CODE QUALIFICATION FOR TRADITIONAL LWR FUEL

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ABSTRACT

Fuel performance codes, commonly referred to as thermal-mechanical codes, are qualified against a large database of separate effects data (material properties) and integral effects data. The types of data that are selected to assess these codes are based on the intended application of the codes. FRAPCON, FAST, and fuel vendor fuel performance codes are used to perform the fuel safety analyses required to demonstrate the various specified acceptable fuel design limits (SAFDLs) will not be exceeded during a specific cycle in a reactor. The SAFDLs are those requirements identified so that fuel system damage will not occur during normal operation and anticipated operational occurrences. Additional criteria are established to ensure that fuel rod failure is accounted for during postulated accidents and that fuel rod coolability is maintained during postulated accidents. However, these criteria are evaluated using a more simplified approach in a systems code and is not performed by common vendor thermal-mechanical codes.

This paper will describe the code assessments that have been performed on FRAPCON and FAST (new version of FRAPCON that extends to longer-term abnormal operational occurrences (AOOs) and design basis events (DBAs)) and how these specific assessments have been selected to ensure that these codes are acceptable for performing such analyses and auditing vendor codes. An example of the evaluation used to demonstrate that the rod internal pressure, transient cladding strain increment, and cladding corrosion and hydriding SAFDLs are met, using FAST, is provided.

1. Introduction

The FRAPCON fuel performance code [1] has been used by the United States Nuclear Regulatory Commission (US NRC) for more than 20 years to perform independent confirmatory analyses of vendor fuel codes and methods that are used to evaluate the performance of light water reactor (LWR) fuel relative to various safety analysis design limits. In addition to the NRC, it is used by over 55 organizations around the world, including various regulatory bodies and technical support organizations (TSOs). Because of its use in the review and approval of safety analysis codes and methods, it is important that FRAPCON be well validated over the entire range of applicability (e.g. burnup level and power level). The assessment of FRAPCON relative to relevant data is continually expanded as more data become available [2].

FAST (Fuel Analysis Steady-State & Transient) [3] is the next evolution of FRAPCON which includes steady-state and transient heat conduction and clad-to-coolant heat transfer models. The assessment of FAST [4] has been expanded beyond that of FRAPCON to include additional steady-state and power ramp data.

This paper will describe how fuel performance codes such as FAST are used in the fuel system safety review and how FAST has been validated to evaluate fuel design bases. An example of the evaluation used to demonstrate that the rod internal pressure, transient cladding strain increment, and cladding corrosion and hydriding SAFDLs are met, using FAST, will be provided.

2. Use of Fuel Performance Codes in the Fuel System Safety Review

The fuel performance code FAST plays an integral role in the NRC's evaluation and confirmatory analyses, ranging from plant operating conditions to dry storage. The role of FAST in these analyses includes:

- Used as part of the evaluation of the fuel system during the review and approval of new codes and methods
- Used during the review and approval of new fuel systems
- Used to provide initial conditions to systems level codes (e.g., TRACE) for plant specific analyses, such as maximum extended load line limit analysis plus (MELLLA+) and loss-of-coolant accident (LOCA)
- Used to ensure safety limits are met for spent fuel storage and transportation, including the fuel drying process and long term storage

For the reviews of new fuel systems, the fuel system safety review provides assurance that:

- The fuel system is not damaged as a result of normal operation and AOOs.
- Fuel system damage is never so severe as to prevent control rod insertion when it is required
- The number of fuel rod failures is not underestimated for postulated accidents
- Coolability is always maintained

