Generic Design Assessment – New Civil Reactor Build

Resolution of GI-AP1000-FD-01
Fuel Pin Modelling Safety Justification

Assessment Report ONR-NR-AR-16-006
Revision 0
March 2017

Published 03/17

LIST OF ABBREVIATIONS

AP1000	Westinghouse Advanced Pressurised Water Reactor
ALARP	As Low As Reasonably Practicable
ASTRUM	Westinghouse Automated Statistical Treatment of Uncertainty Method
BMS	(ONR) How2 Business Management System
EA	Environment Agency
IAEA	International Atomic Energy Agency
LBLOCA	Large-Break Loss of Coolant Accident
LWR	Light-water Reactor
NPP	Nuclear Power Plant
ONR	Office for Nuclear Regulation
PAD	Westinghouse fuel performance computer code
PCI	Pellet-Clad Interaction
PCSR	Pre-construction Safety Report
PSR	Preliminary Safety Report
RI	Regulatory Issue
RP	Requesting Party
RQ	Regulatory Query
SAP	Safety Assessment Principle(s)
TAG	Technical Assessment Guide(s)
TCD	Thermal Conductivity Degradation with irradiation
US NRC	United States Nuclear Regulatory Commission
WENRA	Western European Nuclear Regulators' Association

EXECUTIVE SUMMARY

This report presents the findings of my assessment of Westinghouse's submissions to support resolution of GDA Issue GI-AP1000-FD-01; Fuel Pin Modelling Safety Justification. The issue was raised in order to request that Westinghouse should:

> *Provide comprehensive documentation demonstrating that predictions of temperatures for fresh fuel will in all cases exceed the expected temperatures of irradiated fuel, including allowances for uncertainty and also demonstration that fission gas release predictions are pessimistic after suitable allowances.*

In order to ensure this, a suitable constraint on fuel power ratings as a function of irradiation, is required.

The intent was to set and substantiate limits and conditions of operation consistent with the assumptions of the current fault analysis. However ONR recognised that the underlying safety requirements can be achieved by other means than those specified above.

Westinghouse's response to this issue has been to develop and validate an updated fuel model with a number of the shortcomings of the old model addressed providing improved representation of the physical processes governing fuel behaviour. This removed the need to demonstrate fresh fuel is limiting in terms of safety margin, but introduced a need to adequately represent the physical processes taking place in the fuel.

I have examined the documentation provided as part of Westinghouse's response to determine whether it meets UK expectations as set down in the SAPs and TAGs. My conclusions are as follows:

- Westinghouse has added reasonable models to those already available in the PAD fuel performance code.
- The PAD code has been qualified against an extended database of information from experiment, monitoring and post-irradiation inspection and is now a significantly better representation of the fuel performance data.
- The extent of the revised dataset used to validate PAD is clearly defined and now encompasses the region fuel is likely to experience in operation.
- The code documentation is a significant step forward, but still relies for completeness on extensive records of correspondence with US NRC. This somewhat obscures the link between safety limits and underling qualification of uncertainty. However, because the code is mainly used by the developers, I regard this as a minor shortfall to be rectified in the next release of the documentation.
- The revised models are judged to be a satisfactory basis for substantiating operating limits for the fuel.

Notwithstanding the above, the application of PAD 5 to the analysis of the large loss-of-coolant accident analysis is not yet complete and will be addressed in the context of a GDA issue in the fault study topic area.

TABLE OF CONTENTS

Annex(es)

TABLE(S)

1 INTRODUCTION

1. The objective of my Fuel and Core Design assessment for the UK AP1000 REACTOR is to review the information provided and to judge whether the arguments made by the Requesting Party (RP) related to Fuel and Core Design that underpin the safety claims are complete and reasonable in the light of our current understanding of reactor technology. This assessment report addresses the topic of modelling the fuel pin. Such models are used to set operating limits on the core design and hence preserve fuel integrity in normal operation and anticipated faults.

2. As part of Generic Design Assessment, I noted that the documentation for the PAD code consisted of a sequence of reports detailing individual model developments and I concluded that the basis for the modelling practices used may have become obsolete. I therefore raised a regulatory issue (Ref. 1), intended to ensure that the assumptions used to set the design limits remain valid:

   - There is a need to provide comprehensive documentation demonstrating that PAD predictions of temperatures for fresh fuel will in all cases exceed the expected temperatures of irradiated fuel, including allowances for uncertainty.
   - Further, that fission gas release predictions are pessimistic after suitable allowances. In order to ensure this, a suitable constraint on fuel ratings as a function of irradiation needs to be qualified and adopted.

3. There were a number of actions requiring Westinghouse to demonstrate that suitable constraints were placed on the core design to underpin the assumption that fresh fuel conditions were bounding in terms of fault transient response and also to quantify the uncertainty associated with the fission-gas release model.

4. The intent of underpinning the fault analysis and setting limits and conditions of operation can of course be achieved by other means.

5. Westinghouse's response to this issue has been to develop an updated fuel model with a number of the shortcomings of the old model addressed and hence to better represent the physical processes governing fuel behaviour.

6. I have examined the documentation to determine whether it meets UK expectations as set down in the ONR Safety Assessment Principles (SAP)s and Technical Assessment Guides (TAG)s.

