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EDF
Pellet-Cladding Interaction Modelling

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Abstract

EDF Energy own a number of Advanced Gas-cooled Reactors whose components are beginning to fail due to forces exerted during nuclear fission processes. The following report investigates the effects of stress and strain on the fuel rod cladding within the reactor. The aim of the following work is to accurately predict these forces in order to reduce them, minimising the likelihood of failures in the cladding. It builds on a previous analytical model proposed by EDF Energy intern Mark Blyth. The results of the improved model are compared to the results of EDF Energy's ENIGMA, the current complex simulation used to predict the forces on the cladding. ENIGMA's prediction of stress are taken as the absolute truth for the report. The report shows that through the addition of a previously ignored factor, crack strain, the model is improved. From this improved model, a basic shutdown procedure is suggested that reduces these forces on the cladding of the fuel rod.

Glossary

EDF Energy: An integrated energy company in the United Kingdom.

ENIGMA: An EDF owned programme designed to predict fuel pin damage.

Fuel Pellets/Pellets: Ceramic Uranium 235 pellets that fit inside the rods.

Cladding: The stainless steel rod cover that protects the Uranium fuel pellets.

Hoop Stress: A normal stress directed tangentially to the cylindrical surface of the cladding.

Crack Strain: The term given to the expansion of the fuel pellets caused by the formation of cracks within the pellet itself.

Rating: The measure of how much energy is extracted from a nuclear fuel source - in our case the energy extracted from each fuel pin (kW/m).

Preconditioning Period: A time period where the coolant temperature and rating in a reactor are reduced, usually for maintenance.

Fault: A sudden, uncontrolled increase in rating which in turn spikes the temperature of the reactor.

Gas Gap: The volume of air between the fuel pellets and the outer cladding.

History Profile: A structured list that describes how the past temperatures and rating of the reactors changes with time.

Burn-up: The amount of energy that has been extracted from a fuel source (MWd/tUO_2).

Original Model: An analytical model developed in referenced technical documents - lacks the incorporation of crack strain.

Updated Model: The original analytical model with an updated thermal strain term that incorporates the crack strain.

Definition of Symbols

s_{tot}: Total Strain in Fuel Pellets

s_{th}: Thermal Strain in Fuel Pellets

s_{el}: Elastic Strain in Fuel Pellets

s_{cr}: Creep Strain in Fuel Pellets

s_p: Plastic Strain in Fuel Pellets

s_{ck}: Crack Strain in Fuel Pellets

ϵ_{tot}: Total Strain in Cladding

ϵ_{th} Thermal Strain in Cladding

ϵ_{el} Elastic Strain in Cladding

ϵ_{cr} Creep Strain in Cladding

ϵ_p: Plastic Strain in the Cladding.

$\sigma_{\theta,max}$: Maximum Internal Thermal Stress

α: Thermal Expansion Coefficient

ν: Heat Conduction Parameter (taken to be 16.5

T_c: Centre-line Temperature

T_S: Temperature at the Surface of the Pellet

T_{cl}: Coolant temperature

T_{sd}: Shutdown temperature

E: Young's Modulus of the Fuel

Contents

1 Introduction

The environmental impacts of using fossil fuels are increasingly becoming a concern. Consequently, organisations who supply energy are becoming more responsible for generating electricity through sustainable methods. In 2017 EDF generated more than 8.9 trillion kWh of electricity through nuclear fission [6], an alternative power source to fossil fuels. The operation of nuclear reactors is a potentially hazardous process which requires sophisticated management to ensure safety for employees and the surrounding environment. Ultimately, EDF wish to operate their nuclear reactors in the safest, most efficient way possible to maximise profit and minimise risk; this is what motivates the work in this report.

One type of nuclear reactor used by EDF is the Advanced Gas-cooled Reactors (AGR). These AGRs are relatively old compared to PWRs (Pressurised Water Reactor) and other reactors which operate at much lower temperatures and are therefore considered safer and easier to maintain [5]. However, despite no new AGRs being built, EDF aim to maximise the lifespan for the remaining AGRs in the most efficient manner before they are shut down. This includes minimising maintenance costs.

The AGR reactors are comprised of thin stainless-steel rods, referred to as the cladding, containing ceramic Uranium 235 pellets. Each reactor contains approximately 2500 rods which contain roughly 100,000 fuel pellets, referred to as the fuel. Each reactor undergoes changes in heat throughout its lifetime, for example during the process of shutting down for maintenance and starting up again. These transients in heat mean that the cladding and fuel pellets undergo thermal strain. Typically, the cladding expands and contracts at a faster rate than the fuel pellets. This can result in additional strain on the cladding when it comes into contact with the pellets. These mechanical pellet-cladding interactions (PCIs) can accumulate damage on both the cladding and the fuel pellets, this damage can be magnified during a fault (see Figure 4, curve A). As the temperature pulses great thermal stresses are caused, putting the cladding at risk of rupturing. This has cost implications for EDF as when the cladding of the rod fails, the entire rod must be replaced. The aim of this project is to provide EDF with an accurate model for predicting the stresses exerted on the steel cladding of the rods so that the likelihood of failure can be reduced.

Traditionally EDF have used a program named ENIGMA to model these stresses; this is an extremely complicated and expensive prediction software. Previous work [1] has tried to replicate the results of ENIGMA through the use of analytical models. However, such previous analytical models are not as accurate as EDF desire. The benefit of an analytical model over more complex simulations (i.e. ENIGMA) is that they are easier to modify, enabling EDF to trace which part of the model contributes what to the dynamics of the system. This gives EDF more freedom to implement additional ideas and models as often as they please, at low cost. The way the current analytical model receives inputs and generates outputs is consistent with the ENIGMA model. Currently, it receives a history profile and then predicts the hoop stress over the duration of the history profile. This study focuses on a particular history profile shown by the curve labelled G in Figure 4. This is the history profile that is most common in the life of an AGR reactor.

In this report we build on the existing analytical model (presented by Blyth) in order to increase the accuracy of its predictions of the thermal stresses in the AGRs. This report focuses on two key objectives. The first, to incorporate crack strain into Blyth's model in order to minimise existing discrepancies between ENIGMA simulation predictions and the updated model predictions. By assuming the ENIGMA prediction to be the absolute truth, we can use the output of ENIGMA with various histories to monitor the accuracy of our modified model. The second key objective is to find an optimal shutdown procedure. Shutdown means lowering the reactor's rating in order for maintenance to be conducted whilst minimising the hoop stresses on the cladding to avoid cladding ruptures.

2 Previous Work

The models developed within this report will build on the work of Mark Blyth [1]. In order to improve this model we must first understand his model and its associated shortcomings. This analytical model [1] for finding the stress in the fuel pellets is summarised below. All terms used are defined in the Glossary on page 1.

The total strain in the fuel pellets is found by summing the different components of strain

$$s_{tot} = s_{th} + s_{el} + s_{cr} + s_p + s_{ck}.$$

The strain in the cladding is found by summing the different types of strain

$$\epsilon_{tot} = \epsilon_{th} + \epsilon_{el} + \epsilon_{cr} + \epsilon_p.$$

The stress on the cladding is given by $\sigma_c = \epsilon_{el} E$. With the assumption that there is no gas gap (the cladding and the fuel pellets remain in contact throughout), the total strain in the cladding is assumed to be the same as the total strain in the fuel pellets

$$\sigma_c = E(s_{th} + s_{el} + s_{cr} + s_p + s_{ck} - \epsilon_{th} - \epsilon_{cr}). \tag{1}$$

The thermal strain in both the fuel pellets and cladding is proportional to the change in temperature:

$$s_{th} = \alpha_f(T_f - T_0) = \alpha_f(\nu R + T_c - T_0),$$

$$\epsilon_{th} = \alpha_c(T_c - T_0).$$

The creep strain is the integral

$$\epsilon_{cr} = \int_0^t \dot{\epsilon}_{cr}[\sigma, T_c]dt,$$

where $\dot{\epsilon}_{cr} = 4.4856\text{x}10^7\sigma^{1.724}e^{\frac{-43801}{T_c}} + 9.4257\text{x}10^{-3}\sigma^{5.8152}e^{\frac{-34789}{T_c}}$.

This model relies on twelve assumptions detailed in Section 11.1.1 of Blyth's report [1], including the assumption of negligible crack strain. These assumptions mean that Equation 1 can be simplified further to

$$\sigma_c = E(s_{th} - \epsilon_{th} - \epsilon_{cr}). \tag{2}$$

The above terms are given by:

- $E = (216923.0 - 68.95T_c)$
- $s_{th} = \alpha_f(\nu R + T_c - T_0)$ and $\alpha_f = 8.5524\text{x}10^{-6} + 1.2793\text{x}10^{-9}T_f + 1.32\text{x}10^{-12}T_f^2$, $\nu = 16.5$
- $\epsilon_{th} = \alpha_c(T_c - T_0)$ and $\alpha_c = 1.436\text{x}10^{-5} + 6.0\text{x}10^{-9}T_c$
- $\epsilon_{cr} = \int_0^t 4.4856\text{x}10^7\sigma^{1.724}e^{\frac{-43801}{T_c}} + 9.4257\text{x}10^{-3}\sigma^{5.8152}e^{\frac{-34789}{T_c}} dt$

2.1 Suggested Improvements

Blyth's analytical model replicating the output of ENIGMA is not as accurate as EDF desire. His report suggests multiple key areas for improvement such as the inclusion of crack strain, the gas gap and inexorable swelling, previously ignored factors [1]. This is report is focused on modelling the crack strain.

