BEST ESTIMATE MODELING OF FUEL THERMOMECHANICAL BEHAVIOUR IN WWER 1000 LB LOCA

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Abstract: The paper summarizes our calculations of the performance of the WWER 1000 NPP fuel rods during postulated LB LOCA. The thermomechanical modeling was performed by FRAPTRAN using the FRACAS-I mechanical model using the boundary conditions calculated by the ATHLET code. The results and their statistical evaluation are presented, the process of the generalization of gained insight into the BE TM predictions in order to define a generic BE TM methodology is outlined.

Keywords: Thermomachanics, Best Estimate, FRAPTRAN, LB LOCA

1. Introduction

The nuclear industry nowadays shows the interest in the best-estimate (BE) evaluations of postulated accident scenarios in order to remove the excessive conservatism. BE approach is often used for the thermal-hydraulic (TH) analyses. Although such analyses usually provide the quantities which can be directly compared with the acceptance criteria for the relevant event [1] (namely the peak cladding temperature and the departure from nuclear boiling ratio), there is some merit in running a subsequent thermo-mechanical (TM) analysis of the fuel rod behavior, for example to obtain a realistic estimate of the quantity of the failed fuel rods or to check that the assumptions made on the fuel rod parameters (geometry, gap heat transfer coefficient) for the TH calculation are not violated in the course of the transient. However, the definition of the "best estimate" TM calculation based on the BE TH data is not straightforward as will be shown in this paper.

2. General considerations

The BE approach is based on the identification of the most-important models and input parameters and quantification the uncertainties related to them. The effect of the uncertainties in the input parameters and in the models on the result is then statistically evaluated. The value to be compared with the acceptance criterion can be the upper (lower) bound or the best estimate value plus its estimated uncertainty [2]. The boundary conditions required for the TM calculation are coolant pressure and mass flow of the coolant or the cladding outer surface temperature as a function of time over the whole transient. Even if one wanted to calculate a very conservative estimate, he would face the selection of the bounding boundary conditions – and things get even more complicated considering that boundary condition provided by the BE system code and the TM code input parameters describing the fuel rod (burnup, fuel-clad gap width, internal pressure, fill gas composition...) are not independent.

The methodology for consistent combination of BE TH / system code calculations and TM calculations we are developing at Nuclear Research Institute Rez plc. as a part of the contract for the support of the Temelin NPP is following:

- Define the bases of the initial states of the fuel rods employing the steady state TM code and using the typical power histories and varying the input parameters within the limits given the fuel supplier. The obtained results are supplemented with the experimental data

- Use above data to define the mean values, uncertainties and correlations for the TM parameters entering the BE TH or system code (typically rod burnup, gap width, internal pressure and fill gas composition).

- Perform the TM calculations with the boundary conditions provided by the TH / system code, carrying over the input parameters that were used to define the run – e.g. if the TH calculation was performed with the assumption that the gap size is ~ 50μm **and** the sensitivity analysis of the

TH calculations proved that the gap size has a significant impact on the results, the same value will be used for the TM calculation. The other TM input parameters are set to values which are considered to be conservative. A sensitivity study performed over will show which combinations of TH / system code input values result in the least safety margin from the TM point of view (limiting boundary conditions for the TM input).

- Select the set of the most limiting boundary conditions and repeat the TM calculations, this time with the input parameters varied within the expected range, respecting the correlations between the input parameters and the boundary conditions. Additionally, a sensitivity study can show which combinations of TM code input values result in the least safety margin from the TM point of view.

- If the sensitivity analyses show that there may exist a realistic case which has not been covered by the inputs and the sensitivity is such that it does not allow the estimation of the results based on already obtained ones, additional calculation will be performed.

This way, the realistic case with the least safety margin will be systematically identified.

3. LB LOCA case

As an example, we have selected the LB LOCA for the Temelín WWER 1000 NPP with the Westinghouse VVANTAGE-6 fuel (a continuation of the work presented in [3]). The system BE calculations were performed by the ATHLET code [4]. It must be noted that these results are not final yet. The analysis used 98 runs, the sensitivity of the results to the input parameters and bounding values were obtained using GRS methodology [4].