7. In response to my regulatory observation, Westinghouse has made a number of technical submissions (Refs. 8 to 10) in which a set of design limits are proposed and justified. The present report details my assessment of these submissions.

8. For resolution of Regulatory Issue GI-AP1000-FD01, the "safety arguments" are interpreted as being:

   - The fuel is designed and operated to comply with a set of functional requirements and that safety limits constrain plant operation so that release of radioactive materials is either prevented or remains within acceptable limits.
   - The resilience of fuel in normal operation and faults is assured by operating limits based on analysis of postulated faults against a defined set of fuel design criteria.
   - The PAD fuel performance code adequately represents the principal physical processes governing fuel performance and is therefore suitable for use in analysis intended to support the setting of operating limits.

9. I have assessed the submission against the following expectations:

- The models and correlations defined within the PAD code are consistent with the current state of knowledge.
- That the models have been verified against data and analytical information as appropriate and that the validity of the code has been tested against experimental results and plant data.
- That the uncertainty associated with code predictions has been quantified and that limits of validity are clearly defined.
- Where assumptions imply limits of validity of the analysis, this is translated appropriately into limits on fuel operation.

2 ASSESSMENT STRATEGY

10. The intended assessment strategy for assessment of the fuel and core aspects of the AP1000 GDA is set out in Ref. 2. My approach specific to this regulatory issue is given below. This identifies the scope of the assessment and the standards and criteria that have been applied.

2.1 Standards and Criteria

11. The goal of the assessment is to reach an independent and informed judgment on the adequacy of the arguments that underpin the nuclear safety case. For this purpose, within ONR, assessment is undertaken in line with the requirements of the How2 Business Management System (BMS) document PI/FWD (Ref. 3) which sets down the process of assessment within ONR and explains the process associated with sampling of safety case documentation.

12. The relevant standards and criteria adopted within this assessment are principally the Safety Assessment Principles (SAP) (Ref. 4), internal ONR Technical Assessment Guides (TAG) (Ref. 5), relevant national and international standards and relevant good practice informed from existing practices adopted on UK nuclear licensed sites. The key SAPs and any relevant TAGs are identified within this section. National and international standards and guidance have been referenced where appropriate within the assessment report. Relevant good practice, where applicable, has also been cited within the body of the assessment.

13. The Safety Assessment Principles (SAPs) (Ref. 4) constitute the regulatory principles against which duty holders' safety cases are judged, and, therefore, they are the basis for ONR's nuclear safety assessment.

14. Furthermore, ONR is a member of the Western Regulators Nuclear Association (WENRA). WENRA has developed Reference Levels, which represent good practices for existing nuclear power plants, and Safety Objectives for new reactors.

15. Therefore, the standards and criteria that will be used to judge the adequacy of the arguments in the area of Fuel and Core Design for the UK AP1000 REACTOR include (see also Annex 1 for further details):

- ONR's Safety Assessment Principles (SAPs) (Ref. 4) including: SAPs EKP, ERL, EAD, FA, and ERC.
- Relevant IAEA standards (Ref. 6):
    - Fundamental Safety Principles. IAEA Safety Standards Series, SF-1, IAEA Vienna, 2006.

    - Design of the Reactor Core for Nuclear Power Plant, IAEA Safety Guide, NS-G-1.12, IAEA, Vienna 2005.
    - Safety of Nuclear Power Plants: Design, Specific Safety Requirements, IAEA Standards Series No. NS-R-1c IAEA, Vienna (2012).
- WENRA references (Ref. 7):
    - Reactor Safety Reference Levels (January 2008);
    - Safety Objectives for New Power Reactors (December 2009) and Statement on Safety Objectives for New Nuclear Power Plants (November 2010);
    - Statement on Safety Objectives for New Nuclear Power Plants (March 2013); and
    - Safety of New NPP Designs (March 2013).

16. The above SAPs, relevant IAEA standards and WENRA reference levels are embodied and enlarged on in the Technical Assessment Guides (Ref. 5). These guides provide the principal means for assessing the Fuel and Core Design aspects in practice. The following Technical Assessment Guides have been used as part of this assessment:

- NS-TAST-GD-005, Guidance on ALARP (As Low As Reasonably Practicable)
- NS-TAST-GD-042, Validation of computer codes and calculation methods.
- NS-TAST-GD-075, Safety Aspects Specific to Nuclear Fuel in Power Reactors.

3 LICENSEE'S SAFETY CASE

17. The principal design tool used by Westinghouse for evaluating fuel rod performance is the Performance Analysis and Design (PAD) code. This is used to calculate the stress in the fuel cladding and the degradation of the fuel matrix in the reactor. It is also used to calculate fuel stored energy and temperatures for use in other models. The models and correlations in the PAD code are detailed in Ref. 9, with further information provided in a supporting information package Ref. 10.

18. This computer program iteratively calculates the interrelated effects of fuel and cladding deformations including fuel densification, fuel swelling, fuel relocation, fuel rod temperatures, fill and fission gas release, and rod internal pressure as a function of time and linear power.

19. PAD is supplied with the power history of a fuel rod as a series of steady-state power levels. The length of the fuel rod is divided into several uniform axial segments.