To provide these assurances, General Design Criteria 10 (GDC 10) requires that SAFDLs be established for all known fuel system damage and fuel rod failure mechanisms. These SAFDLs establish limits that should not be exceeded during any condition of normal operation, including the effects of AOOs. Further, GDC 27 and 35 require that fuel coolability criteria are provided for all severe damage mechanisms. These criteria ensure that control rod insertion capability and coolability are maintained during accident conditions. The applicant is responsible for proposing SAFDLs and other necessary safety criteria, as well as proposing codes and methods that will be used to ensure that SAFDLs and safety criteria will not be exceeded. The applicant should also provide relevant data and other justifications for the proposed safety criteria, SAFDLs, codes, and methods. The NRC uses independent codes (such as FAST), methods, data, and expert analysis to determine if the proposed safety criteria, SAFDLs, codes, and methods will be acceptable to provide these assurances. Because the NRC staff relies on FAST predictions during this review, it is necessary for FAST to be highly validated and for code uncertainties to be well understood. FAST is used to evaluate those SAFDLs relevant under normal operations and AOOs. System codes and other codes are used to evaluate those SAFDLs relevant under accident conditions with FAST providing initial conditions.

To assist the NRC staff and the applicant in developing safety criteria and SAFDLs, the Standard Review Plan section 4.2 (SPR 4.2) [5] outlines mechanisms for fuel system damage, fuel rod failure, and fuel coolability for uranium dioxide fuel in zirconium cladding as shown below.

Fuel System Damage

- Stress, strain, or loading limits for spacer grids, guide tubes, thimbles, fuel rods, control rods, channel boxes, and other fuel system structural members
- Fatigue of structural members mentioned above
- Fretting wear at contact points
- Oxidation, hydriding and CRUD buildup
- Dimensional changes and mechanical compatibility
- Rod internal gas pressure
- Worst case hydraulic loads
- Control rod reactivity and insertability

Fuel Rod Failure

- Hydriding
- Cladding collapse
- Overheating of the cladding
- Overheating of the fuel pellets
- Excessive fuel enthalpy
- Pellet/cladding interaction
- Bursting
- Mechanical fracturing

Fuel Coolability

- Cladding embrittlement
- Violent expulsion of fuel
- Generalized cladding melting
- Fuel rod ballooning
- Structural deformation

Many of the mechanisms for fuel system damage are related to fuel assemblies and assembly components other than fuel rods. In these cases, limits are proposed and methods for demonstrating the limits will not be exceeded are provided. In most cases, these methods do not involve a code such as a fuels code, but rather consist of citing manufacturing controls, historical data, or a hand calculation. An example of this would be on the assembly hold down force where simple calculations are performed on the hydraulic lifting force, and the spring relaxation. Additionally, historical data is included that show that vendor has not experienced problems with assembly liftoff.

For the SAFDLs related to the fuel rod, design bases must be addressed by an evaluation performed in the areas listed in Table 1. These design bases are divided into two categories: those that are analyzed using a fuel thermal mechanical code such as FAST and those that are analyzed using a system analysis code such as TRACE. Initial conditions for design bases addressed by system analysis codes are provided from a fuel thermal mechanical code such as FAST.

Table 1: Design bases related to fuel rods.

Fuel rod design bases addressed with a fuel thermal mechanical code	**Fuel rod design bases addressed with an system analysis code with initial conditions from a fuel thermal mechanical code**
Cladding stress	Overheating of cladding
Cladding strain	Excessive fuel enthalpy
Cladding fatigue	Bursting
Cladding oxidation and hydriding	Cladding embrittlement
Fuel rod internal pressure	Violent expulsion of fuel
Internal hydriding	Generalized cladding melting
Cladding collapse	Fuel rod ballooning
Overheating of fuel pellets	
Pellet-to-cladding interaction	

3. Validation of Fuel Performance Codes to Evaluate Fuel Design Bases

In this section the design bases that are analyzed using a fuel thermal mechanical code such as FAST identified in the first column of Table 1 are discussed, along with the typical limits proposed for each design bases. The other SAFDLs in Table 1 are relevant to accident conditions and are not discussed in this paper as a fuel performance code such as FAST is only used to provide initial conditions to these accident analyses. However, a description of the validation completed to demonstrate that FAST has adequate predictions in these areas is also provided.

