

## Heat Dissipation Study in Hall- Héroult Cells During Power Outage

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### Abstract:

The power outages in aluminium smelters are troublesome and could be frequent phenomena in few smelters. During power outage, heat loss distribution in the pot gets modified as the materials will lose the stored heat. The ledge thickness increases as time passes and may make it difficult to bring the pot back to life after 4–5 hours of power outage. Therefore, it becomes very important to consider this phenomenon while developing a cell lining for productivity enhancement or energy reduction, thereby enabling pot to perform robustly and recover successfully after outages. To investigate this phenomenon in detail, a computational study has been carried out using transient thermo-electric model to compare the behavior of different lining designs. It has been observed for some cases that, the temperature of anode cover decreases with time, whereas for few others, it increases initially for around an hour before proceeding on downward trend. Temperature of the steel shell near collector bar & bottom decreases after outage, however, the regions on shell near metal & bath may get heated up initially under certain conditions. The findings of this study have been used to finalize the new cell lining design which is expected to maintain higher temperature as compared to existing design during power outage. To extend the survival time of the pot in case of prolonged outage, high heat capacity insulation material at specific locations (internal as well as external) are evaluated, to retard the bath solidification. This paper would discuss the results in detail about various measures to enhance the sustainability of pot during power outages.

**Keywords:** Outage, Heat loss distribution, Transient computational analysis, Lining design, Pot operation

### 1. Introduction

The Hall-Héroult process is used to produce liquid aluminum through electrolysis of alumina in molten cryolite bath. During the reaction, alumina reacts with carbon anode and form liquid aluminum and CO<sub>2</sub> gas. Internal joule heat is generated due to current passing through various cell components. Under steady condition this heat is dissipated from the cell boundaries while maintaining the operating temperature in the cell. The total heat loss distribution of a cell reported by A. Jha et. al. [1] is ~40 % of total heat is dissipated from top, ~44 % from side walls, ~11 % from bottom and ~5 % of the heat is lost through collector bars. The heat loss distribution can be diverse for different technologies however, the greatest proportion of heat is lost from the top and sides of the cell. In an aluminum reduction cell, the cell lining is designed to provide thermal resistance to the heat being lost through cell boundaries. This helps in maintaining the required isotherms at proper locations in the cell.

During a power outage, internal heat generation stops in the cell / pot, and at this zero-power scenario, the cell loses the heat from all the boundaries thereby, the pot starts cooling and thus disturbs the thermal balance of the cell. The heat dissipation rate may remain unaltered initially for short period, but pot starts to lose the internal energy stored in it. In absence of heat generation, the bath starts to solidify on the ledge, and it may extend towards the center of the cell. As the time passes, ledge will start building up ultimately reducing the heat flux through the sidewalls. Due to lack of heat source, other boundaries like top cover, cell bottom, etc. will also start cooling. In case pots have a forced cooling network (FCN) system, shell temperature should increase initially due to stoppage of FCN. If outage sustains for longer durations, pot may need to be shut down as bath will solidify completely below  $\sim 850$  °C [2]. Zhao *et al.* [3] reported few quick actions like closing the feeding holes, tap holes, increase the anode cover thickness, etc. to reduce heat loss.

To increase the pot survival time, the lining insulation and other pot parameters should keep the bath & metal in the molten phase for a long time after a power outage. Therefore, it is very important to consider heat dissipation during a power outage while developing a low energy cell lining. Lining material with low thermal conductivity along with high heat capacity should delay the solidification of bath. Modifications in lining arrangement can also be considered to increase total solidification time. Apart from cell lining, a provision of temporary insulations during outages at sidewalls, top of anode cover or pot cover reduces the cooling rate.