20. Fuel densification and swelling, cladding stresses and strains, temperatures, burnup and fission gas releases are calculated separately for each axial segment and the effects are integrated to obtain the overall fission gas release and resulting internal pressure for each time step.

21. The coolant temperature rise along the fuel rod is calculated based on the flow rate and axial power distribution, and the cladding surface temperature is determined with consideration of potential effects of corrosion and local boiling. The fuel pellet is modelled as a solid cylinder with allowances for dishing, edge chamfering and pellet chipping.

22. A compilation of the licensing basis documentation for all of the significant PAD fuel and clad performance models is provided in Ref 9.

23. Westinghouse argues that the model updates incorporated into the PAD5 code address all of the fuel and cladding performance models required for high burnup fuel design. Key fuel performance updates to the PAD5 models include: fuel Thermal Conductivity Degradation (TCD) with burnup, enhanced high-burnup athermal fission gas release (pellet rim effects) and enhanced high burnup fission gas bubble swelling. Cladding creep and growth models are also updated to reflect high burnup cladding performance.

3.1 Validation Data

24. Validation data are provided to demonstrate the acceptability of the individual fuel and clad performance models. Fuel performance data has been obtained over the past five decades from a number of sources.

25. Commercial reactors provide a substantial portion of the in-reactor fuel performance database. This has been obtained from both on-site and hot cell examinations to characterise fuel and cladding behaviour under normal operation conditions.

26. In addition, test reactor programs have been used for the examination of fuel and cladding performance under off-nominal conditions, such as transient power increases or very high power operation.

27. For each PAD5 performance model, data selected from the database has been segregated into two sets: one for model Calibration and one for Validation.

28. The PAD5 fuel performance models are substantiated for application to a rod average burnup up to 62 MWd/kgU for all ZIRLO™ rods and higher for Optimized ZIRLO™ cladding. The extent of the qualification is sufficient for current requirements of the UK AP1000 design.

29. The database used to validate the PAD 5 for fuel temperature predictions includes test data obtained from rods refabricated and tested in the Halden reactor. The data includes samples obtained by all three measurement approaches currently available to the industry. The combination of all of these data provide a substantial database that bounds both open gap and closed gap operation conditions.

3.2 Modelling Details

30. The major performance models in PAD5 are discussed in Sections 3 through 6 of Ref. 9. These can be categorised as follows:

- Thermal Model, including Thermal Conductivity Degradation;
- Gas Release and Internal Pressure Model;
- Fuel and Clad Deformation Models; and
- Fault Transient Modelling.

3.3 Thermal Model

31. The thermal model includes a simple convection model that is tuned to more complex subchannel models and uses well established correlations.

32. The surface heat transfer makes allowance for forced convection and boiling processes and employs optional empirical models to account for the thermal

resistance of any crud that might be present on the clad surface in both convection and boiling conditions.

33. The oxide film thickness is correlated as a simple function of a boiling duty index and the 95% probability upper-bound oxide thickness is evaluated based on an extensive operational data base.

34. The conductance of the pellet-clad gap takes account of the efficiency of energy interchange between solids and gases and also the contact pressure between the pellet and the cladding when the gap is closed. The modelling of the open gap width takes account of the potential for fuel fragmentation and the relocation of fragments (which reduces the size of the effective gap). Westinghouse argues that this model is similar to others developed based on temperature measurements made at Halden.

35. The radial power distribution in the PAD fuel pellet is a tabulated function of fuel burnup and burnable absorber loading. The parameters for these functions are calculated by a suitable reactor physics code.

36. The pellet thermal conductivity is derived from the model developed at Halden, as implemented in the STAV 7.3 code.

3.4 Internal Pressure Model

37. The release of fission gas from the fuel pellet is modelled as a process of release via interlinked gas bubbles at the grain boundaries. The model is empirical and has threshold temperatures for release that are defined as piece-wise linear functions of burnup.

38. In addition, a low-temperature, athermal release model is included, which has a simple empirical function of burnup, including an enhancement at high burnup.

3.5 Fuel and Clad Deformation Models

39. The cladding deformation model takes account of plasticity as well as thermal creep and irradiation growth. The thermal creep model includes a primary creep phase and the models are calibrated against a limited body of data.

40. The fuel creep model includes fuel swelling and densification. It is essentially unchanged for PAD5, but is tuned to a wider set of data than previously.

3.6 Fault Transient Modelling

41. The fault transient response of the fuel involves models other than PAD and these may be peripherally affected by the changes to the modelling in PAD where this involves the supply of fuel data. Information on the safety analysis methods and preliminary results are found in Westinghouse's response to RQ-AP1000-1295 and in particular, the effect of thermal conductivity degradation is discussed in Ref. 8.

42. Westinghouse argues that the models used to predict core kinetic response are based on the results of 3D core neutronics codes, which take account of fuel burnup appropriately. These codes have been confirmed to be consistent with actual plant measurements for plants similar to AP1000 REACTOR and are therefore not affected by the PAD modelling regulatory issue.

43. More generally, Westinghouse argues that the inclusion of fuel pellet thermal conductivity degradation has a negligible impact on the transient core thermal response for most fault analyses. The significant exception is the large-break loss-of–

coolant accident (LBLOCA); where stored energy in the fuel significantly influences heat transfer.