Crack strain is defined as the expansion of the fuel pellet caused by cracks in the pellet itself.

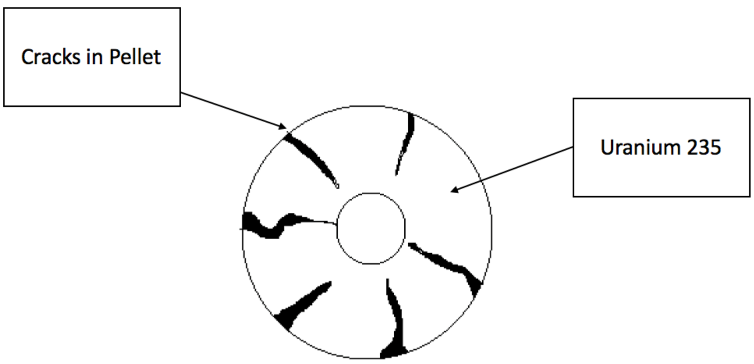


Figure 1: A diagram to show the effect of unstable temperature changes on a fuel pellet and the subsequent cracks formed.

Cracks on the pellet form due to the centre of the pellet having a significantly higher temperature than the edge. Figure 1 shows an example of a cracked pellet. This results in varying thermal expansion throughout the pellet. A crack subsequently forms when the thermal stress exceeds the ultimate tensile strength of the pellet. This report follows the assumption that the fuel pellets are brittle meaning they crack (opposed to stretch) under stress.

Previous analytical models ignore the effect of crack strain. It is believed that this omission partly provides an explanation of the difference in the hoop stress predictions between ENIGMA and the analytical model. Therefore, incorporating crack strain is believed to increase the accuracy of the model.

2.2 Crack Strain Relationship

Here we determine whether crack strain is linearly dependent on (and can be predicted by) factors such as fuel temperature, creep strain, input rating and burn-up.

For a range of temperatures, crack strain is plotted against features such as time, burn-up and creep strain (all variables from the output of ENIGMA). From the graphs in Figure 5 we can infer that there is no linear relationship between crack strain and one feature; crack strain should be modelled as a function of multiple features. Therefore a more complex model is suitable, taking into consideration multiple factors. We examine two previously proposed crack strain models proposed by Blyth [1].

3 Brutzel's Model: Crack Strain in Relation to Thermal Stress

The first model approximates the crack strain due to its relation to the internal thermal stresses. According to a model proposed by Brutzel [3], these can be approximated by the temperature gradient between the centre-line temperature, T_c, and the temperature at the surface of the pellet, T_s,

$$\sigma_{\theta,max} = \frac{E\alpha}{2(1-\nu)}(T_c - T_s).$$

This equation for the maximum internal thermal stress depends on the assumptions listed below.

- The AGR operates at a constant thermal power.
- The thermal expansion coefficient, α, is a temperature-independent constant.
- Finally, the Young's modulus of the fuel, E, and the the thermal conductivity parameter, ν, are constant.

Using a simple model suggested by Blyth [1], the crack strain is given by

$$s_{ck} = k\sigma_{\theta,max}, \tag{3}$$

where k is the *crack constant.*

The value of k is chosen to minimise the difference between the proposed model and the ENGIMA results. This expression for the crack strain is then added to the Blyth's model. Now σ_c becomes $E(s_{th} + s_{ck} - \epsilon_{th} - \epsilon_{cr})$ (noticing the addition of s_{ck} to the original Equation 2).

In addition to the assumptions made, conjectures made using this particular crack strain model will be made with a value for a constant that has no physical explanation. The value of this parameter is not taken from experimental data meaning that this value could cause over-fitting.

3.1 Brutzel's Model Results

The first crack strain model (see Equation 3) requires a value for the *crack constant*, k, which is an unknown. We experimented with a large range of values for k looking at the corresponding error graphs for the disparity between ENIGMA and the output of our model. By observation of the error graphs, the optimal value is found to be approximately 10^8 (see Figure 6). Using this optimal value, we can compare the results of ENIGMA, Blyth's model and Brutzel's crack strain model. We can see that Brutzel's model mirrors Blyth's original model; Brutzel's model does not reduce the error to ENIGMA. It can be seen in Figure 6 the curves overlap. It matches qualitatively with ENIGMA hoop stress curve at the higher temperatures but deviates for lower temperatures.

Figure 7 shows an absolute error plot of the original and Brutzel's model, where the ENIGMA hoop stress curve is considered the absolute truth. At each temperature the residual between the ENIGMA hoop stress curve and both analytical model hoop stress curves are observed. Studying this error plot, we can see that Brutzel's model only improves on Blyth's in small segments of the 600°C, 15kW/m absolute error plot. The average error for each of the preconditioning subplots can be visualised in Table 3, which shows that Brutzel's model fails to improve on Blyth's model. Therefore, we can conclude that the addition of the first proposed crack strain model fails to make significant improvements on the original model and therefore should be disregarded.

4 Blyth's Crack Strain Model: Component of Thermal Stress

Blyth suggests an alternative model in Section 13.0.2 [1], where the crack strain is considered to be a component of the total thermal strain. When this is incorporated into Blyth's original model, this is known as the updated model. This model uses a radial temperature distribution across the fuel pellet. This is calculated numerically using finite element analysis. The total thermal strain is then calculated as s_{tg} which replaces s_{th} in Equation 2. Our new thermal strain is calculated as

$$s_{tg} = \int_0^1 r\alpha(T)T(r)dr, \tag{4}$$

where r is the radius of the fuel pellet, α is the thermal coefficient and $T(r)$ is the temperature distribution. $T(r)$ is further given by,

$$T(r) = \text{rating} \times [-17.438r^3 + 3.575r^2 - 2.550r + 16.473] + \text{clad temp.}$$

We take the same equation for α as used in the ENIGMA code. We can formulate an expression for α in terms of temperature,

$$\alpha(T) = 8.5524\text{x}10^{-6} + 1.2793\text{x}10^{-9}T + 1.32\text{x}10^{-12}T^2,$$

where T is the fuel temperature. Substituting the expressions for both $\alpha(T)$ and $T(r)$ into Equation 4 yields a solution to the integral

$$\begin{aligned} s_{tg} = {} & 660\text{x}10^{-15}T_c^3 + (639.650\text{x}10^{-12} + 18.979\text{x}10^{-12}R)T_c^2 \\ & +(4.276\text{x}10^{-6} + 12.262\text{x}10^{-9}R + 227.103\text{x}10^{-12}R^2)T_c \\ & +73.367\text{x}10^{-9}R^2 + 989.458\text{x}10^{-12}R^3 + 40.989\text{x}10^{-6}R. \end{aligned}$$

where T_c is the temperature of the cladding (in Centigrade) and R is the rating in kW/m. In contrast to the previous crack strain model, the s_{tg} term will directly replace the s_{th} term in Equation 2 of Blyth's model, $\sigma_c = E(s_{tg} - \epsilon_{th} - \epsilon_{cr})$.

There are three main flaws to modelling the crack strain in this manner [1]. These are as follows:

- The temperature distribution is assumed to remain constant after cracking and thermal expansion occur.
- Any thermal stress is assumed to induce a crack in the cladding. However, in reality, only thermal stresses exceeding the ultimate tensile strength of the stainless steel material will lead to cracking.
- In reality, the degree of crack opening in limited. This is not the case in our model due to the omission of: the compressive effects of the cladding and the friction between the pellet and cladding.