The TM inputs correspond to the VVANTAGE-6 fuel rod at the end of the 1st one year cycle. The state of the fuel rod was evaluated by the TRANSURANUS code [5]. 29 typical power histories were considered, each with and without a power ramp at the end of the first cycle simulating a hypothetical Condition 2 event. The results are summarized in table 1. The quantities are strongly correlated, two basic input sets were therefore defined – one with maximum pressure and minimum gap (“nominal A”) with and vice versa (“nominal B”). The selection of the internal pressure as the limiting parameter was based on the previous experience and US NRC phenomenon identification and ranking process [6]. As the statistical treatment of the ATHLET data showed high sensitivity of the cladding temperature to the gap width, the gap widths were modified individually for each run by a factor corresponding to the one used in the ATHLET calculation.

Transient analysis code FRAPTRAN 1.4 switched to the “old” mechanical model (FRACAS-I) [7] was used to evaluate the thermo-mechanical behaviour of the fuel rod. A final check of the nominal FRAPTRAN input has been performed by adding a short time interval with a power history corresponding to the first 400s of the FRAPTRAN run (steady-state conditions) to the power history used in the TRANSURANUS and by comparing the results.

First, all 98 ATHLET cases (figure 1) were run through FRAPTRAN, once with “nominal A” input and once with “nominal B” input, with following findings:

- 6 fuel rod failures with “nominal B” input / 16 cases with the “nominal A” input.
- All failures occurred in during the “refill” phase, the “nominal B” rods burst later in all cases.
- There was not a case in which there would be “nominal B” failure and not a “nominal A” failure.
- Apart from the cases where the FRAPTRAN reported rod burst, there were 1 / 4 cases where the total hoop strain of the cladding ε_{hoop} exceeded 4%.
- The ECR did not exceed 2.5%.

The results and input data were analyzed to check whether the “burst” cases could have been chosen from the ATHLET outputs a priori – figure 2 shows that the rod failure was predicted in those cases, which had either high peak cladding temperature or high time averaged cladding temperature during the refill stage. On the other hand, the peak temperature during the blowdown phase had smaller effect (although it represents the total maximum of the cladding temperature for most of the runs).

The next step consisted of the preparation of the set of FRAPTRAN input with the fuel rod parameters varying according to the TRANSURANUS steady state calculations. The quantities listed in table 1 were varied. It must be noted, that correlations predicted by the steady state calculation were respected. Therefore the main aim of the analysis was not to estimate the transient calculation sensitivity to individual parameters, but to obtain the realistic conservative estimate of the spread of the results. Two boundary conditions were selected – one which has resulted in a fuel rod failure in both “nominal A” and “nominal B” cases (“run 10”) and one, for which the rod failure was not predicted, but which have exhibited noticeable deformation (4.65% ε_{hoop} for “nominal A” and 1.3% ε_{hoop} for “nominal B”) (“run 38”).

“Run 10” runs ended with the rod failing in all 24 cases, within 12s interval (figure 3). This confirmed that selected boundary condition is indeed limiting for the whole considered range of the fuel rod parameters. In the case that such limiting run is distant from the others (for example in the terms of the parameters used as the coordinates in the figure 2) and, at the same time, it threatens the safety margin when used as a basis for the TM calculation, the input data for the case should be examined for excessive accumulation of conservatism.

FRAPTRAN did not predict cladding failure for any of the 24 calculations of “run 38” with varying TM parameters. The spread of the predicted ε_{hoop} was 1.5% to 5.5%. This shows that “nominal A” was quite close to the conservative realistic case, but were there any doubts about the safety margin, the calculation would have been repeated with the limiting boundary conditions.

The internal pressure is confirmed to be the most influential TM parameter for the considered scenario – table 2 presents the calculated ordinary (Pearson’s) correlation coefficients, the results are plotted in figure 4. Note also the correlations between the TM parameters.

In order to confirm the importance of the correct treatment of the dependences of the input parameters “Run 38” was repeated with the input ignoring the correlations suggested by the steady state calculations. Cladding failure was predicted although the input internal pressure was lower than in some of the previous 24 calculations.

4. Conclusions

In the authors opinion, the role of the thermo-mechanical analysis in the BE framework should not be to blindly apply statistics theorems (especially when it is dubious whether the conditions ensuring their applicability had been met), but to identify the limiting yet realistic boundary conditions. This is an iterative process, as the boundary conditions consists of the TM quantities describing the state of the fuel before the event and of the output of the TH / system code analysis, which requires some TM input. The process has been outlined for the LB-LOCA analysis of Temelin NPP.