44. Westinghouse has adjusted their Automated Statistical Treatment of Uncertainty Method (ASTRUM) LOCA model to account for thermal conductivity degradation with irradiation.

45. Westinghouse argue that the global thermal-hydraulic behaviour of the AP1000 plant LBLOCA response is not substantially impacted by modelling fuel pellet thermal conductivity degradation (TCD) and the primary effect of TCD on the LBLOCA transient is on the magnitude of the hot rod peak cladding temperature response.

46. The modelling approach is documented in an attachment to their core evaluation report (Ref. 10). Fuel pellet thermal conductivity degradation (TCD) and peaking factor burndown were not explicitly considered in the standard LBLOCA analysis, but this has been rectified for the calculations presented in (Ref. 10).

47. To demonstrate that the AP1000 plant continues to meet the acceptance criteria, changes were made to the statistical uncertainty method to explicitly consider and adequately account for the burnup-dependent aspects of the fuel performance changes caused by representing TCD. Specifically, the following changes were made:

- Fuel performance data which explicitly accounts for the effects of TCD was used as input, into the LBLOCA thermal-hydraulic models: COBRA/TRAC and HOTSPOT.
- The prediction of the peak cladding temperature is evaluated by sampling the likely operating conditions as they vary with burnup and the 95% probability level identified on a conservative basis.
- Hot rod and hot assembly peaking factor burndown is explicitly accounted for to avoid an over-conservative representation of the fuel.

48. The results of calculations based on a preliminary version of the TCD model indicate that acceptable margins to the fuel design criteria for LBLOCA are maintained.

4 ONR ASSESSMENT

49. This assessment has been carried out in accordance with HOW2 guide NS-PER-GD-014, "Purpose and Scope of Permissioning" (Ref. 3).

4.1 Scope of Assessment Undertaken

50. The purpose of my GDA Regulatory Issue was to ensure that the limits on fuel operation demonstratively reflect the performance of fuel over the range of irradiations and in core designs now practiced. This has been achieved by increasing the fidelity of the fuel modelling used to set the limits and increasing the extent of the validation data.

51. My intention in this assessment has been not to repeat assessment previously undertaken during Step 4 of GDA (Ref. 1). However in order to satisfy myself that the issues raised have been resolved, I judge it necessary to complete a systematic assessment of the models present in the PAD5 fuel performance code. This is particularly so given that the code contains a set of sub models that are substantially inter-related and much of the tuning of parameters has been based on the integral performance of the code. Nevertheless, my approach remains that of sampling and the level detail of my assessment has been informed by my judgements on the novelty and safety significance of the topics.

52. Westinghouse has qualified their models, but has not explicitly demonstrated the effect of using PAD5 on safety margins in fault studies. I have therefore largely confined myself to confirming that the models in PAD5 are suitable for use in determining the safety margins and have not confirmed the adequacy of proposed operating limits with this version of the code. This remains to be done when the revised analysis is presented as part of assessment of a revised PCSR.

53. Westinghouse has provided copies of information supplied to US NRC in relation to safety margins based on an interim version of PAD (Ref. 8) and I have based my assessment of the likely adequacy of the safety case on this information.

54. The functional requirements of fuel are set out in TAG075. Briefly, I expect that the reactor core will be operated in such a way as to maintain the fuel cladding intact or where this is not practicable, to limit release of fission products from the fuel to acceptable levels.

55. The PAD computer code is used by Westinghouse to predict cladding stress and fission-gas release. The results of PAD analysis are used to set limits on code power shape and fuel discharge irradiations. These limits are used to set operational rules and parameters in automatic protection systems.

56. PAD predictions are also used to provide data for use in fault analysis codes which demonstrate the adequacy of the safety injection system.

57. My focus has been to ensure that Westinghouse can demonstrate with a high level of confidence that calculation methods used for the analyses adequately represent the physical processes taking place and that where uncertainty in the data exists, an appropriate safety margin is provided (see SAPs AV1-3).

58. In order to facilitate the above, ONR expects that documentation should be provided to facilitate review of the adequacy of the analytical models and data. The requirements for verification and validation of computer codes used for safety analysis are set out in TAG042 and this is used to inform my expectations.

4.2 Validation Data

59. In accordance with the requirements of SAP AV.3, Westinghouse has taken measures to demonstrate that the modelling used is valid under relevant circumstances. Uncertainty in the data has been systematically quantified and the limits of applicability of the fuel rod model are defined in terms of key parameters such as fuel grain size, gadolinium loading and uranium enrichment. From my experience, the parameter ranges claimed as valid are likely to encompass modern light water reactor fuel. I am therefore satisfied that the limits of applicability of the data has been identified and respected.

60. The qualification of individual models is considered below, with particular attention to whether the requirements of AV.5 are met by the documentation; that it permits review of the adequacy of the models and data.

4.3 Thermal Model

61. I recognise the convective and boiling models employed as appropriate to PWR operating conditions. However, details substantiating the crud thermal model were brief. This model is present explicitly when calculating the oxide-metal interface temperature in the cladding corrosion model for Zircaloy 4 and is not used for ZIRLO™; where boiling is implicitly accounted for in the corrosion model as a correlation parameter. I examined the corrosion model and found it to be essentially empirical and supported by a commendable body of data. I am therefore satisfied with this and with the quantification of uncertainty for this model.