For each limit, it must be demonstrated with a high level of confidence that no rod will fail. In order to do this, the worst case power history and fuel rod parameters for each limit should be identified. An analysis is typically performed using an analytical code that has been validated against relevant data. The effects of operations uncertainties (e.g. power level and coolant flow rate), manufacturing uncertainties, and modeling uncertainties should be used to derive an upper tolerance limit on the code prediction. Typically a 95% upper tolerance limit with 95% confidence is used. Statistical methods for combining uncertainties, including worst-case analysis, root mean square, and Monte Carlo methods, have been used. Alternatively, an applicant may choose to take a conservatively bounding approach to show the limits are met.

3.1. Cladding Stress

Cladding stress limits are typically taken from the ASME Boiler and Pressure Vessel Code [6]. Because the strength of zirconium based alloys (Zr-alloy) used for cladding in current LWRs is known to increase with irradiation, unirradiated yield stress and ultimate tensile strength are typically used to derive conservative cladding stress limits. The maximum stress is driven by high rod internal pressure, therefore the maximum rod internal pressure determined through the analysis described in Section 3.5 of this paper is used in a hand calculation to demonstrate that stress limits are not exceeded.

It is not possible to directly compare the cladding stress predictions in FAST against data as it is not possible to directly measure stress. Because of this, the FAST predictions of pressure are assessed as discussed in Section 3.5 and the ASME code is used to determine stress as it has been universally applied in other stress analyses.

In addition to the fuel design criteria in SRP 4.2, cladding stress is a limit under spent fuel storage and transportation, as defined in Interim Staff Guidance (ISG) 11, Revision 3 to meet the regulations in 10 CFR Part 72. [8] This limit is not required to be met by fuel vendors in order to load fuel into reactors but is required of cask vendors during drying and loading of fuel into casks to minimize the possibility of significant radial hydride reorientation. Also, unlike in the SAFDLs, ISG 11-Rev. 3 requires that the structural cladding thickness for stress calculations be reduced by the amount of oxide and hydride rim thickness justified by measurements, validated codes against experimentally measured data, or others appropriate means. In order to meet these criteria, FAST has been validated against end-of-life rod internal pressure and oxidation measurements as outlined in Section 3.4 and 3.5.

3.2. Cladding Strain

There are typically two cladding hoop strain limits set on Zr-alloy cladding. One is on the total (i.e. elastic plus plastic) strain in the positive and negative direction during normal operation. The second is on the increment of plastic strain due to an AOO. The first limit protects the cladding from excessive creep deformation and is typically around 1% total strain. The second limit protects the cladding from excessive plastic deformation and is typically around 1% plastic strain increment.

FAST has been assessed against a number of separate effects data including cladding creep, fuel thermal expansion, and fuel irradiation swelling. This assessment has demonstrated that FAST has adequate predictions for cladding deformation due to creep driven by differential pressure and pellet expansion under normal operation, therefore FAST is validated to be able to predict the first type of cladding strain limit. FAST has also been assessed against integral effects data from power ramped rods. This assessment has demonstrated that FAST has adequate predictions for cladding hoop strain during power ramps, therefore FAST is validated to be able to predict the second type of cladding strain limit.

3.3. Cladding Fatigue

Typically the cladding fatigue limit used is the irradiated Zr-alloy design curve proposed by O'Donnell and Langer [7]. A conservative estimate of events that cause strain in the cladding should be used and a fatigue damage fraction based on the number of each event can be determined. The fraction from each event can be added up to demonstrate a fatigue damage fraction less than 1.

As mentioned in the previous section, FAST has been assessed against a number of separate effects data including cladding creep, fuel thermal expansion, and fuel irradiation swelling, such that it is validated to be able to predict cladding deformation due to creep driven by differential pressure and pellet expansion under normal operation. FAST has also been assessed against integral effects data from power ramped rods that demonstrate its ability to predict cladding hoop strain during power ramps.