References:

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Table 1 – Range of the most important TM parameters for considered fuel rods (non-IFBA VVANTAGE-6) after the 1st one year cycle, STP:

Parameter	Range
Fuel pellet outer diameter [mm]	7.87 - 7.94
Radial gap [μm]	10 - 50
Free volume [cm^3]	15.5 - 18.7
Internal pressure [MPa]	1.7 - 2.4
Cladding thickness [mm]	0.561 - 0.571
Rod average Burnup [MWd/kgU]	11 - 17

Table 2 – Correlation coefficients for "run 38" – rod burst not predicted, max. hoop strain 1.3 – 5.5%

	Fuel pellet o.d.	Radial gap	Fuel rod o.d.	Internal pressure	Free volume	Max. hoop strain
Fuel pellet o.d.	1.00					
Radial gap	-0.87	1.00				
Fuel rod o.d.	0.58	-0.14	1.00			
Internal pressure	0.75	-0.65	0.45	1.00		
Free volume	-0.51	0.46	-0.28	-0.42	1.00	
Max. hoop strain	0.72	-0.62	0.44	0.98	-0.46	1.00

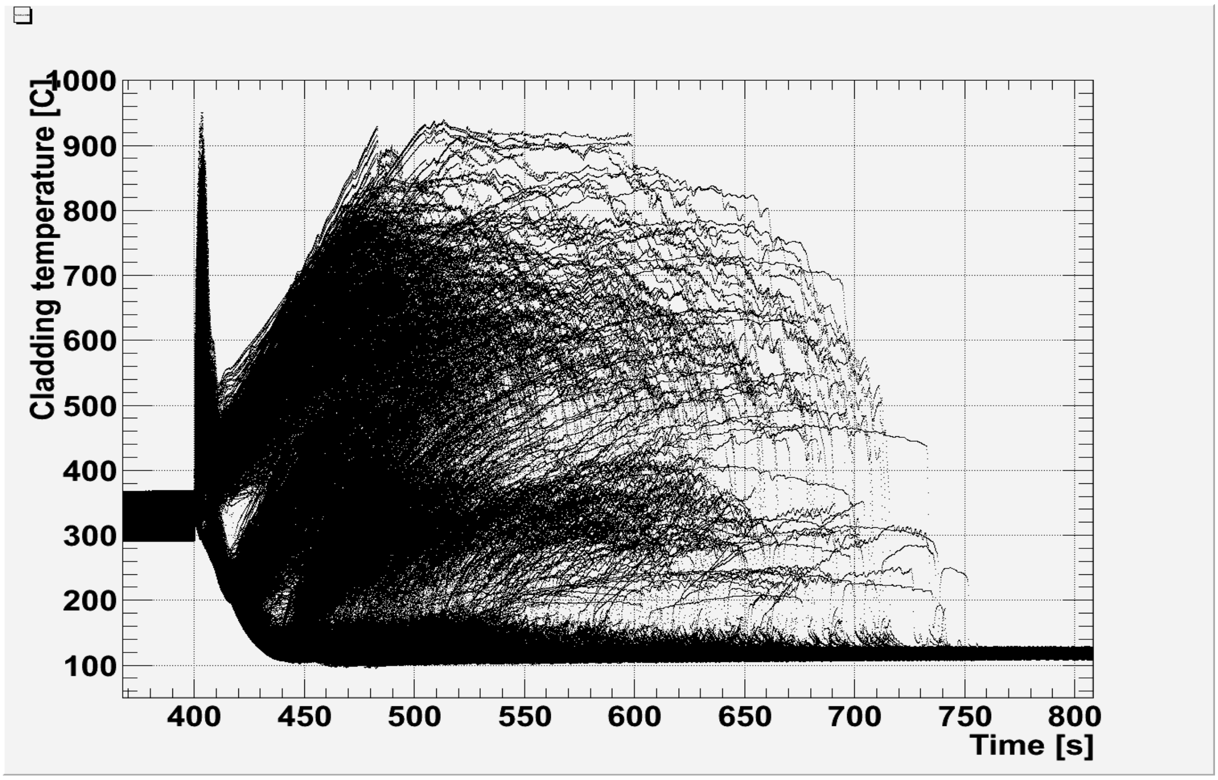
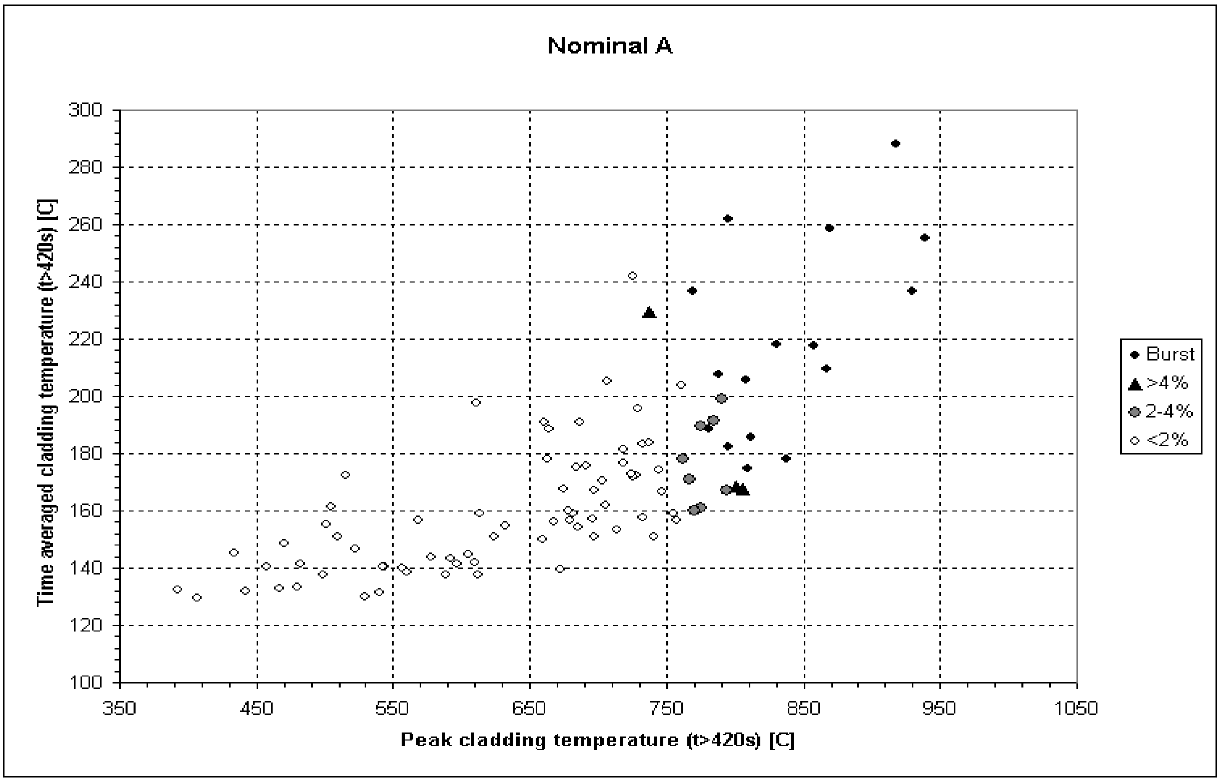