62. The crud model can also have an impact on the cladding surface temperature and hence the cladding creep rate. I therefore considered whether the omission of an explicit crud thermal resistance model for ZIRLO™ cladding is appropriate and asked for further justification (RQ-AP1000-1319).

63. Westinghouse argues that there is little difference between the behaviour of the oxide and coherent crud in the context of surface heat transfer and in practice, the in-pond measurement techniques do not generally discriminate between oxide and crud. The oxide thicknesses measured in practice encompass the crud; which in normal-chemistry conditions is thin (Ref. 12). I accept this argument as reasonable provided that control of crud deposition is maintained. I have already raised two assessment findings requiring the licensee to carry out surveillance on this topic (Ref. 1) and therefore I am content with the model.

64. I considered the cladding-pellet gap model in the context of information found in Ref. 11 and my previous experience with such models. The Westinghouse gap-conductivity model is based on reasonable arguments and bisects two correlations of published data. The correction for the efficiency of heat transfer between solids and gases has the recognised form. The gap model also includes a term to account for fuel pellet fragmentation and radial movement. The model is reasonable and essentially empirical. Westinghouse relies on the overall qualification of pin temperature predictions to substantiate this. The model is tuned to the pellet centre temperatures of fresh fuel on the basis that the fuel conductivity of fresh UO2 is well characterised and variations are likely to be due to changes in geometry. The model assumes that fuel fragmentation stops at approximately 10 MWd/kgU. I accept this on the basis of my experience of characterising pellet fragmentation.

65. Particular models apply to the conditions present when the pellet-cladding gap has closed. Ref. 11 suggests that when clad pellet gap closes, heat transfer is good and substantially independent of the fill gas composition and pressure since it corresponds to a solid bond between fuel and cladding. There is some debate as to

whether or not the conductance depends on interfacial pressure, but since this model will have little effect, I have not pursued this.

66. The change in the thermal conductivity of the pellet with irradiation is not discussed in detail in the topical report. This is a shortfall in the completeness of the document, but I do not consider it to be serious. It is adequately discussed in documentation responding to USNRC comments (Ref. 10). The document demonstrates improved agreement with measured fuel-rod centre temperatures as a result of the new model.

67. I examined the qualification data for any adverse trend with linear rating. Fuel centre line temperatures are well represented across the range of burnup and for linear ratings up to around 25 Kw/m, after which some over-prediction of temperatures starts to be suggested. Generally a slight over prediction of the temperature will be pessimistic and therefore this is not a serious issue.

68. The experimental data is also used to qualify upper and lower-bound fuel thermal conductivity for use in pessimistic calculations. These pessimistic values appear to represent the limits of the data adequately.

69. Overall, I am satisfied that the thermal model adequately represents the physical processes taking place within the fuel and that uncertainty in the data is adequately represented.

4.4 Pellet Radial Power Profile

70. I recognise that an empirical approach based on data from a suitable physics code, is the most practical approach; especially where a variety of burnable poison methods need to be represented. I support the approach adopted.

71. I have not chosen to independently confirm the values used because they look plausible based on my experience and I judge that any uncertainty is likely to have a second order effect on current safety margins.

4.5 Internal Pressure Model

72. The fission-gas release model is essentially empirical and includes components to represent the main physical effects. The model has been recalibrated to be consistent with the revised fuel pin thermal model.

73. The qualification data includes a significant degree of uncertainty (as I expected) and I judge that the determination of the level of uncertainty is appropriate.

4.6 Fuel and Clad Deformation Models

74. Cladding yield stress is based on an irradiation-hardening model, taken from the general literature and supported by a modest amount of data.

75. The fuel rod irradiation creep model is a simple empirical representation of an athermal process. Westinghouse has tuned this to a substantial body of irradiation data for ZIRLO™ and qualified it against a similar body. Westinghouse has demonstrated that there is some observed variation in cladding growth rate with material composition within the range of the specification spanning ZIRLO™ and Optimised ZIRLO™. Westinghouse has not explicitly considered this dependency in design studies, but has set upper and lower bound values of growth rate based on data from a number of plants. I asked for justification of this approach. Westinghouse

advised that their sensitivity studies indicate that this effect actually provides a small part of the total diameter change and that the uncertainty in the diameter growth due to chemistry and processing variations is accounted for in the overall creep model uncertainty (Ref. 14). I judge this particular model to be of low safety significance and the response to be adequate.

76. The fuel swelling and densification models are also qualified against moderately large body of data and this is used as a basis to quantify uncertainty. Overall, I consider the qualification of the creep model to be adequate.

4.7 Fault Performance Modelling

77. Westinghouse has addressed the issue of thermal conductivity degradation by responses to US NRC regulatory questions. They have systematically considered the impact of this phenomenon on the fault studies results.

78. Westinghouse has recognised that the fuel temperatures can increase with irradiation as a result of TCD, but argue that this will be mitigated by a reduction in power density associated with the depletion of ^{235}U. They argue:

For current PWR reload core designs, the maximum peaking factors typically occur in the fresh fuel, which at low burnups is not significantly affected by TCD and normally, the power in fresh fuel declines with burnup because of reactivity depletion effects. For fuel having a burnup greater than 30 MWd/kgU, the power is significantly less than the peak power rod since the fuel is not sufficiently reactive to sustain high power levels or peaking factors near the limits assumed in the safety analysis. This has been confirmed by reviewing core depletion calculations for the initial cycle of AP1000 plants and representative reload core designs.