3.4. Cladding Oxidation and Hydriding

A cladding oxidation limit is set to ensure that the cladding wall thickness is not overly thinned and to prevent cladding spallation (cladding spallation can cause a local cool area that promotes hydrogen migration that can result in a hydride blister and degraded local mechanical properties). A typical oxide thickness limit is around 100 μm. A cladding hydrogen content limit is set to preclude cladding embrittlement, which has been observed to occur at high hydrogen content. A typical average hydrogen content limit is around 600 ppm wt.

FAST has been assessed against post-irradiation examination (PIE) data from high burnup cladding samples that demonstrate its ability to predict average hydrogen content for US approved cladding alloys. Additionally, FAST has been assessed against poolside and PIE data on oxide thickness measurements from high burnup fuel rods that demonstrate its ability to predict oxide thickness for US approved cladding alloys.

3.5. Fuel Rod Internal Pressure

The most conservative fuel rod internal pressure limit is one that restricts the fuel rod internal pressure from exceeding the reactor coolant system pressure. SRP 4.2 [5] allows for other limits justified based on, but not limited to:

- No cladding liftoff during normal operation
- No reorientation of the hydrides in the radial direction in the cladding
- A description of any additional failures resulting from departure of nucleate boiling (DNB) caused by fuel rod overpressure during transients and postulated accidents

Typical limits are justified based on a determination that the no cladding liftoff is the most limiting of these three. To demonstrate no cladding liftoff, a pressure limit is set based on the upper bound cladding creep rate (driven by rod internal pressure) and the lower bound fuel swelling rate (driven by burnup rate).

FAST has been shown to accurately predict in-reactor creep tests and data on fuel swelling rate such that these rates can be determined and justified. Additionally, FAST is assessed against fission gas release data (primary driver of pressure increase) and end of life pressure and void volume data that demonstrate its ability to predict fuel rod internal pressure.

3.6. Internal Hydriding

Cladding internal hydriding (i.e. as-fabricated initial hydrogen level) is not typically assessed using an analytical model such as FAST, but rather manufacturing controls are cited that limit the pellet moisture content to low values such that there are no significant sources of hydrogen available for internal hydriding.

3.7. Cladding Collapse

Cladding collapse is not a phenomenon that has been observed in modern LWR fuels. Modern fuels are typically pressurized with helium to avoid a large pressure differential at beginning of life. Additionally, pellet design features, such as pellet chamfers, and an increase in pellet manufacturing quality control have effectively eliminated the drivers of pellet lock up that could lead to the formation of axial gaps between pellets. Nevertheless, cladding creep collapse analyses are still performed to demonstrate that cladding collapse in very small axial gaps and the plenum will not occur.

FAST has been assessed against in-reactor creep tests such that the creep model in FAST could be used to perform a cladding collapse analysis.

3.8. Overheating of Fuel Pellets

A fuel centerline temperature limit is set as the melting temperature. The fuel melting temperature should be justified against irradiated and unirradiated pellets to be able to accurately predict fuel melting as a function of burnup.

FAST has been assessed against fuel melting temperature data on unirradated and irradiated pellets. Additionally, the FAST temperature predictions have been assessed against a large database of Halden tests with fuel centerline temperature measurements over a range of conditions and burnups such that the FAST temperature predictions are well validated.

3.9. Pellet Cladding Interaction

Typically no additional analytical analyses are performed for pellet cladding interaction. This is because the cladding strain and fatigue analyses are considered to effectively encompass any limits needed for pellet cladding mechanical interaction. Manufacturing controls are used to ensure that there will not be pellet or cladding defects that can lead to stress concentrations. Various other design features and PIE data are cited to demonstrate that there will be no failures due to chemical/stress interactions.