4.1 Blyth's Crack Strain Model Results

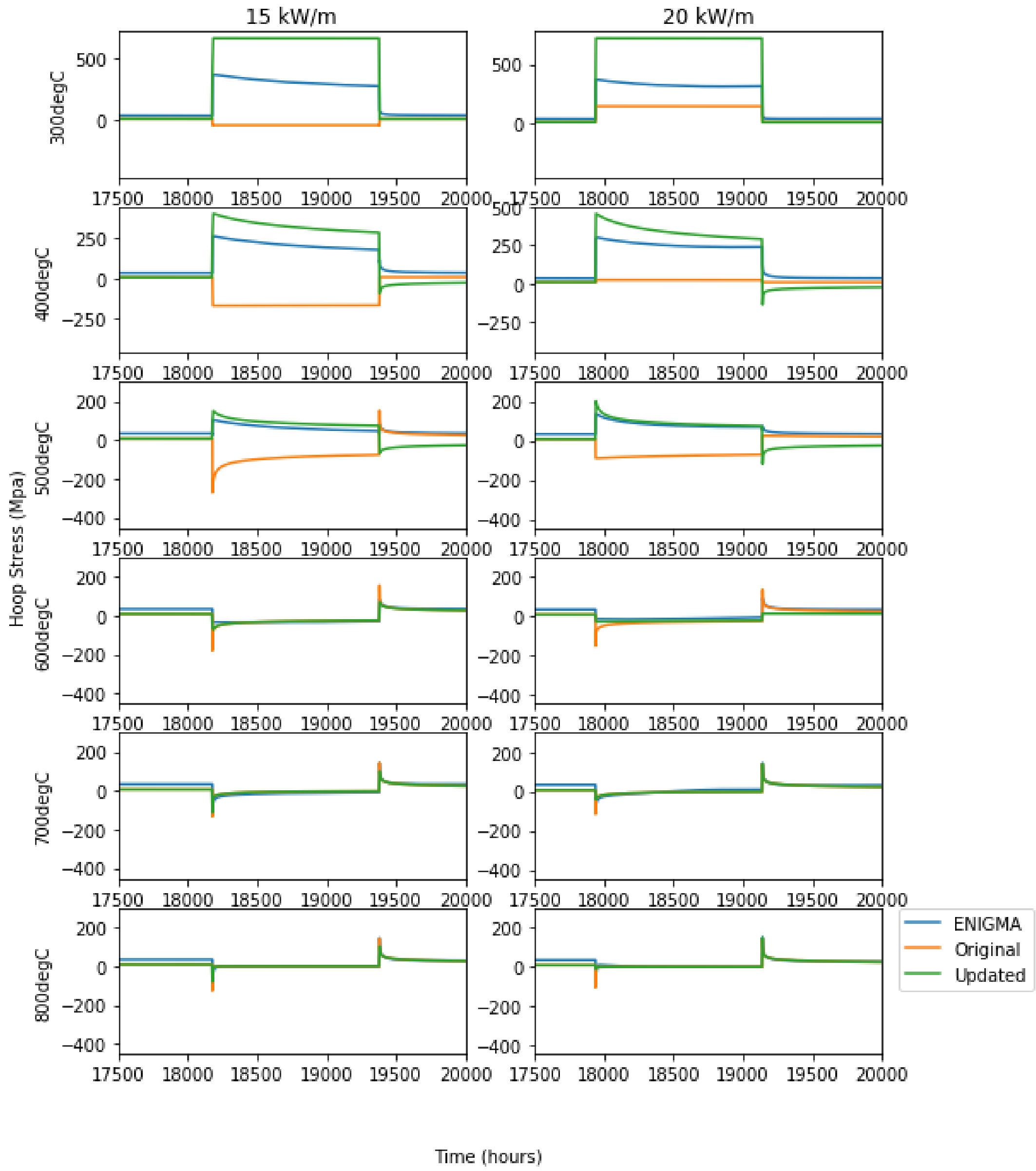


Figure 2: Comparison of hoop stress against time for different temperatures and ratings. The plots show the ENIGMA, Blyth's model and the updated analytical model incorporating the second crack strain model. Assumes 612°C and 25kW/m operating conditions where the preconditioning conditions are as noted in each individual subplot.

	Blyth's Model		Updated Model	
Rating / Temperature	15kW/m	20kW/m	15kW/m	20kW/m
300°C	184.9	102.4	186.9	206.5
400°C	195.8	126.9	81.7	70.9
500°C	86.0	87.0	37.5	33.9
600°C	11.6	17.0	11.5	19.4
700°C	12.7	10.3	12.8	10.4
800°C	9.4	6.8	9.4	6.8

Table 1: Normalised cumulative absolute error (sum of residuals between ENIGMA and the updated model) between times 17500 hr and 20000 hr for Blyth's model (developed in reference [1]) and the updated model (with the second crack strain model incorporated).

In order to visualise if and where the updated model incorporating the second crack strain model improves on Blyth's model, we compare the predicted hoop stresses of the three models (ENIGMA being the third). As each model uses different/irregular time steps the data must first be interpolated to give appropriate approximations at regular time intervals. The error is defined as the absolute difference between the model output and the corresponding ENIGMA output. A graph of these errors is plotted in Figure 8 for a time frame of 175000 and 20000 hours. A normalised error is calculated over the whole time frame. These errors are compiled in in Table 1 as a measurement of the new model's success compared to Blyth's model.

Comparing the results of the three models - the updated model (where the crack strain is modelled as a function of thermal strain), Blyth's model and the ENIGMA output - we can see how the additive crack strain effects prediction of the hoop stress. As seen in Figure 2, the updated model incorporating crack strain is generally more accurate at predicting the stress compared to Blyth's model: in other words, at most temperatures and ratings the updated model replicates the output of ENIGMA equally or better than Blyth's model.

The graphs in Figure 8 (showing the error between the updated model and ENIGMA) supports the argument that the updated model incorporating crack strain offers a more accurate prediction of the hoop stress. At various temperatures, the success of the updated model varies, offering a more accurate prediction at specific conditions. However, despite this, it is important to note where the updated model fails at accurately modelling ENIGMA.

At temperatures of 400°C and 500°C, the updated model offers a significant improvement to Blyth's model. At 400°C, despite a remaining disparity between the hoop stress predicted by ENIGMA, the shape of the graph is accurate. Blyth's previous model predicted a negative (or zero-value) hoop stress while the output of ENIGMA was a positive, curved function. The updated model predicts a positive, curved function, similar to ENIGMA, and therefore is a huge improvement.

At the lowest temperature of 300°C, the updated model is not able to replicate the output of ENIGMA accurately. The fact that the 20kW/m for 300°C is significantly worse at predicting ENIGMA than the version without crack strain suggests that in the current model, the rating is having too great an effect compared to the temperature.

At temperatures of 600°C to 800°C Blyth's model was able to approximate the hoop stress successfully, there was not a need for significant improvement at these higher temperatures. The updated model is able to maintain these predictions, while also improving the prediction of lower temperatures as mentioned above.

5 Optimal Shutdown Procedure

Shutdown is the ramp down of rating to a preconditioning period, where the reactor is brought down to a low-power state so that maintenance can take place. This process is shown by the rating curve G in Figure 4. During these shutdowns, the cladding and fuel pellets contract. Generally, the cladding tends to contract and expand at a higher rate than the fuel pellets. Therefore, this contraction results in mechanical pellet-cladding interactions, inducing stress in the cladding. The cladding then expands when the reactor is subsequently brought back to a higher power, which again induces a stress in the cladding. The magnitude of the resulting stresses is dependent on the preconditioning of the fuel.

Given a significant period of time at a constant temperature, the cladding can creep onto the fuel pellet, resulting in a slow release of internal stresses. In other words, it deforms in accordance to its surrounding environment. An optimal shutdown procedure will have both optimal ramp down and ramp up periods that will make use of the creep phenomena. This optimal shutdown must be considered in order to maintain minimum hoop stress, more importantly a minimum positive hoop stress value, in order to minimise the accumulated damage caused to the cladding. This optimal procedure can depend on several parameters, including the shutdown/start-up period, the time the reactor spends in shutdown (time spent at preconditioning conditions) and the temperature and rating the reactor operates at during the shutdown period (preconditioning conditions).

In theory, the optimal shutdown procedure would be one in which the peak hoop stresses in the cladding is zero. However, in reality, this is impractical because as noted in Section 7.1 of Wheen's report [2], the ramp up duration needs to be significantly longer than the preconditioning period. An infinitely long ramp up period would in theory reduce the hoop stress to zero [2].

The models presented below examine how to minimise the positive stress within the reactors. The positive stress is the focus of the report as it is more damaging to the reactors than the negative stress. This is because the positive stress implies that the cladding is expanding indicating there are tensile stresses acting on the cladding. If these tensile stresses exceed the ultimate tensile stress of the material, it can cause the cladding to rupture. In contrast, the negative stress implies the cladding is compressing.

5.1 Optimal Temperature-Rating

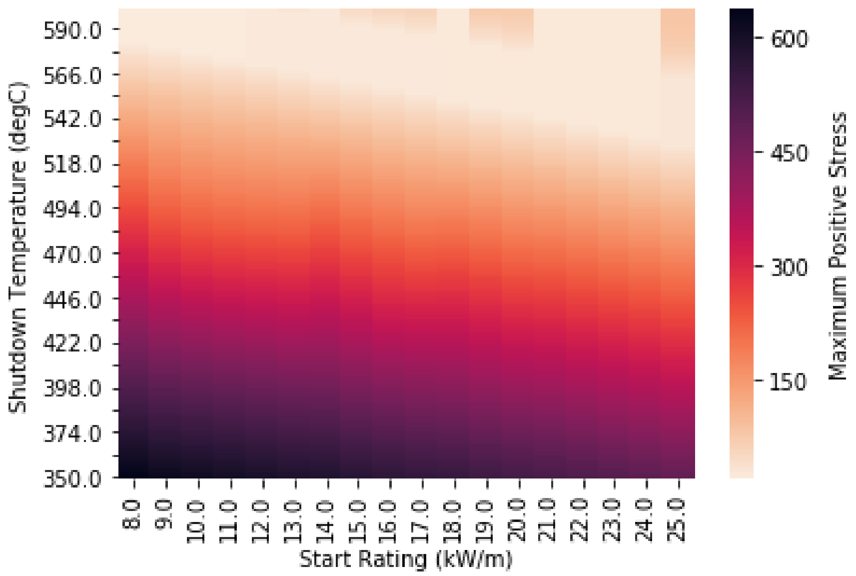


Figure 3: Shutdown to 40% of the rating from a start temperature 612°C. Maximum positive stress during shutdown is shown by the colour gradient with darker colours demonstrating the higher stress. The optimal line of minimum stress can be seen in Equation 5.