79. In order to quantify this reduction in rating, Westinghouse has calculated the rate of change in linear rating in the AP1000 reference core design and this rate of depletion has been applied to the generic limit on radial form factor normally employed as a core-design constraint. The resulting fuel local rating constraint has been used in combination with the TCD to argue that the overall effect of TCD is generally not significant.

80. I judge that the bounding rating shape is plausible, but this approach might not fully allow for the potential for high ratings in second-dwell fuel should a licensee diverge from Westinghouse’s current core design practice. The licensee will need to formally recognise the constraint that they have assumed on the core design by placing a limit on the fuel linear ratings. Westinghouse has advised that this is controlled by a Core Operating Limits Report (COLR) which is updated for each cycle and referenced by the Technical Specifications. I am therefore satisfied that this generic argument is likely to be supportable and on this basis, I have not raised an assessment finding because I consider the topic covered by regulatory issue CC-001 and my finding AF-AP1000-FD-01 (Ref. 1), which requires identification of limits on the core design.

81. Westinghouse has considered fault groups in turn to determine the effect of TCD on the performance of the fuel models in order to identify the shortcomings in the existing analysis methods (Ref. 10).

82. In most reactivity faults, the simplified models employed are based on more complex core model results, which explicitly include appropriate modelling. For some events, additional allowances are added to the minimum or maximum values for the Doppler coefficients and Doppler defects which are conservatively selected on an event-specific basis.

83. I am familiar with the qualification of the reactor physics model ANC, which is used as the basis for the simplified core performance data. I am satisfied that this code is a suitable representation of general core neutronic performance. I am therefore content with this argument.

84. The main topic that required further study was the large-break loss-of-coolant accident (LBLOCA). This is considered in detail below.

4.7.1 Modelling LBLOCA

85. In analysis to date (e.g. Ref. 16), the prediction of performance of the average core uses stored energy data from PAD 4 and does not account for thermal conductivity degradation. This means that the stored energy of the core is under-predicted, the critical heat flux is reached late and the heat removed during the blow-down phase of the LBLOCA is over-predicted by WCOBRA/TRAC. Westinghouse carried out a sensitivity calculation (with the conductivity corrected and constraints on core power shape tightened). The analysis showed that accepting tighter power constraints, the peak cladding temperature for the average rod is about 50^0C too low in the original analysis, but the change also affected the rate of blowdown, which resulted in earlier reflood. The net effect on the peak temperature in reflood was essentially neutral.

86. I accept that the sensitivity study supports the claim of the adequacy of the safety injection system, although I expect that if the full analysis needs to be repeated for any reason, then it should fully utilise the new modelling in PAD 5. I do not consider that requiring this is necessary at this stage.

87. The hot assembly model is sensitive to stored energy and this analysis has been revised. Westinghouse model the effect of burnup in the fault - not by taking the most limiting operating condition - but by sampling a uniform distribution of burnup values (on the assumption that the fault does not become more likely over time). I accept this approach on the basis that the fault is judged to have a low probability and introducing limiting operating conditions for all operating parameters is unduly pessimistic.

88. A number of assumptions are made relating peak assembly irradiation to that of the average core. These appear to be reasonable simplifications.

89. The overall approach is to define a function relating limiting core radial form factors to core irradiation and to use this as a constraint for core design. The limit defined appears to be a reasonable approach to providing an interface between fault studies and core design and is similar to limiting rating envelopes used in fuel design more widely. I consider the approach acceptable in principle.

90. Ref.10 states that for the LOCA calculation, WCOBRA/TRAC employs its own conductivity model. The document claimed that the models are in close agreement, but did not provide evidence. I therefore requested further information on the qualification of the LOCA model. In response to RQ-AP1000-1320 (Ref.13), Westinghouse provided a comparison of the WCOBRA/TRAC model against the PAD TCD model (which in turn has been satisfactory qualified against operational data. There is no significant difference between the predictions of the models and therefore I am satisfied that the model within WCOBRA/TRAC is a suitable representation of the physical processes.

91. The initial conditions for the LOCA are calibrated by setting the gap width to match between WCOBRA/TRAC and PAD volumetric average temperatures. The internal pressure is specified to be consistent with PAD predictions.

92. The original LOCA analysis used a statistical sampling of time in cycle as part of its uncertainty qualification and fuel modelling was originally confined to the first cycle of irradiation. However the sampling has been extended to second cycle; including both the effects of TCD and burndown.

93. Results of analysis of the base-case LBLOCA transient (based on an interim version of PAD) have been supplied to ONR. The peak cladding temperature in the analysis increased from 1080^{0}C to 1120^{0}C. This is significant compared to a design limit of 1204^{0}C.

94. For the UK, we required that a sensitivity study should consider the effect of an unrevealed check valve failure. This analysis was provided in Ref. 16 and shows acceptable PCT results.

95. On the basis of the information supplied, I judge that a safety case is likely to be made, but there may be some need to adjust constraints on core designs.