3.10.Initial Conditions for System Analysis Codes

The design bases that are listed in the second column of Table 1 are those that are analyzed using a system analysis code, but initial conditions are provided from a fuel thermal mechanical code. The initial conditions for many of these accident analyses are directly tied to safety performance and therefore should not be underestimated, such as the criteria in 10 CFR Part 50 that requires the steady-state temperature distribution and stored energy in the fuel shall be calculated for the burnup that yields the higher calculated stored energy.[9] The primary input for accident analyses is fuel temperature and stored energy, but other inputs such as thermal conductivity, gap size and composition are also important.

FAST has been assessed against a large database of fuel centerline temperature measurements, fission gas release data, corrosion data, void volume data and cladding strain data such that the FAST predictions of initial fuel conditions prior to an accident are well validated.

4. Example Evaluations of Selected SAFDLs using FAST

In this section an example evaluation of assessing various SAFDLs will be performed using FAST. The SAFDLs that will be considered are; rod internal pressure, transient strain increment, and cladding corrosion and hydriding. This section is not meant to be fully representative of the selected fuel design, but rather demonstrate the process of assessing the SAFDLs. For this sample evaluation, a Westinghouse 17x17 PWR fuel rod with ZIRLO™ cladding has been selected.

4.1. Selection of Power History

A method should be determined to find the power history for the most limiting rod in the core for each SAFDL being analyzed. This may be done using a limiting power history that is greater than all the power histories in the core. This may also be done by using several power histories that bound all the power histories in the core. Alternatively, a method such as running every power history to determine the most limiting power history for each SAFDL may be used.

For this sample, a single power history will be used as representative of the most limiting power history for all the SAFDLs being evaluated. The power history that has been selected has relatively high power and in order to account for AOOs, includes two power increases to 125% with a hold time of 21 minutes. A longer hold time than would be expected by a typical AOO is used to ensure that the amount of fission gas release is not under-predicted with diffusion-based models. This power history is shown in Figure 1.

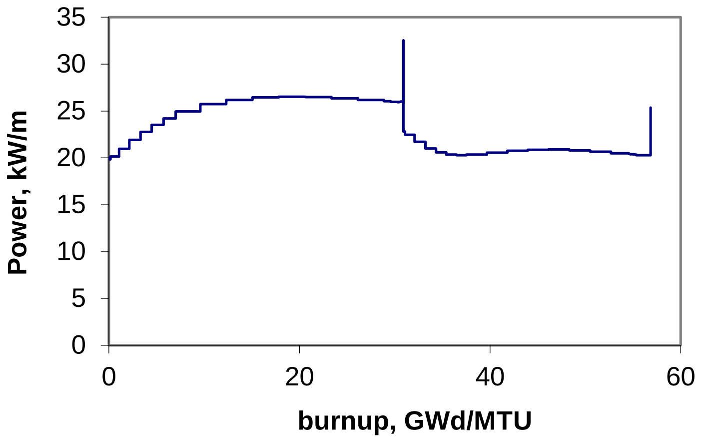

Figure 1. Power history used for sample evaluation of SAFDLs.

4.2. Determination of acceptance criteria for SAFDLs

For rod internal pressure, the most conservative acceptance criteria is that the rod internal pressure does not exceed the system pressure, which in this case is 15.5 MPa (2250 psi). If more margin is required, it is also possible to justify a greater limit as that pressure where the cladding creep rate exceeds the fuel swelling rate, thus allowing for the possibility of the fuel/cladding gap to open after it had previously closed. For this sample, the system pressure of 15.5 MPa will be an adequate limit.

For transient cladding strain increment, a limit of 1% elastic + plastic cladding strain will be used. Burst tests on irradiated cladding have demonstrated that this level of ductility is available in the cladding to high burnup.

For cladding oxidation and hydriding, an oxide thickness limit of 100 μm and a hydrogen content of 600 ppm will be used. Above 100 μm of oxide thickness, the potential for oxide spallation that can lead to hydride blisters increases. Above 600 ppm of hydrogen in the cladding, the ductility begins to go below the 1% strain mentioned earlier.

