 12).

##### 4.1 Scope of Assessment Undertaken

51. The scope of my assessment is described in Section 2.1, alongside the description of the submissions that formed the basis for that assessment in Section 3.4.

##### 4.2 Assessment

52. This section describes my assessment of the Westinghouse responses to GI-AP1000-RC-03.

53. I have structured my assessment around the main summary report provided to address the GDA Issue (Ref. 19). I first considered the system design and the safety functions it provides, before assessing the justification for its suitability under both normal operational conditions and faults.

54. The assessment that follows is based on the latest version of Ref. 19. This was updated during my assessment in order to respond to several of my RQs, notably RQ-AP1000-1379 and 1380 (Ref. 20).

##### 4.2.1 Hydrogen Dosing System Description

55. As described previously, the hydrogen dosing system is part of the CVS, but it also interfaces with other systems in order to perform its functions, notably the Plant Gas System (PGS) for the hydrogen gas supply and the Reactor Coolant System (RCS) where the gas is injected. The overall system is straightforward and a simplified sketch of the hydrogen dosing system is shown in Figure 2.

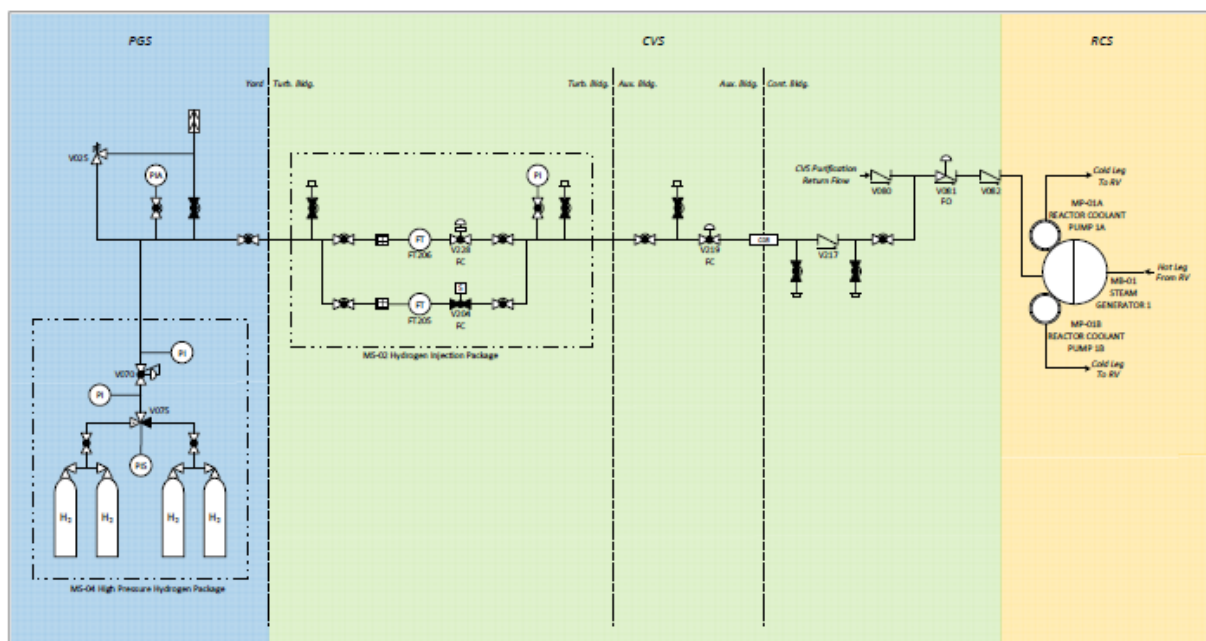


Figure 2: Simplified sketch of the AP1000 hydrogen dosing system

56. Hydrogen gas is taken from one of two banks of (two) standard gas cylinders which are located in the plant yard. Ref. 19 provided details of the controls and alarms that allow the gas supply to remain uninterrupted, which are consistent with normal industrial practices as applied at other UK nuclear power stations.

57. The piping then enters the turbine building, which contains the hydrogen injection package (CVS-MS-02). Two flow paths are provided through this package; one for 'continuous' (low flow) addition and one for 'batch' (high flow) addition. These two flow paths are necessary to account for the differing demands placed on hydrogen dosing during the different operating modes, discussed further in Section 4.2.4. Various manual isolation valve alignments are necessary to operate the system, but the amount of hydrogen injected is controlled by flow measurements which automatically control the flow rate (in continuous addition) or volume (in batch addition). The addition rates using these two different flow paths are between [REDACTED] and [REDACTED] cc min<sup>-1</sup> for continuous addition, and [REDACTED] cc min<sup>-1</sup> for batch addition (where cc is at Standard Temperature and Pressure (STP)).
58. The piping leaving the hydrogen injection package is then routed through the auxiliary building, before entering containment after passing through the inboard and outboard containment isolation valves. These isolation valves close on receipt of a containment isolation signal, in the same way as other lines that exit containment. The line connects to the CVS coolant return line, which returns the coolant back to the RCS via the steam generator channel head.