96. In the containment modelling, Westinghouse assumes that the advanced first core is bounding in terms of energy release. This is not substantiated, so I queried this assumption. Westinghouse advised that core stored energy is not a significant part of the energy released prior to peak containment pressure being reached and the calculation used is substantially conservative (Ref. 13). I judge that this response is satisfactory.

4.8 Documentation

97. The safety case documentation related to PAD 5 is generally well written and concise, with only a small number of omissions. The main reference supporting PAD refers to design criteria used in the USA relating to PCI failure. In the UK there are additional criteria that have been the subject of GDA assessment and are not mentioned.

98. Documentation relating to the LBLOCA details measures taken to address shortcomings in historic calculations using responses to regulatory questions without revision of the original code qualification reports.

99. While this documentation is satisfactory as an interim measure, I judge that it is potentially confusing for the code user and informed customers for the analysis. I judge that the analysis work needs to be consolidated into more coherent documents. I do not believe that this needs to be done urgently because final selection of a core design will occur late in the project. However, a potential licensee needs to consider how to provide documentation that will meet UK expectations as part of a suitable safety case. I have therefore identified an assessment finding requiring a potential licensee to revise the documentation as follows:

AF-FD-GDA 021 Fuel Pin Modelling Documentation

The licensee shall revise the existing documentation on fuel pin modelling to provide a comprehensive and coherent set of documents to facilitate review of the adequacy of the analytical models, calculation methods and data, taking into account the UK expectations and consolidating information currently found in the correspondence record of code assessment.

5 CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

100. This report presents the findings of the ONR assessment of Westinghouse's submission (Refs 9,10 & 11) seeking resolution of GDA issue GI-AP1000-FD-01; Fuel Pin Modelling Safety Justification.

101. To conclude, I am broadly satisfied with the claims, arguments and evidence laid down within the RP's safety case satisfies the requirements of ONR SAPs and relevant TAGs (in particular TAG 42 relating to computer codes) .

102. Resolution has been achieved by increasing the fidelity of the fuel modelling used to set fuel design limits and increasing the extent of the validation data. A revised version of the fuel performance code PAD 5 has been issued and documented. The documentation is generally good, but needs to be updated to incorporate technical arguments currently documented in correspondence if the code is to be used by staff outside the development team at Westinghouse.

103. The PAD code is used to define safety limits by the application in fault analysis and this process has not yet been completed for UK LBLOCA studies using PAD 5. However, studies performed to date indicate that this is likely to be successful. This will be resolved within the scope of the fault studies assessment.

5.2 Recommendations

104. My recommendations are as follows.

- Recommendation 1: That ONR accept that Regulatory Issue UKAP1000-FD-001 is now closed.

- Recommendation 2: That ONR accept the following finding:

  The licensee shall revise the existing documentation on fuel pin modelling to provide a comprehensive and coherent set of documents to facilitate review of the adequacy of the analytical models, calculation methods and data, taking into account the UK expectations and consolidating information currently found in the correspondence record of code assessment.

- Recommendation 3: That ONR reviews the revised analysis of the LBLOCA accident when performed with new data from PAD5 in support of a consolidated PCSR.

6 REFERENCES

1. *Step 4 Fuel and Core Design Assessment of the Westinghouse AP1000® Reactor*, ONR-GDA-AR-11-005, TRIM REF. 2010/581526.

2. *UK AP1000 Assessment Plan for Closure GDA Fuel Design Issues 1 to 3*, ONR-GDA-AP-15-001 Revision 0, January 2015. TRIM REF. 2015/69477.

3. *ONR How2 Business Management System. BMS: Permissioning – Purpose and Scope of Permissioning*. PI/FWD – Issue 3. August 2011

4. *Safety Assessment Principles for Nuclear Facilities*. 2014 Edition Revision 0. November 2014. http://www.onr.org.uk/saps/saps2014.pdf

5. *Technical Assessment Guides:*

ONR Guidance on the Demonstration of ALARP, NS-TAST-GD-005.

Validation of computer codes and calculation methods, NS-TAST-GD-042.

Safety of Nuclear Fuel in Power Reactors, NS-TAST-GD-075.

http://www.onr.org.uk/operational/tech_asst_guides/index.htm

6. IAEA guidance –

Fundamental Safety Principles. IAEA Safety Standards Series, SF-1, IAEA Vienna, 2006.

Design of the Reactor Core for Nuclear Power Plant, IAEA Safety Guide, NS-G-1.12, IAEA, Vienna 2005.

Safety of Nuclear Power Plants: Design, Specific Safety Requirements, IAEA Standards Series No. NS-R-1c IAEA, Vienna (2012).

www.iaea.org.

7. *Western European Nuclear Regulators' Association. Reactor Harmonization Group. WENRA Reactor Reference Safety Levels*. WENRA. September 2014. www.wenra.org.

8. *Response to RO-AP1000-092 and Actions RO-AP1000-092.A1.1 and RO-092.A1.2– Documentation for the Current Frozen Version of the Fuel Performance Code*, WEC70126R TRIM Ref. 2015/42025.

9. *Westinghouse Performance Analysis and Design Model (PAD5)*, WCAP-17642-P, TRIM Ref. 2015/42025.

10. *AP1000 Core Reference Report*. WCAP-17524-P and associated supplements, TRIM Ref. 2015/42036.