4.3. FAST Best Estimate Predictions of SAFDLs

FAST was run using the nominal design parameters, the power history from Figure 1, 40 equal-length axial nodes and nominal reactor coolant system parameters. Based on the number of figures of merit, hundreds of FAST cases were run using the NRC's statistical package with variations in model uncertainties and fuel fabrication parameters. The output of FAST was examined and the maximum pressure, strain increment, oxide thickness, and cladding hydrogen content were obtained. It should be noted that the entire burnup range and length of the rod were examined to determine this maxima as shown in Figure 2.

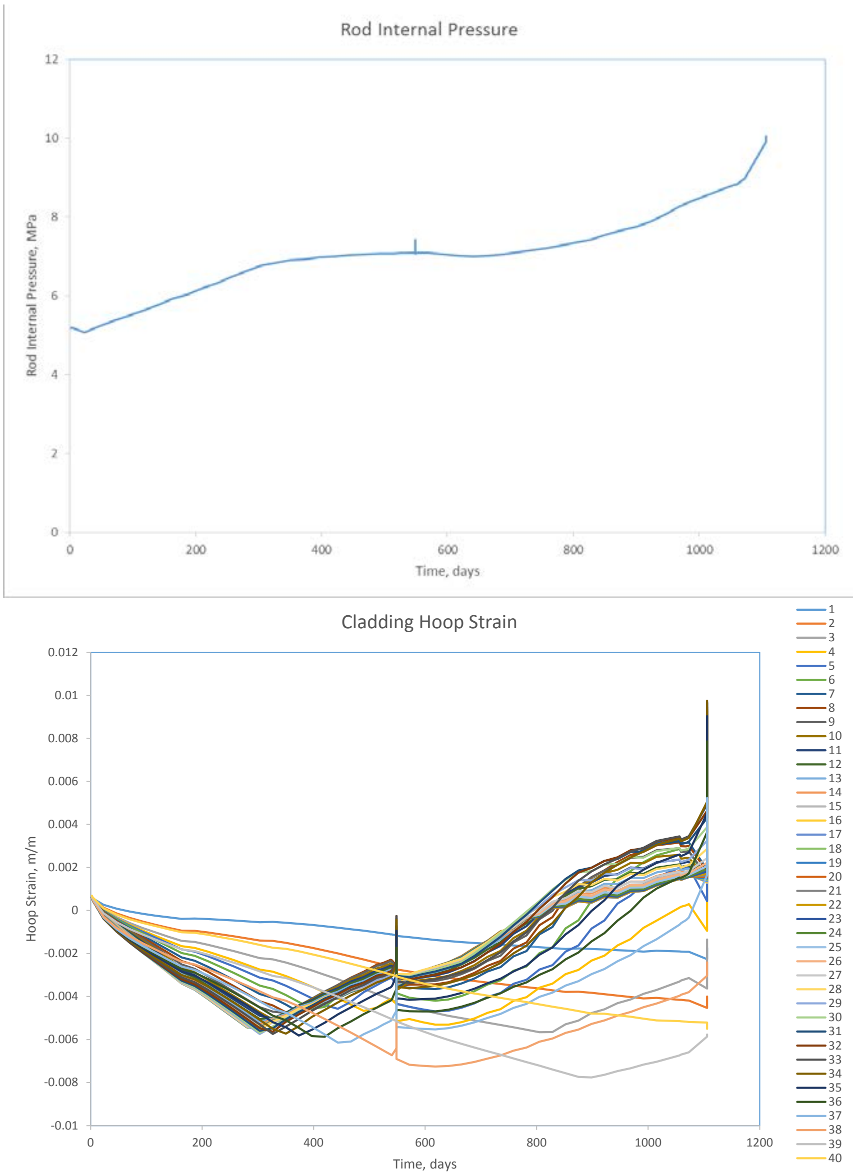

Figure 2. FAST predictions of rod internal pressure, cladding total hoop strain, cladding oxide thickness and cladding hydrogen content for sample power history