An important assumption to find the optimal temperature and rating for shutdown is that they can be treated as independent variables. The maximum positive stress during shutdown is found for a range of temperatures and ratings. The rating is reduced to 40% of its initial value for shutdown [4]. The results of this are seen in Figure 3. The pale colour near the top of the figure demonstrates that the stress is minimised along this optimal line. Linear regression is used to establish the equation of this line, relating the temperature at shutdown to the start rating

$$T_{sd} = (-3.266 \times R) + 611.171, \tag{5}$$

where T_{sd} is the temperature during shutdown and R is the rating before shutdown occurs. Overall the figure shows that the stress is minimised when the temperature is kept high as the rating is reduced. This result suggests that the drop in temperature is a significant aspect of the increase in positive stress in the reactor. Furthermore a comparison of the 500°C graph in Figure 2 and Figure 11 shows that this optimal line does reduce the hoop stress as it is significantly less in the latter.

5.2 Optimal Time

The previous model relies heavily on the assumption of the independence of temperature and rating. In reality, as the rating decreases, so does the temperature. Therefore this second model improves on this assumption. If the rating is reduced by 40% then the temperature also reduces [4]

$$T_{sd} = ((T_{st} - T_{cl}) \times 0.4) + T_{cl}, \tag{6}$$

where T_{sd} is the shutdown temperature, T_{st} is the start temperature and T_{cl} is the temperature of the coolant (300°C). The length of time to ramp down to the shutdown rating is then varied for rating curve G (see Figure 4). The history profile is therefore similar to the one used previously to produce the results in Figure 2. However, the time taken to ramp to the shutdown rating is increased. Plotting this for a range of ratings (and thus temperatures as they are now related by Equation 6) demonstrates the effect of time on the maximum positive stress during shutdown. The range of starting conditions is taken from the normal range of operating conditions (10-25kW/m and 550-850°C for high burn-up [4]). Furthermore, it is assumed that the temperature and rating for the starting conditions decrease proportionally. For example, decreasing the temperature by 50% also decreases the rating by 50%.

In Figure 12 the colour gradient of the positive stress does not give sufficient information to pick up the important trends. From Figure 13 the effect of time can be more clearly seen as the stresses are plotted for individual ratings. This Figure suggests that as the time increases there is a reduction in the stress, however these changes are relatively small. Therefore it can be concluded, for the range of time plotted, that the start rating has a greater effect on the positive stress than the length of time taken to ramp down.

Figure 14 shows the maximum negative stress during shutdown, there is no noticeable trend for the ratings plotted. This could be due to the implications of the assumptions made, causing issues within the model. A rating 10kW/m correlates to a 550°C start temperature and a shutdown temperature of 400°C. The model used does not accurately predict the negative stress for temperatures around 400°C, as seen in Figure 2. For the range of temperatures, 400-600°C negative stress is not modelled accurately. This is roughly the range of temperature at shutdown suggesting that the current model is not suited to finding the optimal shutdown procedure in relation to negative stress.

6 Discussion

Referring back to the Introduction of this report, the two key objectives of this project are listed below.

- Incorporate a crack strain model into a previous analytical model to remove the disparity between the ENIGMA hoop stress prediction and the analytical model hoop stress prediction.
- Use the improved analytical model to predict an optimal shutdown procedure.

Analysing our findings for the implementation of Brutzel's crack strain model, we found that the model incorporated failed to make significant improvements to the analytical model (Blyth's model), in terms of minimising the discrepancies between the analytical model and ENIGMA. Moreover, it also includes a constant that would require experimental data in order for it to be evaluated correctly. Given the time-scale and the confidentiality of the project, evaluating this constant accurately proved to be a challenging task.

Consequently, we decided to reject this crack strain model and explore other models that release some of the assumptions made in its derivation. This is because the first version models crack strain linearly.

Temperature \ Rating	15kW/m	20kW/m
300°C	+ 2	+ 104.1
400°C	-114.1	- 56
500°C	-48.5	- 53.1
600°C	-0.1	+2.4
700°C	+0.1	+0.1
800°C	0	0

Table 2: A table showing how the updated model performs in comparison to the original model (the change in discrepancies between ENIGMA and the updated model and the discrepancies between the original model and ENIGMA). A negative value indicates an improvement and a positive value indicates a deterioration from Blyth's model.

Following the rejection of the first, a second proposed model of crack strain was analysed in which crack strain is modelled as a component of thermal strain. Here, the effect of incorporating the second crack strain model into the original analytical model is analysed. Table 2 above shows how the normalised absolute error varies for different preconditioned temperatures and ratings. The table is colour-coded in the following way (a significant change is assumed to be any absolute value greater than 1).

- If the incorporation of crack strain causes a significant improvement in the accuracy of Blyth's model then the cell is highlighted in GREEN.
- If the incorporation of crack strain causes a significant reduction in the accuracy of Blyth's model then the cell is highlighted in RED.
- If the incorporation of crack strain has little or no effect on the accuracy of Blyth's model then the cell is highlighted in GREY.

For temperatures 700°C and 800°C Blyth's model was sufficient in predicting the hoop stress; the updated model matches this success. However, the updated model offers a significantly improved version at temperatures of 400°C and 500°C. In reality, the, lowest operating temperature is suggested to be 550°C [4]. Reactors working at 550°C do not typically reach temperatures lower than 400°C even during shutdown procedures. Therefore, we envision that improving the accuracy of the original model at 400°C and 500°C will have the greatest benefit to EDF.

This is a useful conclusion for EDF; we advise them to build on the second model of crack strain (whilst disregarding the first). We suggest they do not take this model as the absolute truth, however it is a useful tool as a foundation for improving previous analytical models. A key advantage of using an analytical model over the current ENIGMA simulation is the ability to easily deconstruct the model. This will allow EDF to change and modify parameters to model hypothetical situations in a more practical manner. Furthermore, the analytical model is considerably easier to understand giving EDF the potential to develop it further, something that cannot currently be done with ENIGMA without expert software developers.

Predicting the optimal shutdown procedure proved to be a complex task with multiple limitations. We were only able to provide a basic model which can be further built upon to accurately predict the optimal shutdown. We have provided a simple model, ignoring the effects of various factors. Despite the simplicity of our model, we are able to demonstrate how the task should be undertaken, offering a foundation which can be further developed by incorporating previously ignored factors to produce an accurate result, predicting the optimal shutdown procedure. Our model showed the advantage of keeping the temperature high while reducing the rating to minimise the hoop stress. Furthermore, the second method suggests that in general it is worth increasing the time for ramp down. However, more work needs to be done to find the optimal time as a shutdown requiring a very long time period is impractical and costly. To conclude, we are able to offer EDF a higher functioning model that can be used to suggest an improved shutdown procedure to reduce the strains on the cladding within the reactor.

7 Limitations and Further Work

As noted above, despite some successes, there are numerous ways in which the models presented in this report could be further improved and developed. Models could be made more complex, incorporating factors previously ignored to produce a more accurate outcome. Here, such improvements are discussed.

7.1 Analytical Model

The model presented in this report does offer an improved version of original analytical models through the incorporation of (previously ignored) crack strain. However, as noted, our model is not perfect; there remains disparity between ENIGMA and the final model presented. The motivation of further work would be to ultimately remove this disparity completely; producing a 'perfect' analytical model replicating the results of ENIGMA identically. There are a number of factors which remain ignored in the updated analytical model. Such factors include the gas gap and inexorable swelling.

The 'gas gap' refers to the volume of air between the fuel pellets in the reactor and the outer cladding (analogous to a packet of polo mints, the gas gap is the air between the edge of the polo mint and the wrapping). In this report, we assume throughout that the fuel pellets are in constant contact with the outer cladding. This is in fact not the case. There can exist a small volume of air between each fuel pellet and the cladding. The omission of the gas gap in our model may contribute to the remaining disparity to ENIGMA; incorporating the gas gap into the updated analytical model may improve its accuracy.

A second ignored factor in the updated analytical model is the potential for inexorable swelling. Again, the omission of this factor could provide reasoning for the remaining inaccuracy in our results. Inexorable swelling occurs when fission gas is released in the reactor. This exerted gas puts pressure on the outer cladding, causing swelling. An extension of our model would be to investigate and incorporate the effects of inexorable swelling. This is a particularly important factor as it means that the cladding is always undergoing a base level of strain. This, in particular, could be causing an issue with the greater negative stress predicted by our model at specific temperatures.

Finally, an extension of this project would be to investigate the behaviour of fuel at two ages: 18G and 1G (a few years old and a few months old respectively). In this project, we assume all fuel is of the same age, we do not investigate the potential difference in behaviour and therefore the effect on the creep strain for fuel of multiple ages.

7.2 Optimal Shutdown

The second part of this report derives a model which can be used to determine the optimal shutdown procedure of a nuclear reactor. The model has areas which could be developed to increase the accuracy of the result, and ultimately offer EDF a safer, more economical shutdown procedure.