#### 4.2.2 ALARP Justification for Direct Injection

59. Before considering this design further it is worth mentioning the reasoning provided by Westinghouse for why it was considered not reasonably practicable to include a more conventional hydrogen dosing system in **A1000**, given this type of system has many thousands of reactor years of successful operating experience. The principal reason is that the CVS operates at full primary circuit pressure. This simplifies the design and allows the CVS to be located within containment, reducing the risks associated with large coolant releases outside containment. The adequacy of this was considered during Step 4 and assessed in Ref. 2. To incorporate hydrogen control via a cover gas in a tank (like a VCT) would firstly require the addition of a suitable vessel into the CVS. Using cover gas on that vessel at full pressure would be hazardous and difficult to engineer, while reducing the pressure would require further components such as high-pressure make-up pumps, which would profoundly change the way that the **AP1000** design operates, in particular in relation to how the reactivity control system works (using grey rods, see Ref. 2). Such a system would also use large volumes of hydrogen and create gaseous effluent which would need to be treated by the radwaste systems.
60. I am therefore content that it can be shown that, on balance, this method of hydrogen addition is reasonable for the **AP1000** design, provided sufficient evidence can be provided that it is capable of meeting the safety functions placed on it and does not introduce significant additional hazards.

#### 4.2.3 Safety Functions

61. Ref. 19 offered a description of the safety functions provided by the hydrogen dosing system. Revision 0 of Ref. 19 did not include such a description, but it was added in response to RQ-AP1000-1333 (Ref. 20). These safety functions are based on the Westinghouse safety classification methodology (Ref. 21) and its application to the hydrogen injection system (Ref. 22). Ref. 22 states that the main function of the hydrogen dosing system is to 'provide hydrogen to the RCS during normal operations to eliminate free oxygen and minimise corrosion of the fuel and primary surfaces'.
62. Ref. 19 further expanded on this and noted that hydrogen gas is added to, and maintained in solution in, the reactor coolant to provide reducing conditions at normal operating temperatures in order to:
- minimise the general corrosion of primary system surfaces;



- minimise the oxidation of fuel cladding surfaces; and
  - mitigate the risk of Stress Corrosion Cracking (SCC) of sensitised stainless steels and nickel-base alloys.
63. I agree that this is a reasonable description of the necessity for hydrogen addition, although I also consider that minimising the generation and transport of radioactivity around the plant would be a further reason to add dissolved hydrogen (although this is partly captured within the first point above). The addition of too much hydrogen would also have a negative impact on fuel cladding integrity, but while this is not explicitly mentioned in Ref. 19, it was noted in the **AP1000** Chemistry Manual (Ref. 23). While suppression of radiolytic oxidising species is not explicitly mentioned, I am content that the effects of this are covered by the functions identified above. I am therefore content that Westinghouse has identified the main safety requirements for hydrogen addition.
64. While the DCP to separate the lines to be used for zinc and hydrogen dosing respectively was sentenced by Westinghouse to be categorised a UK level 1 change, on the basis of Refs 21 and 22, Westinghouse has categorised the hydrogen dosing system as providing a Category C function, which provides long-term support of the Category A function of maintaining the reactor coolant pressure boundary. It is therefore a Class 3 system. Other parts of the overall system carry a higher categorisation and classification (such as the associated containment isolation valves, which are A1). This methodology (Ref. 21) is in line with the expectations of the SAPs (ECS.1 and 2) (Ref. 6) and TAG (094) (Ref. 7) regarding the approach to categorisation and classification. I considered its application to the hydrogen dosing system (Ref. 22) as adequate, given my assessment that follows.

#### 4.2.4 Hydrogen Dosing Requirements

65. The amount of hydrogen dosing necessary in the **AP1000** design varies depending upon the operating mode and conditions. During operations at power the hydrogen concentration in the coolant is maintained within a range sufficient to achieve protection against radiolytically produced oxidants. Ref. 19 (based on Ref. 23) stated that the required range is ■ to ■ cc(STP)/kg H<sub>2</sub>O of coolant (hereafter referred to as cc kg<sup>-1</sup>). This applies when the reactor is critical (Modes 1 and 2). Ref. 23 also stated that hydrogen must be >■ cc kg<sup>-1</sup> when the coolant temperature is > 121 °C (Modes 3 and 4). Ref. 24 noted that the assumption in the plant design is to potentially have up to 80 cc kg<sup>-1</sup> of hydrogen in the coolant, although as noted above this is not expected. These requirements can therefore be summarised as below:

Condition	Dissolved Oxygen / ppb	Dissolved Hydrogen / cc kg <sup>-1</sup>
Coolant < 121 °C and heating	< ■	n/a
Coolant > 121 °C, reactor subcritical	< ■	> ■ (at criticality)
Power operation	< ■	■ to ■

**Table 3:** Dissolved hydrogen requirements

66. At times Ref. 19 was somewhat confusing over these 'limits' as different values are quoted for different parts of the response. These were clarified in RQ-AP1000-1467 (Ref. 20) and are consistent with Table 3.
67. Although unavailable at the time Ref. 19 was produced, I have also checked the generic AP1000 Technical Specifications (Ref. 25) to see if they place any requirements on the hydrogen concentrations. At present they do not. I would not consider this appropriate given the significance of this parameter, but this is outside

the scope of this present assessment and considered further as part of GI-AP1000-CC-01 (Ref. 11).