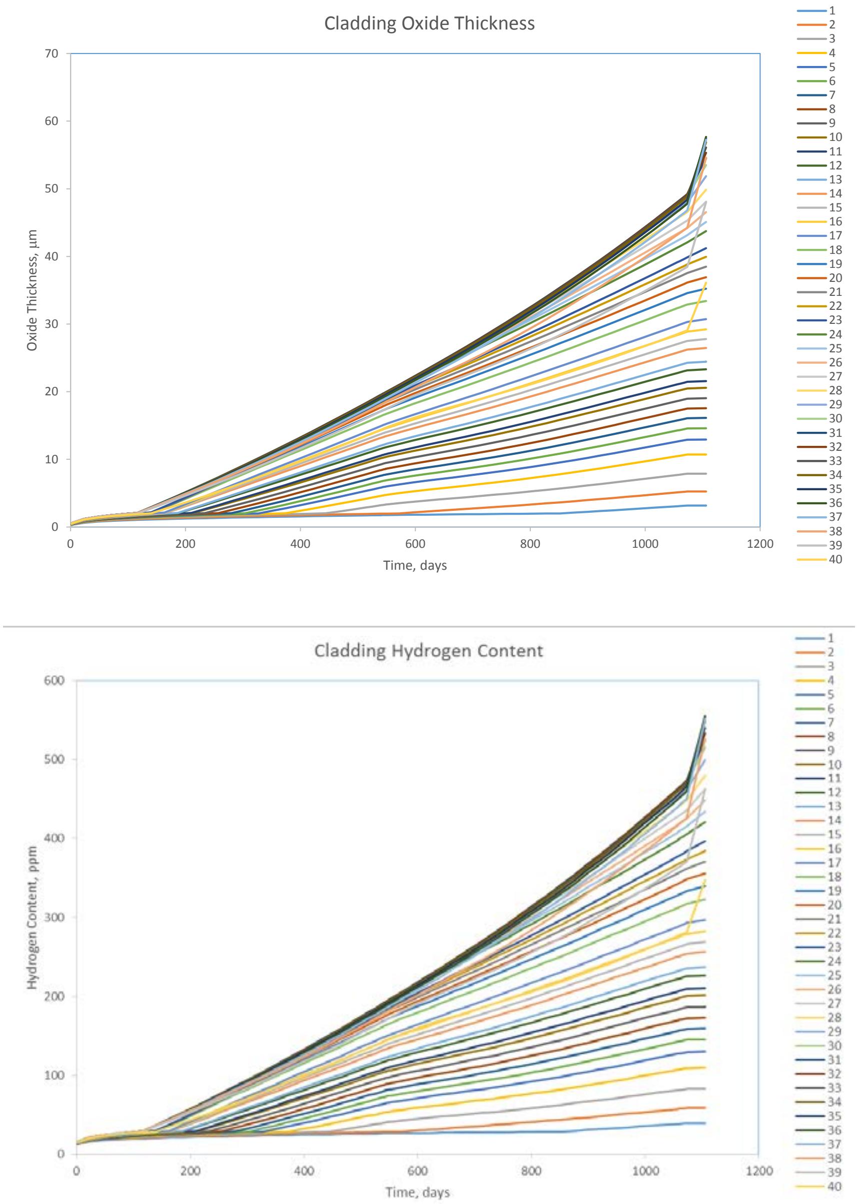

Figure 2 (cont.). FAST predictions of rod internal pressure, cladding total hoop strain, cladding oxide thickness and cladding hydrogen content for sample power history