One area in which EDF have the potential to develop the model is to investigate the negative stress produced. The optimal relation of temperature and rating for negative stress is not investigated in this report; we focus on only the positive stress as this is taken to be more damaging to the reactor and therefore our primary concern. This is not to say that negative stress does not damage the reactor. The impact of negative stress should be investigated further once the analytical model has been improved.

EDF have previously suggested that lowering the rating over a longer time period optimises the shutdown of nuclear reactors [4]; our model backs up this hypothesis for positive stress. An area left for EDF to investigate is finding the optimal time taken to reduce the rating of the reactor effects as our method only establishes the fact that there is a reduction.

References

[1] M Blyth. *"An Investigation Into The Contribution Of Creep Models To Preconditioning." 2018. used on 02-2018*

[2] L Wheen. *"ENIGMA Parametric Study." 2017. used on 02-2018*

[3] L Van Brutzel, R Dingreville, and TJ Bartel. *"Nuclear fuel deformation phenomena." 2015. used on 02-2018*

[4] C Young, EDF. *Private Communications, Febuary 2019.*

[5] The Institution of Electrical Engineers. *Nuclear Reactor Types, November 2015. used on 02-2018*

[6] EDF Energy. *EDF Facts and Figures, 2017.* `https://www.edf.fr/en/the-edf-group/dedicated-sections/investors-shareholders/financial-and-extra-financial-performance/edf-group-s-facts-and-figures` *used on 02-2018*

Appendix

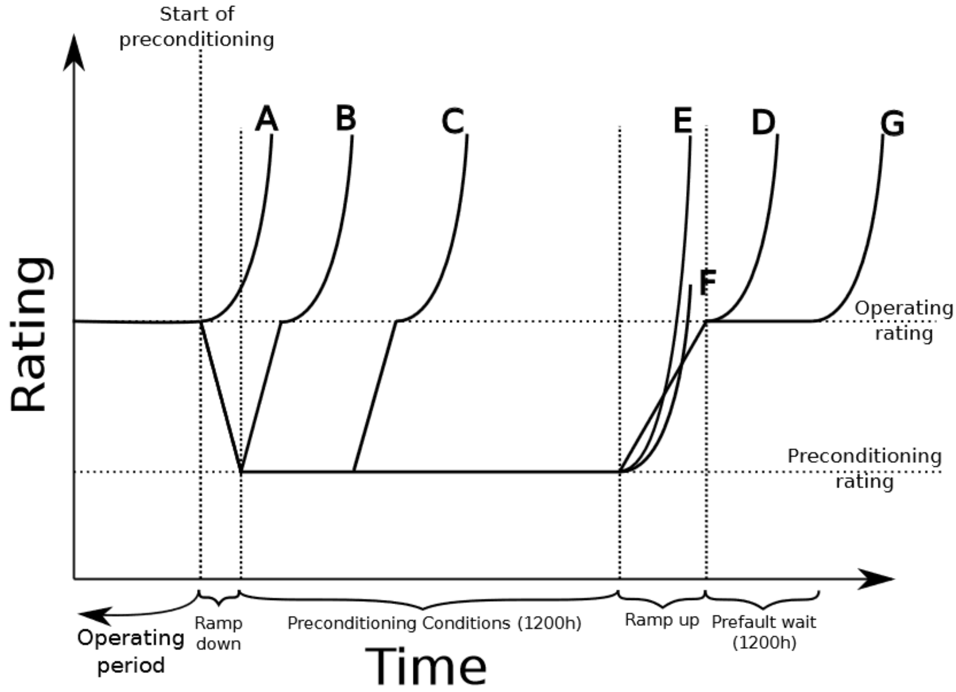
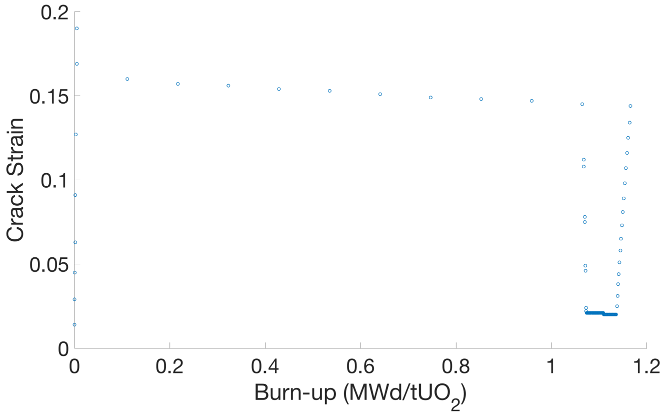
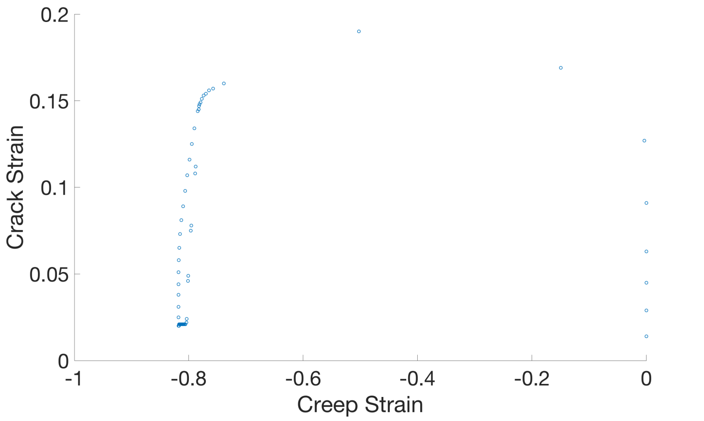


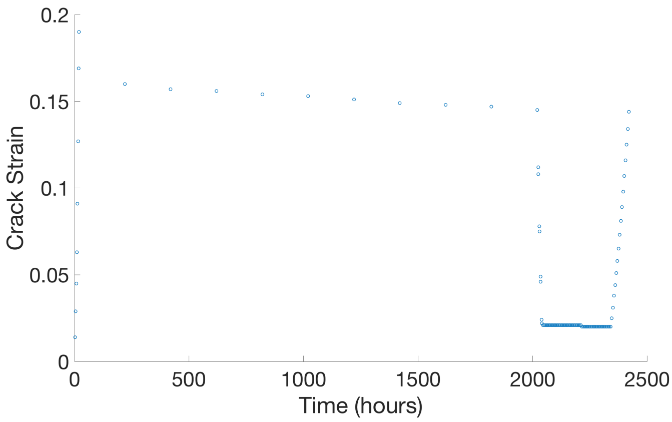
Figure 4: History profiles for the preconditioning cases, where the time spent at preconditioning conditions is labelled the preconditioning period. Case G is the particular history profile that is explored in this scientific document; the other cases are examples of faults occurring at various points along the shutdown procedure. The reactor is ramped down to a preconditioning period and then ramped back up to a pre-fault period - Figure taken from Bylth's report [1].



(a) A graph to show the relationship between burn-up and crack strain at a temperature of 650°C.



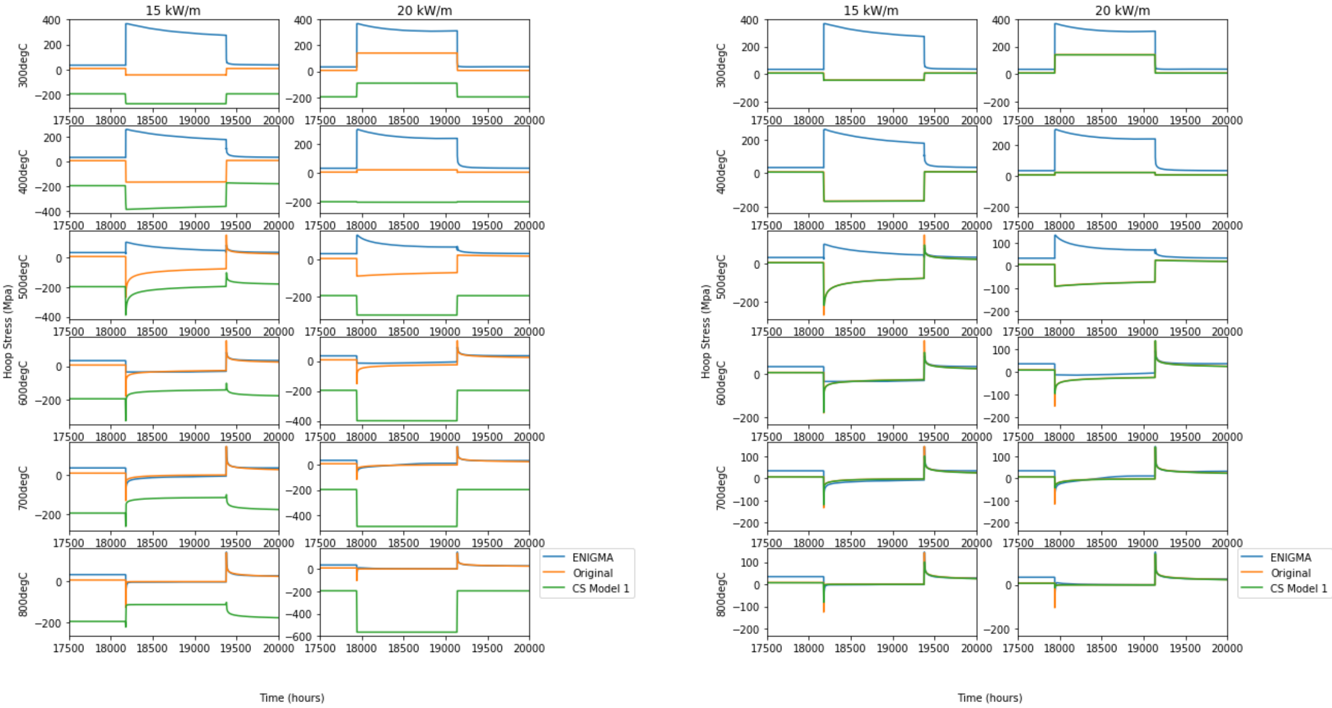
(b) A graph to show the relationship between creep strain and crack strain at a temperature of 650°C.