Figure 1 – Cladding temperatures (98 ATHLET runs, boundary conditions for the TM calculations)



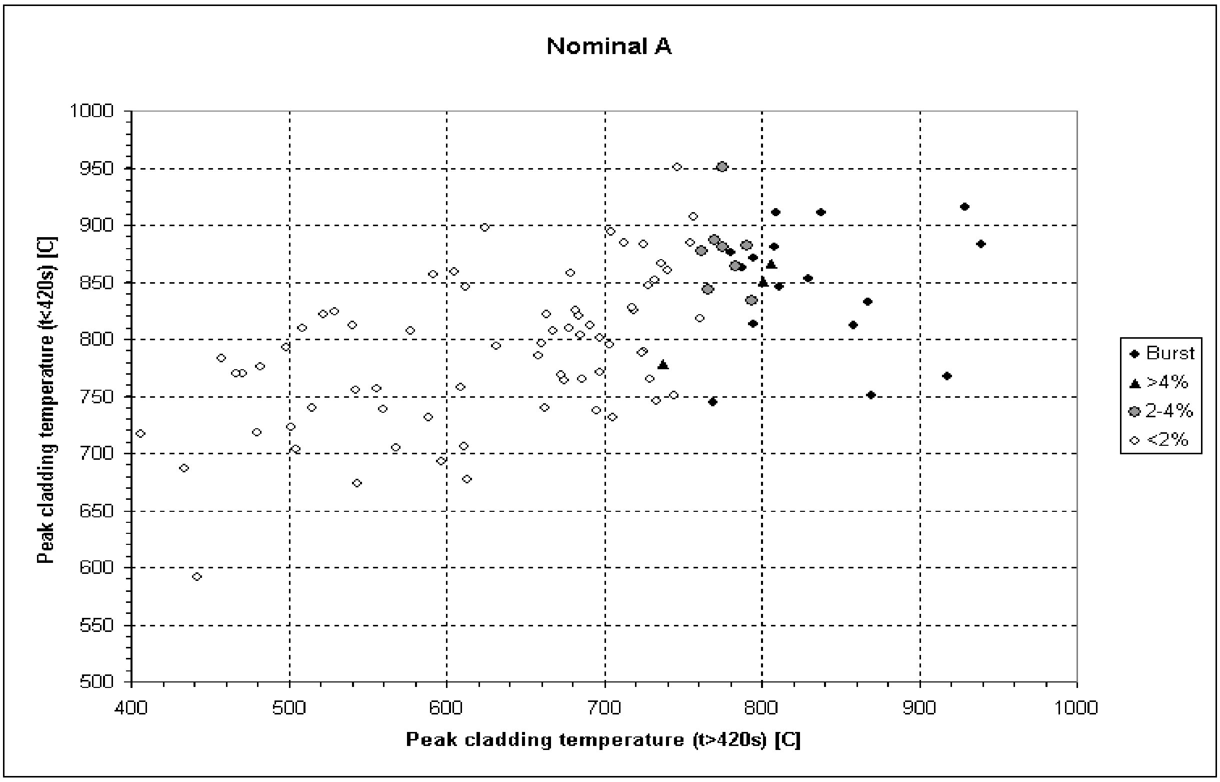


Figure 2– Scatterplots of the FRAPTRAN results for 98 ATHLET boundary conditions. Peak and time averaged cladding temperatures during the blowdown and refill+reflood stages used as the coordinates, the marker type indicates the run results.