4.4. Application of Uncertainties

It should be demonstrated with a confidence level that no rod in the core will exceed any of the SAFDLs. Typically this is done by finding the upper tolerance level of 95% probability that the most limiting rod will not fail with 95% confidence (95/95). There are many parameters in the FAST best estimate predictions that are uncertain and should be included in a statistical analysis to find the 95/95 upper tolerance level. These parameters include, uncertainties in the power level, uncertainties in the coolant conditions, manufacturing uncertainties, and model uncertainties in FAST. There are several ways to combine uncertainties from each of these sources including a worst case analysis, a root mean square analysis, and a stochastic analysis. Historically, a root mean square analysis was used by the fuel vendors, and this analysis will be performed here as it is easy to demonstrate.

In the root mean square approach, the best estimate value of the parameter of interest is determined. Then each uncertainty is applied one at a time and the increase in the parameter of interest relative to the best estimate value is determined. Each of these differences is squared and the square root of the sum of these squares is found. This result is added on to the best estimate value. If each uncertainty is applied at 1.65σ, then the resulting upper tolerance level will be approximately 95/95. This entire analysis assumes the input uncertainties and output distributions are normally distributed.

The results from the root mean square analysis for each of the selected SAFDLs is shown in Table 2. For this analysis, a power uncertainty of ±5% was assumed and an uncertainty on the coolant inlet temperature of ±5°F was assumed. Manufacturing uncertainties on number of pellets and fill pressure were assumed and the FAST FGR, hydrogen, corrosion, and fuel thermal expansion models were biased to +1.65σ. These model uncertainties and manufacturing uncertainties are by no means exhaustive, and it would be the responsibility of the applicant to explore the impact of all power, operation, manufacturing, and model uncertainties.

In this example, the SAFDLs related to rod internal pressure, transient cladding strain and cladding oxidation are all met at a 95/95 level. However, the cladding hydrogen content is not met. Based on this, the applicant would need to determine if a different core design could allow this SAFDL to be met. Alternatively, more data may be obtained to justify a lower hydrogen pickup model, or a lower uncertainty on that model.

Table 2: Best estimate values for SAFDLs, impact of uncertainties, and sample 95/95 upper tolerance level. (Only values that increase the parameter of interest are shown)

	Rod Internal Pressure (MPa)	Elastic + Plastic Strain Increment (%)	Cladding Oxide Thickness (μm)	Cladding Hydrogen Content (ppm)
Nominal	**10.06**	**0.796663**	**57.66**	**555.69**
Power +5%	11.59	0.816813		
Power -5%			61.34	591.63
T_{inlet} +5°F	10.25	0.801779	57.69	556.02
+1 extra pellet		0.801377		
-1 extra pellet	10.25			
Fill pressure +15 psi	10.30			
Fill pressure -15 psi		0.802671		
UB FGR model	13.74			
UB hydrogen model				737.19
UB corrosion model	10.50	0.813295	82.4	570.87
UB fuel thermal expansion model	10.12	0.901876		
Upper Tolerance Level, 95/95	**14.09**	**0.905**	**82.67**	**741.33**
Acceptance Criteria	**15.51**	**1**	**100**	**600**

5. Conclusions

This paper described the how fuel performance codes such as FAST are used in the fuel system safety review. The criteria for fuel system damage, rod failure and fuel coolability have been identified. Based on these, design bases related to fuel rods are identified. Some of these design bases are applicable to normal operation and AOOs and are evaluated using a fuel performance code. Others are applicable to accident conditions and are evaluated using a system code or other code with initial conditions being provided with a fuel performance code.

For each fuel rod design bases that is applicable to normal operation and AOOs and is evaluated using a fuel performance code, typical values for criteria are given as well as how they are justified. For each of these design bases, the FAST assessment that provides validation that FAST is appropriate to use to assess performance relative to each criteria was discussed.

An example of the evaluation used to demonstrate that the rod internal pressure, transient cladding strain increment, and cladding corrosion and hydriding SAFDLs are met, using FAST, was provided.

6. References

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