68. In order to control the concentration within these limits, account must be made for the various sources and sinks of hydrogen. Even during operations at power (Modes 1 and 2), hydrogen needs to be added to remove any oxygen that is introduced into the system. Transient amounts of oxygen can be introduced to the primary coolant during boration operations as a result of the presence of dissolved oxygen in the bulk boric solution used for make-up. Similarly, the demineralised water used for dilution purposes may contain dissolved oxygen, although this is reduced in the **AP1000** design due to deoxygenation of the water supply. Hydrogen is also lost as it suppresses the radiolysis reactions, and is also absorbed and diffuses into solids (in particular the steam generator tubing). While some hydrogen is produced as a by-product of corrosion, this is negligible in a passivated plant.
69. During plant start-up, the coolant needs to transition from fully oxidising conditions (exposed to air during refuelling) to the reducing conditions required for power operations. During the initial heat-up phase, hydrazine is added to the reactor coolant and the pressuriser to scavenge dissolved oxygen in the system. The temperatures are not raised above 121 °C until the oxygen content has been reduced below [REDACTED] ppb and the hydrogen concentration must be increased to greater than [REDACTED] cc kg<sup>-1</sup> before the reactor is taken critical.
70. In order to shut down the plant, hydrogen is removed from the reactor coolant through mechanical and/or chemical degassing before controlled oxygenation and the establishment of oxidising conditions. This needs to happen before the opening of the primary system to the atmosphere. There may be times during shutdown, such as when the gas space in the pressuriser is collapsed, when the **AP1000** design may experience hydrogen levels somewhat higher than the upper limit of [REDACTED] cc kg<sup>-1</sup>. This temporary increase results from the gaseous hydrogen in the pressuriser vapour dissolving into the coolant when the pressuriser is made water solid. This is no different from other PWRs but must be factored into the plant design, and may be larger for the **AP1000** reactor given the larger pressuriser volume. I have not considered this to be a significant risk, given that the effect would be very short-lived and features are available in the design to minimise these event (via pressuriser venting).
71. These requirements were recognised in both Refs 19 and 23. I judge that Westinghouse has a good understanding of the hydrogen control requirements, which are identified from the safety case. I consider whether the design is adequate to achieve these in Section 4.2.5. I specifically consider the chemistry aspects of limits and conditions, of which hydrogen is one parameter, as part of GI-AP1000-CC-01 (Ref. 11).

#### 4.2.5 Performance During Normal Operations

72. In this part of my assessment, I considered the adequacy of the demonstration provided by Westinghouse that the hydrogen dosing system can meet its performance requirements during all modes of normal operation, including expected transient events.

##### Operating Experience

73. The response to TQ-AP1000-1230, raised during Step 4, states, 'There is no known commercial operational experience [of direct hydrogen dosing] for nuclear power; reliance on direct injection for the **AP1000**® Plant is a first of a kind approach.' This was one of the main uncertainties at the end of Step 4 that led to GI-AP1000-RC-03 being raised. Revision 0 of Ref. 19 contained very little Operating Experience (OpEx).

RQ-AP1000-1379 (Ref. 20) requested further evidence, which was provided in the later revision of the report.

74. Appendix B of Ref. 19 contained a summary of OpEx considered by Westinghouse. This included US PWR experience, Boiling Water Reactor (BWR) applications and other applications outside the nuclear industry. The conclusion reached by Westinghouse is that there is some evidence for direct hydrogen injection, including within the nuclear industry, but none that operates under the same conditions as proposed for the **AP1000** design. Not referenced by Westinghouse, but the UK EPR design also features a form of direct hydrogen injection (again with many differences) discussed in Ref. 26. This is based on experience from a number of German PWRs.
75. I am therefore content that there is some evidence for this method of hydrogen injection, albeit under differing conditions. The main differences relate to temperature and pressures, but these should work in favour of the **AP1000** design. It therefore remains important to provide a suitable and sufficient degree of supporting evidence that the design is adequate.

#### Maximum Addition Rate

76. Before considering whether the dosing requirements can be met, it is useful to determine the maximum addition rate before the coolant becomes saturated. If this were to be exceeded, hydrogen gas pockets would form in high points within the system. Ref. 17 provided a calculation of this. Assuming the CVS purification loop is operating at the normal letdown flow rate means that over 600,000 cc min<sup>-1</sup> of hydrogen can be added without reaching the saturation limit for the returning coolant. This is over 20 times the maximum that can be supplied by the plant when in batch mode. This is based upon the most penalising conditions during start-up, with at power conditions allowing for even higher addition rates. Even at room temperature and pressure, around 8,000 cc min<sup>-1</sup> could be added, so at the much higher pressures in the primary system there is shown to be considerable margin. This resolves one of the queries raised in TQ-AP1000-1230 (Ref. 16), regarding the margins in the design, that remained incomplete at the end of Step 4.
77. Not presented in Ref. 19, but it can be calculated using the information in Refs 17 and 18, is the hydrogen concentration in the returned letdown flow. Assuming the normal letdown flow rates and the maximum batch addition rate yields an additional concentration of around 80 cc kg<sup>-1</sup> (that is, if the letdown coolant is 25 cc kg<sup>-1</sup>, the return will be 105 cc kg<sup>-1</sup>). This would be rapidly diluted within the bulk of the primary coolant. However, even this very short-lived higher hydrogen concentration in the letdown return is sufficiently below the theoretical saturation limit that the risk of the formation of hydrogen gas pockets is negligible.
78. The most important assumption in the calculations described above is that the hydrogen instantaneously dissolves within the coolant. Ref. 18 provided additional evidence regarding why this was reasonable, but also looked at the potential nuclear safety consequence if it were not. In summary, the main arguments put forward to support this assumption were:
- The maximum injection rate is significantly below the solubility limit (based on Ref. 17).
  - The piping system is tortuous and will enhance mixing.
  - Significant dilution would take place in the steam generator volume, further enhancing dissolution.
79. It was noted in Ref. 18 that a previous Westinghouse calculation suggested that hydrogen may not fully dissolve before it leaves the CVS piping and enters the RCP and core. This calculation takes no account of the latter two factors given above and is

therefore highly conservative. Notwithstanding this, the identified concerns would be the interaction of undissolved hydrogen with the RCPs (causing cavitation) and with the reactor fuel (reactivity changes caused by voids). These are addressed by:

- Westinghouse has identified the limiting case for the RCP suction head to occur during start-up conditions. Although assuming no dissolution of hydrogen adds only a very small void fraction to the RCP suction, Westinghouse has identified a requirement to not inject hydrogen before the isolation of the RNS (to ensure there is margin with respect to the RCP suction pressure). This prohibits hydrogen injection at less than 135 °C and 3.172 MPa. The effect is to shorten the time available to reach the  $\blacksquare$  cc kg<sup>-1</sup> hydrogen needed before criticality. But as discussed later I did not consider this time constraint to be safety related (but commercial). More importantly, I have not seen this condition mentioned elsewhere in the Westinghouse submissions, but considered that it needs to be reflected in the plant ORs in an appropriate manner. **I consider this to be an Assessment Finding:**

CP-AF-AP1000-RC-07 – The licensee shall ensure that any safety related conditions associated with starting hydrogen dosing to the primary coolant in the **AP1000** design have been appropriately captured within the safety case.