11. *Proceedings of the Seminar on Thermal Performance of High Burn-Up LWR Fuel*, 3-6 March 1998 Commissariat à l'Énergie Atomique (CEA) Cadarache, France, Ref. 2015/79648.

12. *Request further information relating to crud modelling in PAD*, RQ-AP1000-1319.

13. Request further information relating to Thermal Conductivity Degradation, RQ-AP1000-1320, TRIM Ref. 2015/134391

14. *Correspondence to ONR on Quantification of Uncertainty in Cladding Growth Rates,* February 2017, DCP_DCP_008535, TRIM Ref. 2015/136356.

15. *Not Used*

16. AP1000 Single Accumulator ASTRUM-Style Uncertainty Analysis to Support Response to UK NII TQ-AP1000-673, UKP-SSAR-GSC-007, October 2010, TRIM Ref. 2015/480127.

ANNEX 1: APPLICABLE STANDARDS

Table 1: Relevant Safety Assessment Principles to be Considered

SAP Number	SAP Title	Notes
EKP.1	**Inherent safety**	The underpinning safety aim for any nuclear facility should be an inherently safe design, consistent with the operational purposes of the facility.
ERL.1	**Reliability Claims**	Measures to achieve reliability
EAD.1 – EAD.2	**Ageing and Degradation**	Demonstration of a safe working life and margins to safety limits throughout life.
AV.1 – AV.2	**Validity of Data and Methods**	Theoretical models and calculation methods

Table 2: Relevant Technical Assessment Guides to be Considered

TAG Number	TAG Title	Notes
NS-TAST-GD-005	Guidance on ALARP (As Low As Reasonably Practicable)	Adequacy of safety measures
NS-TAST-GD-042	Validation of computer codes and calculation methods.	Substantiation of limits of applicability and code uncertainty
NS-TAST-GD-075	Safety Aspects Specific to Nuclear Fuel in Power Reactors.	Requirements on the fuel

Table 3: Relevant IAEA Standards to be Considered

Reference	Title	Notes
SF-1	Fundamental Safety Principles. IAEA Safety Standards Series, IAEA Vienna, 2006.	Safety principles
NS-R-1	Safety of Nuclear Power Plants: Design, Specific Safety Requirements	General requirements
NS-G-1.12	Design of the Reactor Core for Nuclear Power Plants,	Specific design requirements

Table 4: Relevant WENRA References to be Considered

Reference	Title / Description	Notes
3.1	The plant shall be able to fulfil the following fundamental safety functions: - control of reactivity; - removal of heat from the core; and - confinement of radioactive material.	
7.2	Criteria for protection of the fuel pin integrity, including fuel temperature, DNB, and clad temperature, shall be specified. In addition, criteria shall be specified for the maximum allowable fuel damage during any design basis event.	
8.7	The impact of uncertainties, which in specific cases are of importance for the results, shall be addressed in the analysis of design basis events.	
5.2	Safety limits shall be established using a conservative approach to take uncertainties in the safety analyses into account.	
2.1	The licensee shall assess structures, systems and components important to safety taking into account of relevant ageing and wear-out mechanisms and potential age related degradations in order to ensure the capability of the plant to perform the necessary safety functions throughout its planned life, under design basis conditions.	

Table 5: GDA Issue Specification

GDA ISSUE:	There is a need to provide comprehensive documentation demonstrating that PAD predictions of temperatures for fresh fuel will in all cases exceed the expected temperatures of irradiated fuel, including allowances for uncertainty. Further, that fission gas release predictions are pessimistic after suitable allowances. In order to ensure this, a suitable constraint on fuel ratings as a function of irradiation needs to be qualified and adopted.
ACTION: GI-AP1000-FD-01.A1	Demonstrate in a documented safety case, to a high level of confidence that for fresh fuel temperatures predicted by PAD are bounding of all irradiated fuel within the burnup range considered. Define a formal limiting condition applied to the core design process to ensure that the assumptions utilised in this Action are realised. The current version of the PAD fuel performance code is deficient as the reduction in thermal conductivity of fuel material with irradiation is not represented. Westinghouse bases its safety case for fuel temperatures on the argument that fresh fuel is limiting due to the reduction of fuel reactivity with irradiation. However, this argument is based on assumptions about the power of the fuel and needs to be made This constraint needs to be considered a limiting condition of operation and controlled as such. The derivation of the constraint will need to make due allowance for uncertainty. With agreement from the Regulator this action may be completed by alternative means.
ACTION: GI-AP1000-FD-01.A2	Present a formal safety justification of the uncertainty of the current models of fission gas release and their limits of applicability. The current version of the PAD fuel performance code is deficient as the empirical fission gas release model does not include a gas release threshold model. Consequentially the prediction of the rate of gas release tends to be too high initially, and then too low later. Westinghouse bases its safety case for fuel pin pressures on the argument that empirical data can be used as a basis for prediction of fission gas release, but the **AP1000**® design envisages operating at fuel pin ratings and irradiations in excess of the current bulk of the data. This brings into question the basis for the assessment of uncertainty in the current safety case and requires a thorough justification of its statistical basis at the limiting conditions of relevance. With agreement from the Regulator this action may be completed by alternative means.