(c) A graph to show the relationship between time and crack strain at a temperature of 650°C.

Figure 5: A selection of graphs to show that crack strain is not linearly dependent on other features such as creep strain and burn-up. Not all features are displayed here but the above give, sufficient proof that crack strain cannot be modelled linearly. The results here indicate that we must model crack strain taking a non-linear approach when incorporating it into the analytical model.

Figures 6, 7, 8, 9 and 10 assume 612°C and 25kW/m operating conditions, where the preconditioning conditions are as given in each individual subplot.



(a) $k = 5 \times 10^5$ (b) $k = 1 \times 10^8$

Figure 6: Comparison of hoop stress predictions against time. The plots compare the hoop stress predictions for ENIGMA, the original analytical model and the proposed model with Brutzel's crack strain model incorporated. Furthermore, the subplots show how the *crack constant*, k, impacts the hoop stress prediction of the proposed crack strain model.

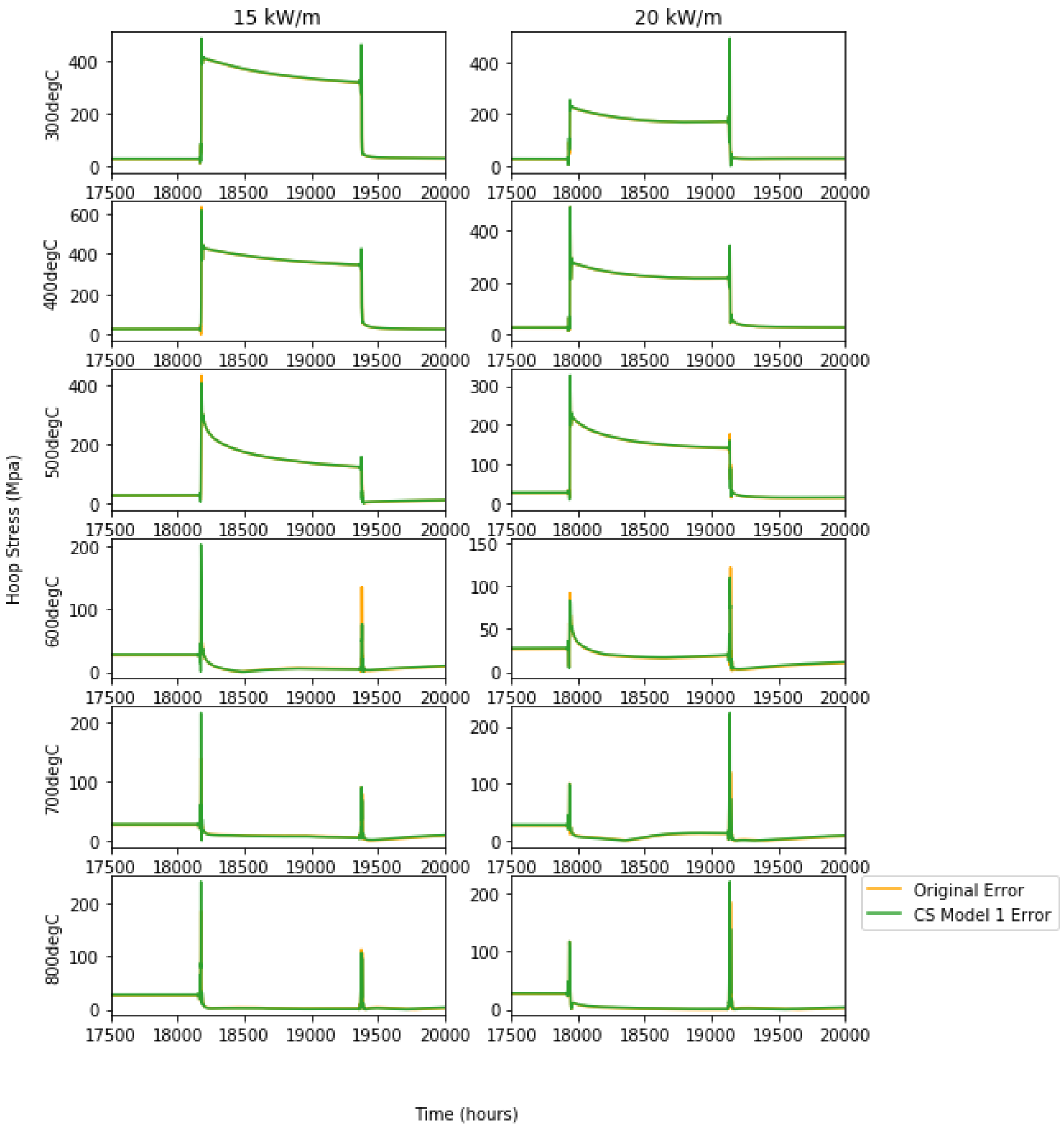


Figure 7: Absolute error plot for the original analytical model and the proposed model with Brutzel's crack strain model incorporated ($k = 10^8$) where the ENIGMA hoop stress curve is considered the absolute truth.

Table 3: Normalised cumulative absolute error (the difference between the ENIGMA hoop stress curve and the model) for both the original model and the proposed model with Brutzel's crack strain model incorporated with $k = 10^8$.

	Original		Proposed Model	
Rating / Temperature	15kW/m	20kW/m	15kW/m	20kW/m
300°C	184.9	102.4	185.9	103.4
400°C	195.8	126.9	196.9	127.7
500°C	86.0	87.0	86.9	87.9
600°C	11.6	17.0	12.1	17.9
700°C	12.7	10.3	13.1	10.9
800°C	9.4	6.8	9.4	7.4

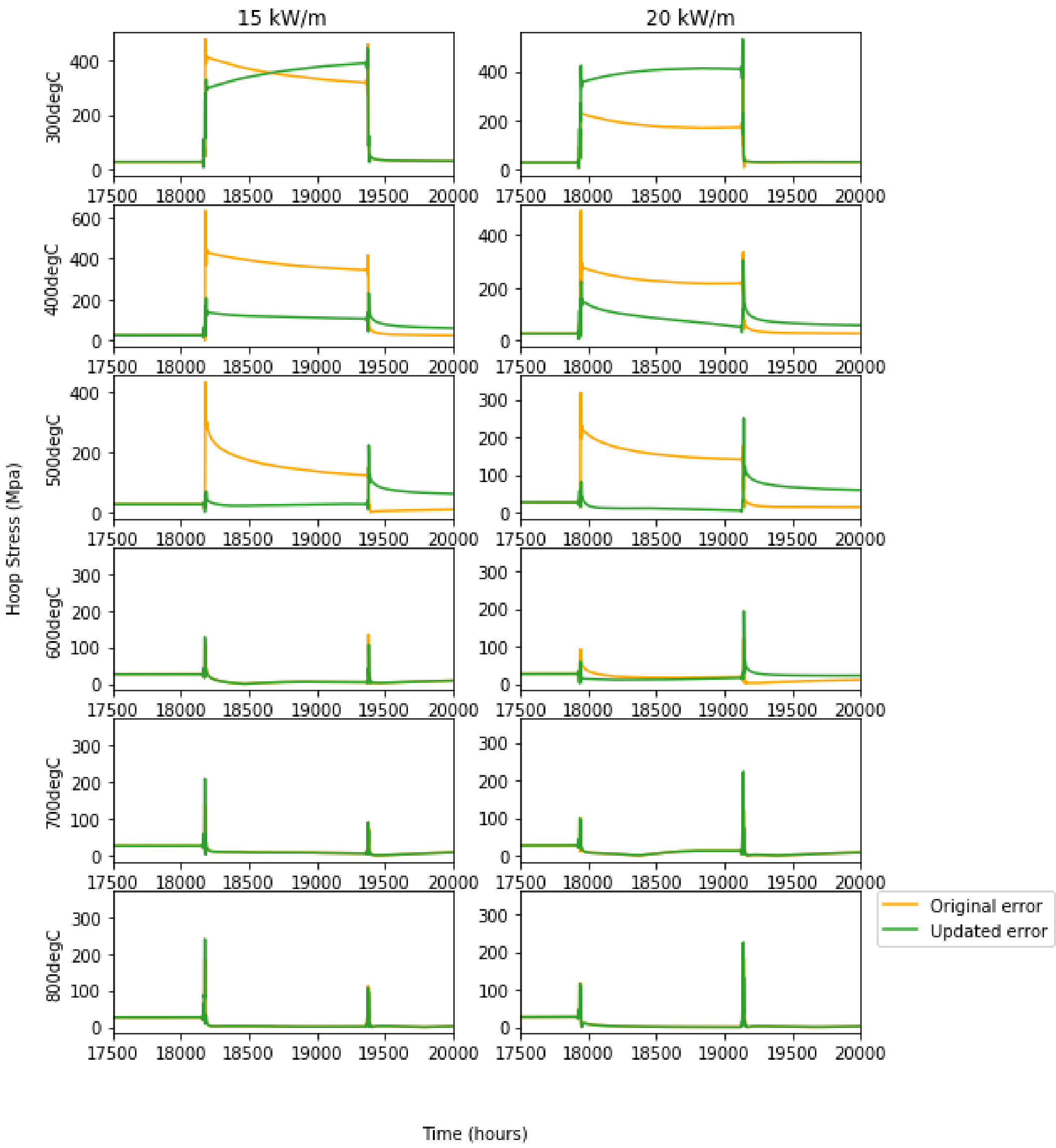


Figure 8: Absolute error plot for the original model and the new, updated, model with Blyth's crack strain model incorporated where the ENIGMA hoop stress curve is considered the absolute truth.