- If no hydrogen were to dissolve before reaching the reactor core, Westinghouse has calculated that a core void fraction of  $1.2 \times 10^{-4}$  % would result. This value would need to be three orders of magnitude larger before it caused any hazard in terms of reactivity changes (in fact, it is suggested that current operating plants already operate at levels similar to this due to other undissolved gases (Ref. 18)).
80. On balance, I am content that sufficient evidence has been provided to suggest that incomplete dissolution of the hydrogen added to the primary coolant is unlikely, and also that even if it did occur to some degree the safety significance would be negligible.

#### Start-up and Power Operations

81. Ref. 19 identified the design criteria for the hydrogen dosing system. These are based on the hydrogen dosing requirements described above (Section 4.2.4). The approach in Ref. 19 was to provide evidence that each of these can be met by the design by undertaking a series of calculations. It should be noted that these calculations do not necessarily align directly with the limits suggested by Table 3, as they were completed at an earlier stage of safety case development. They are, however, still relevant and are useful exemplars of the system performance that can be expected. In summary, these are:
- Increasing the hydrogen concentration from 0 to  $\blacksquare$  cc kg<sup>-1</sup> in 8 hours
  - Increasing the hydrogen concentration from  $\blacksquare$  to  $\blacksquare$  cc kg<sup>-1</sup> in 24 hours
  - Maintaining a 'steady' concentration in the range of  $\blacksquare$  to  $\blacksquare$  cc kg<sup>-1</sup>
  - Maintaining the concentration in the range of  $\blacksquare$  to  $\blacksquare$  cc kg<sup>-1</sup> during normal transients, such as water movements to and from the primary circuit
82. The first two of these relate to start-up periods, while the latter two refer to power operations. I did not consider the time constraint associated with the first of these (8 hours) to be a safety parameter, but instead commercially driven as reaching this concentration is often a critical path in order to restart the plant. The second (24 hours) is safety related, as it is necessary to meet this timescale or take corrective action, including potentially shutting down the plant. The important difference is that during the second period the reactor is critical, whereas during the first it is not.

83. The calculations that prove that these first two increases during start-up can be met were summarised in Ref. 19, and detailed in Ref. 17. It is determined that an addition rate of  $6,230 \text{ cc min}^{-1}$  is necessary to increase the hydrogen concentration from 0 to  $15 \text{ cc kg}^{-1}$  in 8 hours. This is greater than can be provided by the continuous flow path, but around 25% of the maximum that can be delivered in batch mode. In reality, this would be achieved by using the batch mode for 25% of the time. While Ref. 17 did not provide a specific calculation for increasing the concentration from 15 to  $25 \text{ cc kg}^{-1}$  in 24 hours, it is rationally bounded by the previous analysis and a more onerous analysis of 0 to  $25 \text{ cc kg}^{-1}$  in 18 hours demonstrated that this can be achieved with around 15% of the batch flow (and even within 24 hours using the continuous flow). There is further conservatism in these analyses as various hydrogen losses were assumed, such as losses through the steam generator tubes and via the pressuriser spray.
84. For normal power operation, when there is the requirement to maintain hydrogen within an assumed normal control band of  $\blacksquare$  to  $\blacksquare \text{ cc kg}^{-1}$ , Westinghouse has assumed that the main loss of hydrogen will be via the steam generator tubes (without any water movements to or from the circuit). Ref. 17 calculated these losses as equal to  $\blacksquare \text{ cc min}^{-1}$ . This is less than the maximum addition rate for the continuous flow path. Given this assumption is effectively determining the system design, I queried the basis and confidence in this value in RQ-AP1000-1380 (Ref. 20). The response (provided in Revision 1 of Ref. 19) notes that this value is based upon unpassivated materials, and hence is expected to be lower for an operating plant. Westinghouse was unable to provide plant OpEx to support these values (due to other plants operating with a VCT and therefore no measurement of hydrogen losses). In Ref. 19 Westinghouse stated that it assumes the passivated values to be 20% of this maximum, or  $\blacksquare \text{ cc min}^{-1}$ , which matches the minimum addition rate for the continuous flow path. If the continuous flow path is unable to meet the hydrogen demand (ie losses are  $> \blacksquare \text{ cc min}^{-1}$ ), the batch mode could be used. Conversely, if the continuous flow path exceeds the hydrogen demand (ie losses are  $< \blacksquare \text{ cc min}^{-1}$ ), either the continuous mode would have to be used in a batch wise manner, or additional letdown and make-up operations would be necessary (ie 'bleed and feed'). In either case, this is clearly not ideal, placing additional demands on both the operators and equipment and leading to a poorly controlled level of dissolved hydrogen (albeit mainly within limits). There is therefore a degree of uncertainty in the adequacy of these design parameters. Further evidence may be available from **AP1000** plants that commission before any UK plants are operated. **I consider this to be an Assessment Finding:**

CP-AF-AP1000-RC-08 – The licensee shall provide evidence that the design parameters for the hydrogen dosing system of the **AP1000** design are adequate to meet both the steady state and transient requirements of the safety case, and reduce risks as low as is reasonably practicable.