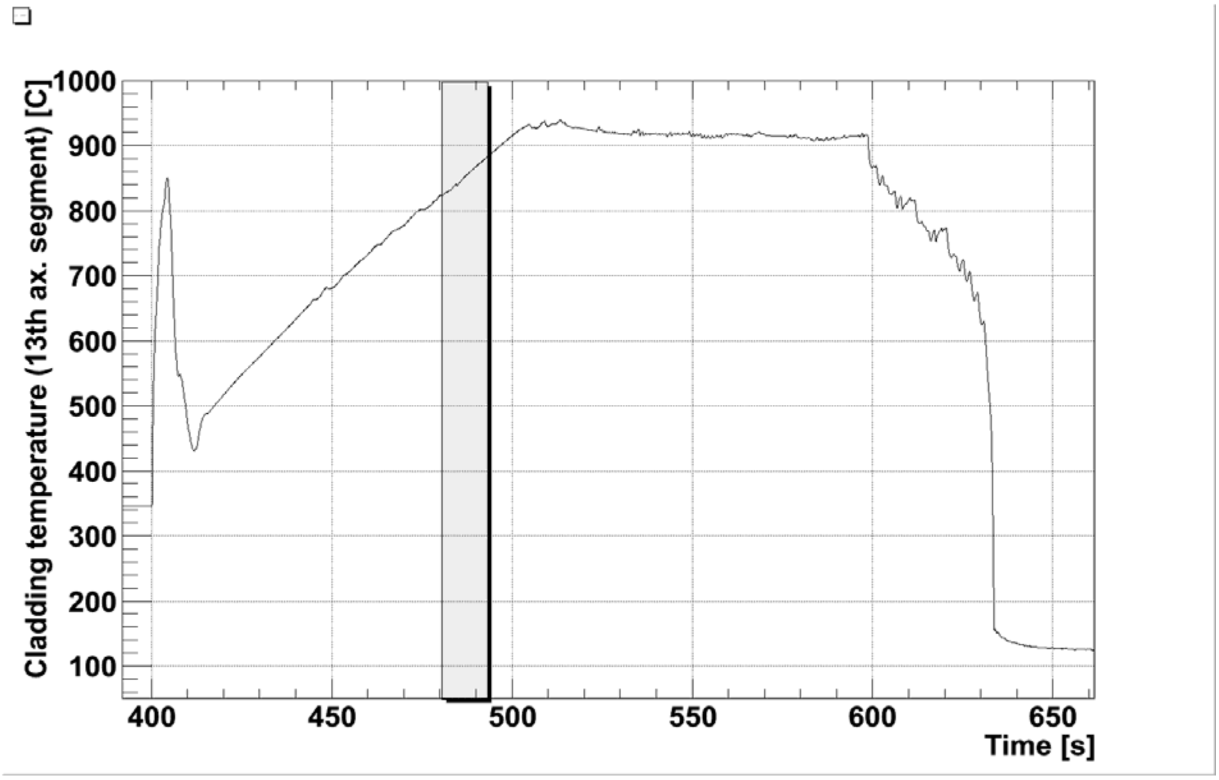


Figure 3 – Cladding temperature of “run 10” at 2.08m (position of the predicted cladding failure). The shaded time interval corresponds to the spread of the estimated burst time.

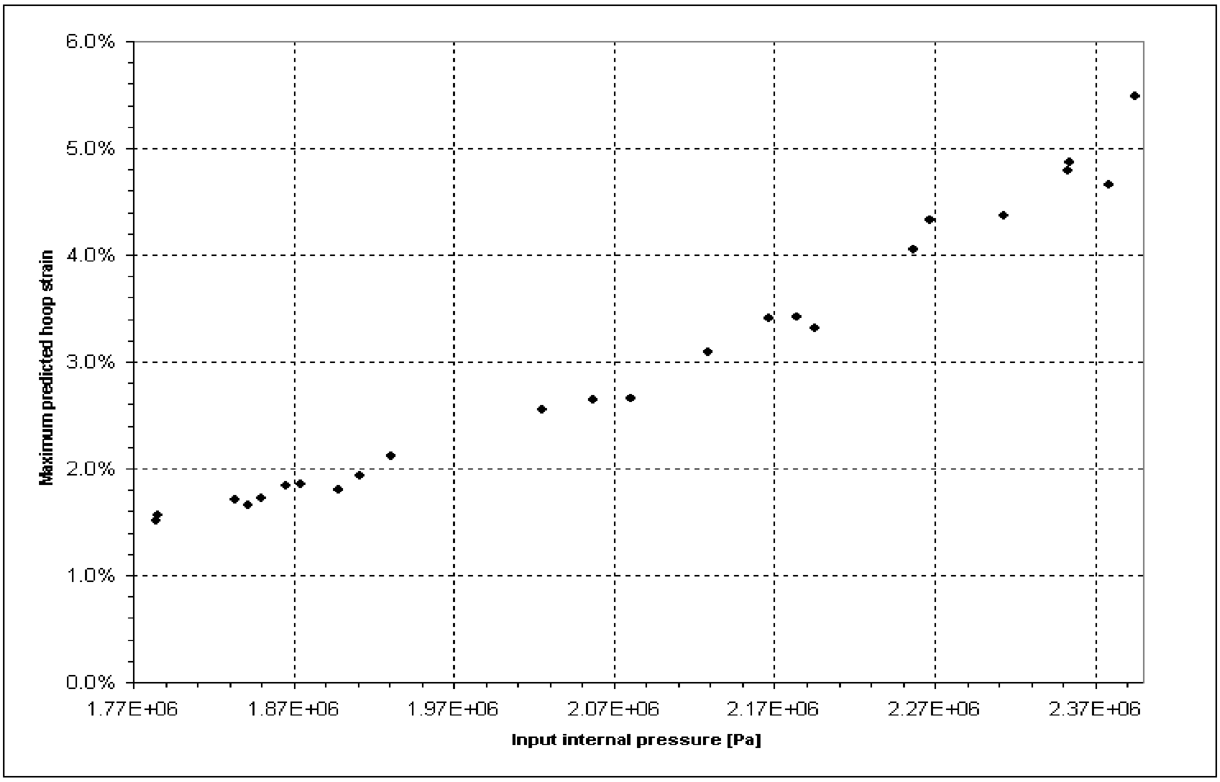


Figure 4 – Max. hoop strain vs. input internal pressure – “run 38” cases.