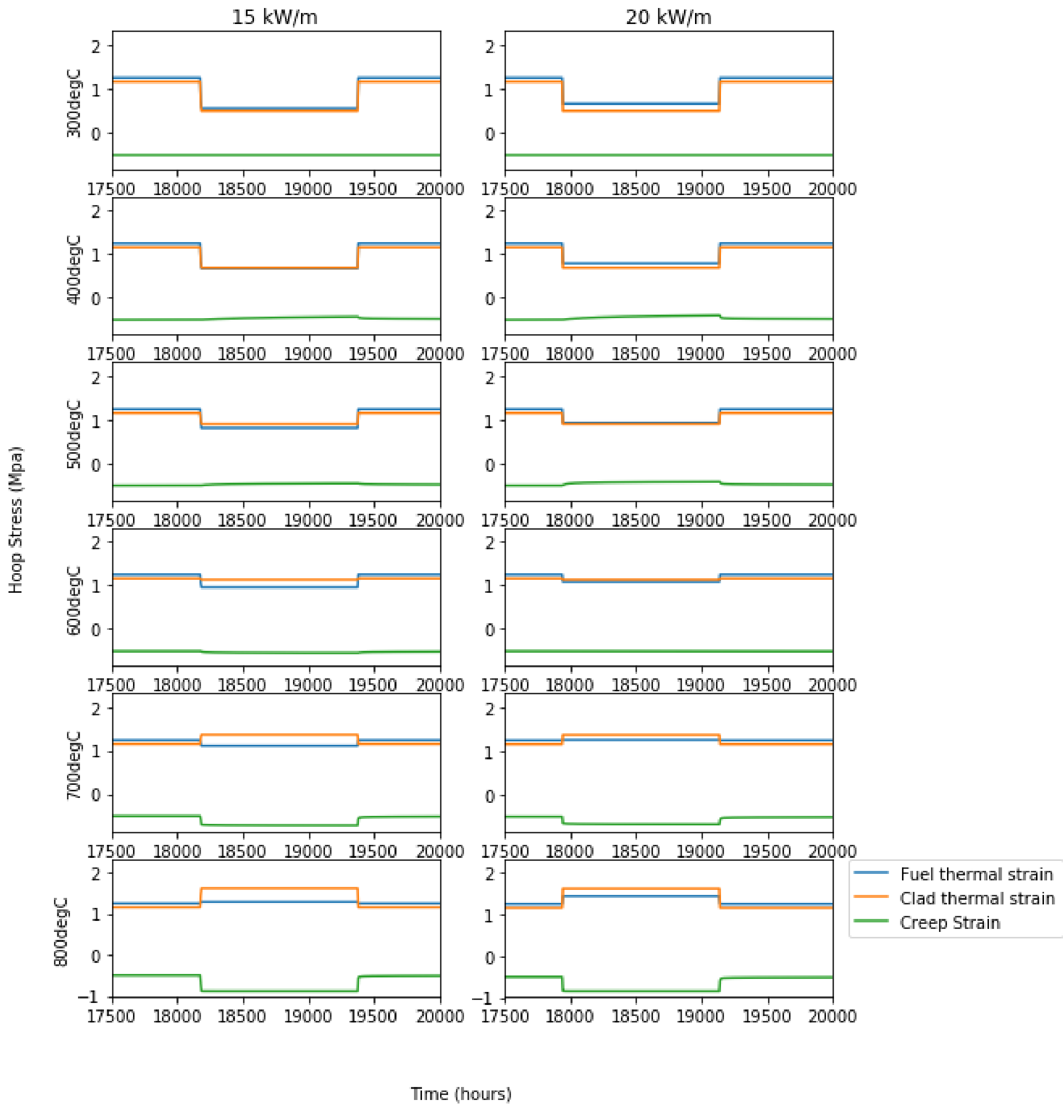


Figure 9: Individual stress components for the updated analytical model.

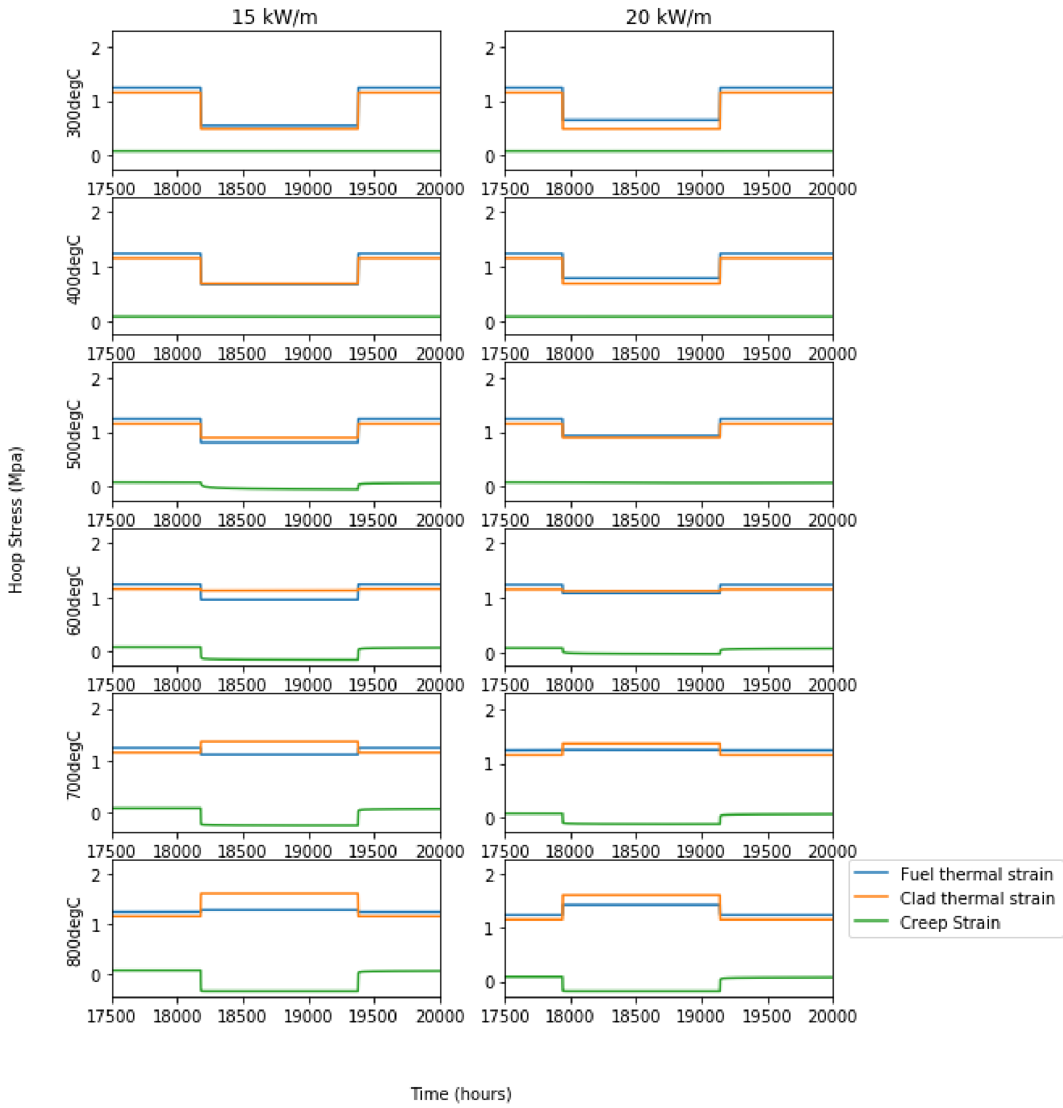
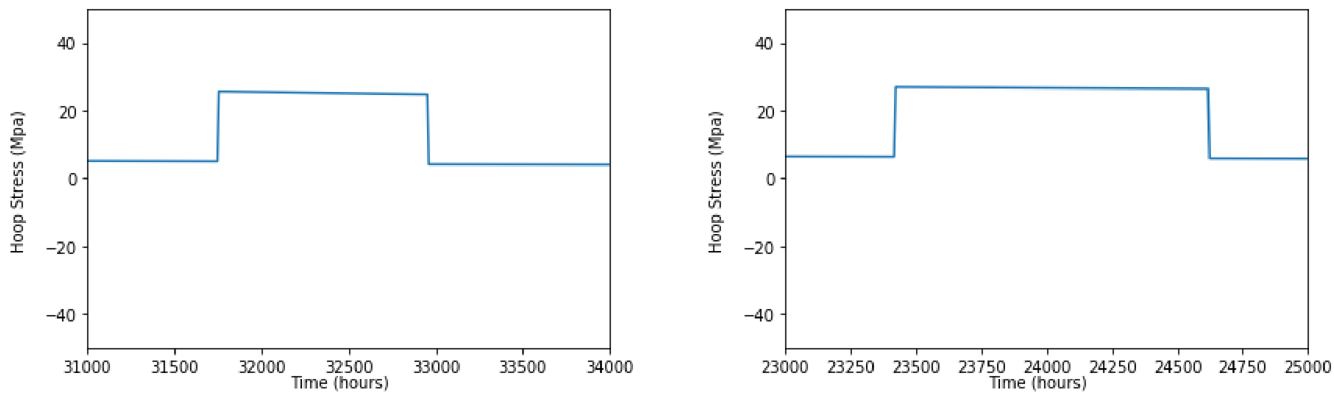