85. While the normal power case above considers those 'steady' periods of operation, it is also necessary to consider what happens when the chemistry is being intentionally changed to account for fuel burn-up (a boron dilution). Ref. 17 considered the case where the full CVS flow is let down and make-up comes from an oxygen saturated boric acid storage tank. Two cases were considered. To maintain the concentration at  $50 \text{ cc kg}^{-1}$  requires an addition rate of  $\blacksquare \text{ cc min}^{-1}$  or 65% of the batch rate. Under the same conditions, to maintain the concentration at  $30 \text{ cc kg}^{-1}$  (ie to allow it to fall from 50 to 30 during the dilution) requires a negligible addition rate ( $\blacksquare \text{ cc min}^{-1}$ ). These calculations showed that maintaining within the normal range should be possible during normal water movements.
86. A summary of the main calculations undertaken by Westinghouse in Ref. 17, and presented in Ref. 19, are given in Table 4 below.

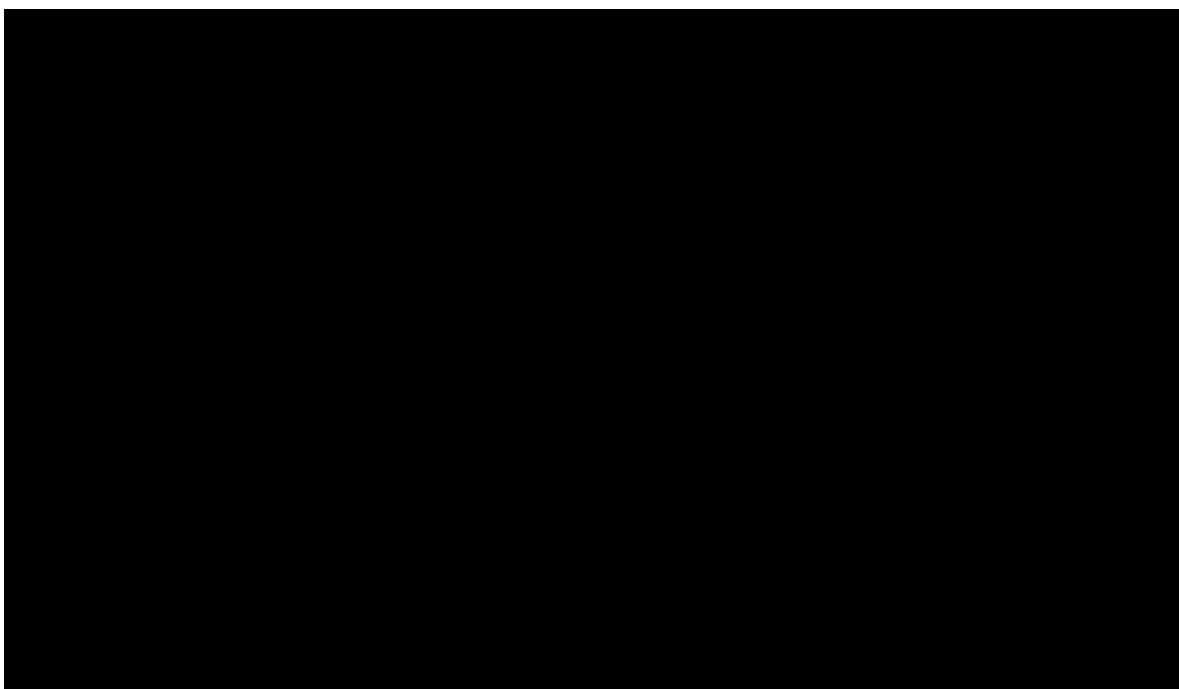
Condition	Addition rate / cc min <sup>-1</sup>	Using continuous addition	Using batch addition
0 to 15 cc kg <sup>-1</sup> in 8 hours	████	Not possible	2 hours
0 to 25 cc kg <sup>-1</sup> in 18 hours	████	76% flow	2.7 hours
Maintaining steady concentration with no water movements	████	25% flow	3 minutes per hour
Maintaining 50 cc kg <sup>-1</sup> with full letdown	████	Not possible	40 minutes per hour
Allowing 50 cc kg <sup>-1</sup> to fall to 30 cc kg <sup>-1</sup> with full letdown	██	5 minutes per hour at minimum flow	Not possible

**Table 4:** Main system performance calculation results

87. One further notable transient considered in Ref. 17, is a mid-cycle shutdown. This is not a planned occurrence, but could occur. It involves a large boration followed by a corresponding dilution and therefore involves a large volume of water movements in a relatively short timescale. Various assumptions need to be made in order to calculate the impact of this (such as the time). During this event the hydrogen concentration varies, from an initial 45 to 41.6 and 41.4 cc kg<sup>-1</sup> after the boration and dilution respectively (but assuming that they happen straight after each other, which is unlikely). With other (more realistic) assumptions, these variations would be smaller or even non-existent. Assuming a high initial concentration (of 45 cc kg<sup>-1</sup>) is also conservative. The calculation therefore demonstrated that even these penalising transients can be accommodated by the system.
88. I am also content that these calculations respond to the queries raised in TQ-AP1000-1184 and 1230 (Ref. 20) and not adequately answered during Step 4, the latter asking specifically for evidence that the proposed system would work as intended.

Effects on Chemistry Control

89. While the calculations described above show that the plant requirements can be met by the **AP1000** hydrogen dosing system design, they do not show the impact on chemistry control. I asked for evidence of this in RQ-AP1000-1467 (Ref. 20). The response provided graphical representations of the coolant hydrogen concentrations during various plant operations, such as letdown, start-up and make-up. These showed that while the relevant targets and limits can be met, the process is more operator intensive than other PWRs. This is exemplified by Figure 3, which shows an example of a possible start-up hydrogen dosing scheme.



**Figure 3:** Example start-up hydrogen dosing scheme

90. This demonstrates one way (of many) of reaching 15 cc kg<sup>-1</sup> within 8 hours and 25 cc kg<sup>-1</sup> within 24 hours. In this example, four 30-minute batches are added in addition to continuous dosing. There is no safety detriment associated with not following the idealised injection rate in this graph; rather it demonstrates the additional operator actions and controls needed in this system design. I consider the potential consequences of maloperation in Section 4.2.6 of my assessment.
91. The main chemistry control concern with the original **AP1000** hydrogen dosing system identified during Step 4 (Ref. 2) was that it only had a batch addition mode. This would lead to a 'saw-tooth' hydrogen concentration, even during steady power operations. I am content that this has been resolved, as demonstrated by Ref. 19 and the response to RQ-AP1000-1467 (Ref. 20).
92. Westinghouse has recognised that because of the differences in the **AP1000** plant design for hydrogen dosing, the minimum surveillance frequency requirement for dissolved hydrogen needs to be increased compared to the EPRI Guidelines (Ref. 27), which are based upon other PWR designs for hydrogen addition. This increases the frequency from one to three times daily. In addition, the Primary Sampling System (PSS) features an online hydrogen meter to continuously monitor the concentration, and display this in the main control room. The adequacy of the PSS is the subject of a separate GDA Issue reported elsewhere (GI-AP1000-RC-02, Ref. 28); thus for the purposes of this assessment it has been assumed that the hydrogen meter performs as intended. I am therefore content that these additional arrangements for the **AP1000** design are suitable and sufficient.

#### **4.2.6 Performance During Faults**

93. In this part of my assessment I considered the impact on safety of the hydrogen dosing system malfunctioning due to failure or maloperation.

##### Effects of Over- or Underdosing

94. Ref. 19, supported by a range of calculations (including Refs 17 and 18), discussed the impact of a range of potential faults. Using the system design parameters, it is possible to show the impact on the plant if more or less hydrogen than intended is added.

These calculations all assumed the plant is at steady state (ie no letdown or make-up operations) and operating at power, therefore the only loss of hydrogen considered is via diffusion through the steam generator tubing. The value for unpassivated material is used. This is a reasonable (and conservative) approach, particularly for not considering start-up or shutdown events, where the consequences would be related to extending the timescales for those activities or would be constrained by the defined limits for power operation, and hence are of limited safety significance.

95. For loss of hydrogen events it was calculated by Westinghouse to take many hours to show an appreciable concentration change. This is because the losses of hydrogen are small compared with the inventory held within the large primary coolant mass. For example, the calculations show that it would take nearly 24 hours to decrease from 35 to 25 cc kg<sup>-1</sup>. Given the continuous monitoring and regular sampling for hydrogen (discussed above), such changes should become apparent before they become a cause for concern.
96. Ref. 19, nor the calculations referenced therein, did not consider the impact of a letdown operation coincident with loss of hydrogen dosing. This may be unlikely, but still credible. For example, should it be required to have a mid-cycle shutdown, up to 25% of the coolant may be let down and made up with water with no dissolved hydrogen. This would reduce the bulk coolant concentration to 75% of the starting value (so, for example, 25 would become 18.75 cc kg<sup>-1</sup>). If the failure were to occur during dilution back to criticality the effect may be even greater, depending on the volumes required.
97. For faults where more hydrogen than intended is added the results depend on whether the continuous or batch flow is considered. For example, assuming that the maximum continuous flow of █████ cc min<sup>-1</sup> is added, it was calculated to take 7.9 hours to increase from 25 to 35 cc kg<sup>-1</sup>. If losses through the steam generators are set to 0 this time decreased to 5.9 hours, and a further 14.8 hours is taken to reach the upper limit of █████ cc kg<sup>-1</sup>. For these continuous injection cases the possibility of operator intervention within the timescales necessary appears credible.
98. For batch additions the same may not be true given the much larger addition rates possible. These cases were not considered in Ref. 19, but under the same conditions as above the timescales would be reduced by a factor of five. So, even crediting the conservative losses through the steam generator, 25 to 35 cc kg<sup>-1</sup> would take 1.6 hours, plus a further 3 hours to reach █████ cc kg<sup>-1</sup>. While recovery actions would be available to the operator in these instances, such as isolating the hydrogen injection system or undertaking letdown and make-up operations, these could occur between the regular sampling (at 8 hourly intervals) and therefore are reliant on the continuous hydrogen meter.
99. From the discussion above, it is clear that faults with the continuous addition mode should be revealed by the proposed controls. I am not convinced that the same is true for faults associated with the batch addition. This may be resolved by detailed design aspects (such as interlocks) or operating procedures (for example, by using the installed meter to determine an anomalous rate of change), but these are not yet available. **I consider this to be an Assessment Finding:**

CP-AF-AP1000-RC-09 – The licensee shall provide suitable and sufficient controls over the hydrogen dosing system of the <b>AP1000</b> design which ensure that risks associated with malfunction or maloperation are reduced so far as is reasonably practicable.
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### Fault Analysis