Figure 10: Individual stress components for the original analytical model.



(a) Initial rating of 15kW/m and a shutdown temperature of 562°C

(b) Initial rating of 20kW/m and a shutdown temperature of 546°C

Figure 11: Comparison of hoop stress predictions against time for the optimal shutdown ratio of temperature and rating (Equation 5). The initial operating temperature is 612°C.

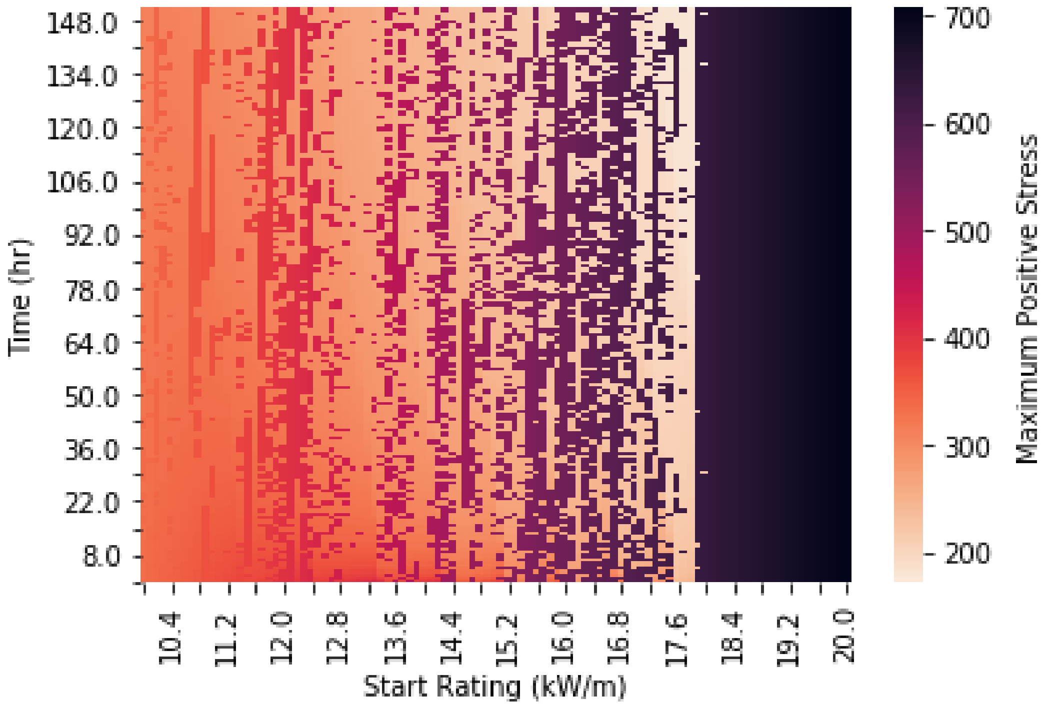
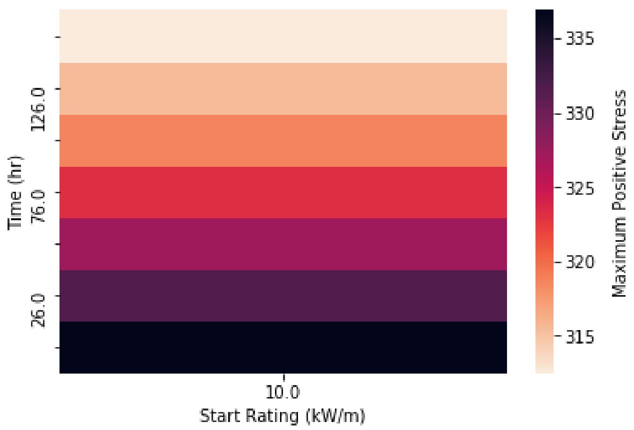
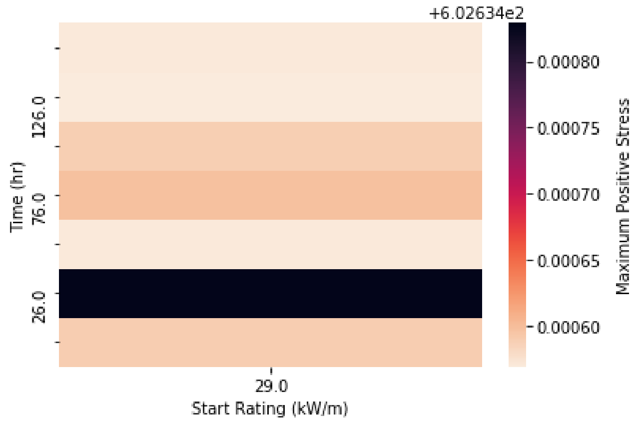


Figure 12: Shutdown to 40% of the rating °C where shutdown temperature is given by Equation 6. Maximum positive stress during shutdown is shown by the colour gradient with darker colours demonstrating the higher stress.



(a) Initial rating of 10kW/m and 550 °C. This is the minimum usual rating.



(b) Initial rating of 20kW/m and 850 °C. This is the minimum usual rating

Figure 13: Comparison of hoop stress predictions against time where shutdown temperature is given by Equation 6.

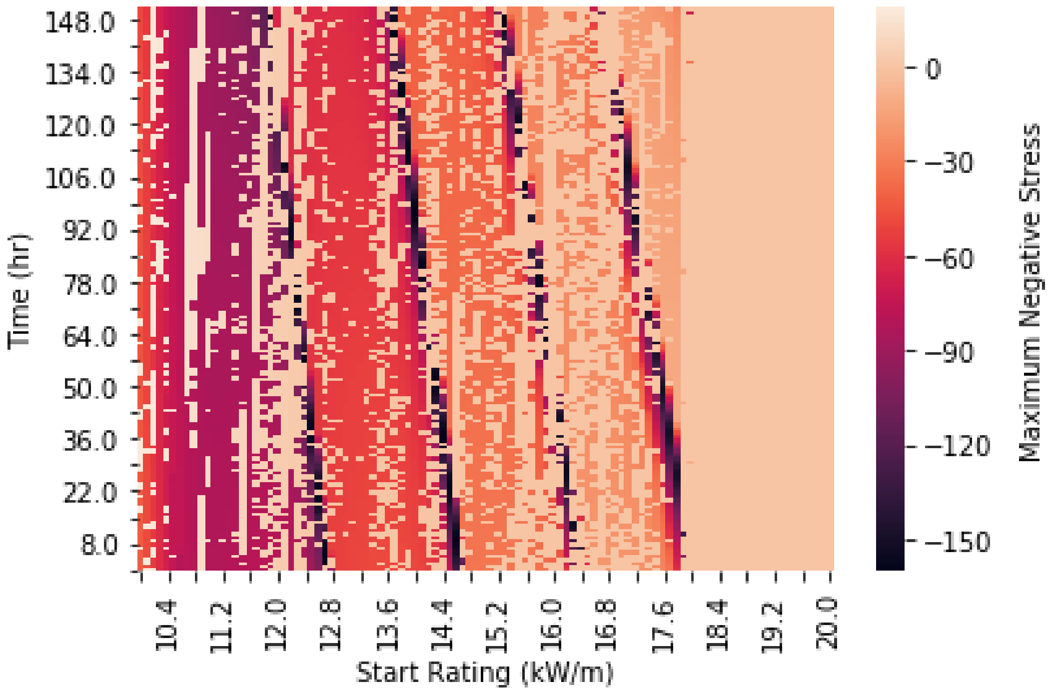


Figure 14: Shutdown to 40% of the rating from 612 °C where shutdown temperature is given by Equation 6. Maximum negative stress during shutdown is shown by the colour gradient with darker colours demonstrating the higher stress.