100. Westinghouse has confirmed in response to RQ-AP1000-1380 (Ref. 20) that the hydrogen dosing system for the **AP1000** design is not required to operate during plant fault conditions.
101. TQ-AP1000-1230 (Ref. 16) asked Westinghouse for a list of potential faults with the **AP1000** hydrogen dosing system itself. The response was brief and incomplete. Ref. 19, provided a more comprehensive review in the form of an FMEA. This was a summary of a more comprehensive FMEA analysis. On the basis of this analysis, the main system failure modes relate to the loss of control over the rate of hydrogen addition. This results in loss of hydrogen control in some manner, but the effects are bounded by the calculations described above.
102. The latest version of the faults schedule for the **AP1000** design (Ref. 29) is contained within the PCSR, Chapter 8, Revision 0C. Based on the safety functions described in Section 4.2.3, loss of hydrogen dosing could result in failure of the pressure boundary (Loss of Coolant Accident (LOCA)), failures of the fuel cladding (resulting in increased doses) or increased corrosion products production and transport (resulting in increased doses). The scale of this is dependent upon the duration and extent of loss of control, but this could in extreme cases lead to a range of LOCA faults or leakage or Passive Residual Heat Removal (PRHR) or steam generator tube ruptures. These faults are considered within the faults schedule. More specific CVS faults, of which hydrogen dosing could be one cause, are also considered under fault 3.4.1 (failure of small lines) and 3.4.10 (failure to adequately control chemistry to manage dose rates). I am therefore content that loss of hydrogen dosing is adequately represented within the fault schedule.
103. In undertaking the work for resolving GI-AP1000-RC-03, Westinghouse has identified three specific operator actions that will receive assessment (by Westinghouse) as part of resolving the Human Factors GDA Issue, GI-AP1000-HF-01 (Ref. 30). These are related to changing the hydrogen gas cylinders, initiating a continuous injection and initiating a batch addition. It is welcome that these have been identified for further consideration, but they are outside the scope of this assessment to consider further.

#### **4.2.7 PCSR Update**

104. As noted in Section 2.2, GI-AP1000-CC-02 (Ref. 10) required Westinghouse to submit a consolidated PCSR and associated references to provide the claims, arguments and evidence to substantiate the adequacy of the **AP1000** design reference point. This would therefore include resolution of all 51 GDA Issues. This assessment does not consider the entirety of chemistry within the PCSR, but does judge whether the proposed changes as a result of resolving GI-AP1000-RC-03 are adequate. The changes identified by Westinghouse are detailed in Ref. 19.
105. The PCSR (Ref. 31) already contains a description of the requirements, technical basis and method of hydrogen addition. The additions provided a more detailed description of the system, supporting arguments and links to evidence that support why the design is adequate mainly via Ref. 19. I also confirmed that these changes were applied in the final consolidated PCSR (Ref. 32).
106. Purely in the context of resolving this GDA Issue, I am content that these changes are reasonable.

#### **4.3 Comparison with Standards, Guidance and Relevant Good Practice**

107. The standards considered as part of my assessment are defined in Section 2.4, and included in Tables 1 and 2.

108. The foremost standards considered for this assessment were the relevant SAPs (Ref. 6). I have considered these throughout my assessment. However, a summary of these is provided below:
- SC.2, SC.3, SC.4 and SC.6 relate to the production of an adequate safety case. I am content that Westinghouse has met the intent of these as part of the submissions provided to resolve this GDA Issue.
  - ECS.1 and ECS.2 relate to classification and categorisation. As described in my assessment I am content that Westinghouse has identified and then categorised the hydrogen dosing system based on its significance with regard to safety.
  - EDR.1 requires due account to be taken of the need for structures, systems and components to be designed to be inherently safe, or to fail in a safe manner, with potential failure modes identified using a formal analysis. I am satisfied that this has been considered to a degree appropriate for a generic design, with further consideration necessary by a future licensee.
  - ECH.1, ECH.2, ECH.3 and ECH.4 relate specifically to the chemistry aspects of safety cases. I am satisfied that Westinghouse has given due consideration to these expectations in resolving this GDA Issue, noting that related limits and conditions are considered as part of GI-AP1000-CC-01 (Ref. 11).

#### **4.4 Assessment Findings**

109. In line with the ONR guidance (Ref. 33), during my assessment three items were identified for a future licensee to take forward in its site-specific safety submissions. Annex 2 contains details of these.
110. 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. I have raised these items as Assessment Findings.

#### **4.5 Minor Shortfalls**

111. In line with the ONR guidance (Ref. 33), I have not identified any Minor Shortfalls.

#### **4.6 ONR Assessment Rating**

112. Not applicable.

## 5 CONCLUSIONS

113. This report presents the findings of the assessment of GDA Issue GI-AP1000-RC-03 relating to the hydrogen dosing system for the **AP1000** reactor.
114. The purpose of this report is to document the assessment of the submissions provided by Westinghouse, in order to come to a judgement regarding whether sufficient evidence has been provided to meet the intent of the GDA Issue, such that closure can be recommended.
115. In response to GI-AP1000-RC-03, Westinghouse provided a single main submission (Ref. 19) which summarised its case regarding the adequacy of the hydrogen dosing system of the **AP1000** design to safely support all modes of operation, including during faults. This was supported by a suite of documentation which contains further detailed evidence. In addition Westinghouse supplied responses to my RQs, providing additional clarification and evidence to support the main submission.
116. As a result of my assessment of these submissions, meetings and discussions with Westinghouse, and consultations with ONR colleagues in different technical areas, my conclusions are:
  - Westinghouse has identified the safety functions that the hydrogen dosing system in the **AP1000** design needs to provide and how these translate into specific dosing requirements during operations.
  - The evidence provided by Westinghouse demonstrated that the system is capable of meeting these requirements. This is principally based on a series of calculations which demonstrated that the system will operate as intended. This has removed the concerns that led to the raising of the GDA Issue during Step 4, regarding insufficient evidence for this method of addition.
  - Westinghouse has considered the likely faults associated with the system, including over- and underdosing and has demonstrated that, for the most part, these are relatively slow-acting and should be revealed by the controls in place. I am content that faster acting faults could be resolved through detailed design or operating procedures, so they do not fundamentally undermine the adequacy of the system.
  - In response to this GDA Issue, Westinghouse has proposed updates to the PCSR. I have reviewed these updates and am content that they accurately reflect the responses to the GDA Issue.
117. I have identified three Assessment Findings 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 and/or decisions to resolve.
118. Overall, on the basis of my assessment, I am satisfied that GDA Issue GI-AP1000-RC-03 can be closed.

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**Table 1:** Relevant Safety Assessment Principles considered during the assessment

SAP No.	SAP Title	Description
SC.2	Safety case process outputs	The safety case process should produce safety cases that facilitate safe operation.
SC.3	Lifecycle aspects	For each lifecycle stage, control of the hazard should be demonstrated by a valid safety case that takes into account the implications from previous stages and for future stages.
SC.4	Safety case characteristics	A safety case should be accurate, objective and demonstrably complete for its intended purpose.
SC.6	Safety case content and implementation	The safety case for a facility or site should identify the important aspects of operation and management required for maintaining safety and how these will be implemented.
ECS.1	Safety categorisation	The safety functions to be delivered within the facility, both during normal operation and in the event of a fault or accident, should be identified and then categorised based on their significance with regard to safety.
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.
EDR.1	Failure to safety	Due account should be taken of the need for structures, systems and components to be designed to be inherently safe, or to fail in a safe manner, and potential failure modes should be identified, using a formal analysis where appropriate.
ECH.1	Safety cases	Safety cases should, by applying a systematic process, address all chemistry effects important to safety.
ECH.2	Resolution of conflicting chemical effects	Where the effects of different chemistry parameters conflict with one another, the safety case should demonstrate that an appropriate balance for safety has been achieved.
ECH.3	Control of chemistry	Suitable and sufficient systems, processes and procedures should be provided to maintain chemistry parameters within the limits and conditions identified in the safety case.
ECH.4	Monitoring, sampling and analysis	Suitable and sufficient systems, processes and procedures should be provided for monitoring, sampling and analysis so that all chemistry parameters important to safety are properly controlled.

**Table 2:** Relevant Technical Assessment Guides considered during the assessment

Reference	Revision	Title
NS-TAST-GD-004	5	Fundamental Principles
NS-TAST-GD-005	7	Guidance on the Demonstration of ALARP (As Low As Reasonably Practicable)
NS-TAST-GD-035	4	The Limits and Conditions for Nuclear Plant Safety
NS-TAST-GD-051	4	The Purpose, Scope and Content of Nuclear Safety Cases
NS-TAST-GD-088	0	Chemistry of Operating Civil Nuclear Reactors
NS-TAST-GD-094	0	Categorisation of Safety Functions and Classification of Structures and Components



Annex 1: GDA Issue, GI-AP1000-RC-03 Revision 0 – Reactor Chemistry – AP1000®

**WESTINGHOUSE AP1000® GENERIC DESIGN ASSESSMENT**  
**GDA ISSUE**  
**HYDROGEN DOSING SYSTEM**  
**GI-AP1000-RC-03 REVISION 0**

<b>Technical Area</b>		<b>REACTOR CHEMISTRY</b>	
<b>Related Technical Areas</b>		Mechanical Engineering	
<b>GDA Issue Reference</b>	<b>GI-AP1000-RC-03</b>	<b>GDA Issue Action Reference</b>	<b>GI-AP1000-RC-03.A1</b>
<b>GDA Issue</b>	Demonstrate that the hydrogen dosing system in AP1000 has the capacity and capability to provide suitable control over the primary coolant hydrogen concentration during all operating modes and potential faults.		
<b>GDA Issue Action</b>	<p>Westinghouse to present a consistent and structured safety case containing suitable and sufficient evidence to support the AP1000 hydrogen addition system, or other means agreed with the regulator. This evidence should provide confidence that the system will meet the functional requirements of the plant under all modes of operation and anticipated transient conditions.</p> <p>Westinghouse should consider physical testing of the design if sufficient evidence cannot be provided by calculations. The case should include an analysis of the likely faults with the hydrogen addition system. This should include consideration of both under and over dosing of hydrogen.</p> <p>The arrangements, either engineered or administrative, to control these faults should be clearly highlighted. The faults should consider all modes of operation where the hydrogen addition system is required to function.</p> <p>With agreement from the Regulator this action may be completed by alternative means.</p>		

**Annex 2:** Assessment Findings to be addressed during the Forward Programme – Reactor Chemistry

Assessment Finding Number	Assessment Finding	Report Section Reference
CP-AF-AP1000-RC-07	The licensee shall ensure that any safety related conditions associated with starting hydrogen dosing to the primary coolant in the AP1000 design have been appropriately captured within the safety case.	Paragraph 79
CP-AF-AP1000-RC-08	The licensee shall provide evidence that the design parameters for the hydrogen dosing system of the <b>AP1000</b> design are adequate to meet both the steady state and transient requirements of the safety case, and reduce risks as low as is reasonably practicable.	Paragraph 84
CP-AF-AP1000-RC-09	The licensee shall provide suitable and sufficient controls over the hydrogen dosing system of the <b>AP1000</b> design which ensure that risks associated with malfunction or maloperation are reduced so far as is reasonably practicable.	Paragraph 99