## 2. Methodology of the Study Performed

To investigate the cell cooling tendency in the power outage scenario, a computational study has been carried out by using a 3 dimensional (3-D) thermo-electric slice model. Steady-state model development and its validation for 86 kA pot has been published earlier [4]. Steady state calculations were performed at 367 kA line current, and its results were used as an initial condition for transient simulations. Since composition of solidified bath (ledge) is different than molten bath, hence while cooling, bath density also changes due to change in composition (especially  $\text{AlF}_3$  wt%), and it may lead to inversion due to increased density of molten bath. However, in the present analysis metal and bath have been assumed to remain at the same position. The change in bath chemistry due to cryolite freezing resulting in increase in  $\text{AlF}_3$  wt% leading to the lowering of liquidus temperature. This phenomenon will slow down the rate of cryolite freezing. Since, the computational model doesn't incorporate any change in bath composition with outage time, therefore, rate of cooling of bath is being over predicted. The changes in bath ratio (ratio of wt% of NaF to wt% of  $\text{AlF}_3$ ) & liquidus temperature [5] with outage time have been plotted using a MATLAB-based dynamic model and shown in Figures 1 & 2. The change in bath volume & composition due to solidification of cryolite has been considered in the dynamic model. The values of liquidus temperature obtained at the different points in time were used to track isotherms obtained from computational model.

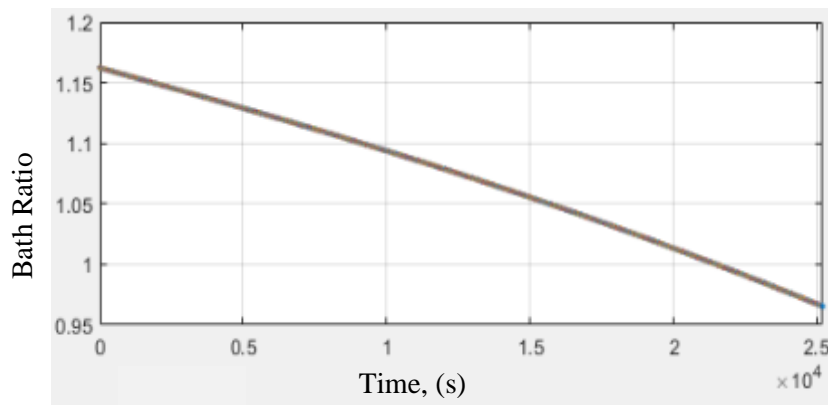
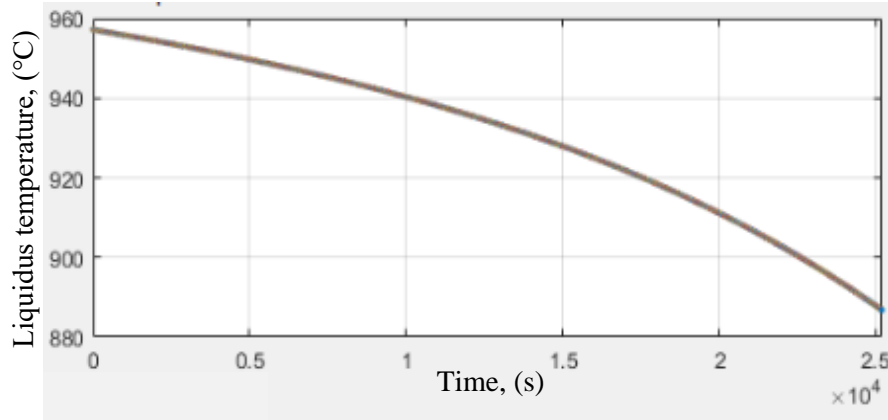


Figure 1. Evolution of bath ratio (weight ratio of NaF/ $\text{AlF}_3$ ) with time.



**Figure 2. Evolution of liquidus temperature with time.**

The base case model was used to calculate the isotherm locations and heat dissipation from the cell in power outage condition up to 7 hours. The performance of different cell lining as well as changes in pot parameters were also tested for few other cases expected to increase the survival time of pot during power outages. The details of the analyzed cases have been listed in Table 1.

**Table 1. Description of analyzed cases.**

	<b>Anode Cover thickness, (cm)</b>	<b>Details of analyzed cases</b>
Case – 1	6	Existing lining design
Case – 2	9	Same as Case – 1 + increase in anode cover thickness
Case – 3	6	Same as Case – 1 + modification to lining material at side and bottom
Case – 4	6	Same as Case – 1 + addition of an external insulation over anode cover
Case – 5	9	Same as Case – 3 + increase in anode cover thickness

### 3 Results and Discussion

The cases described in Table 1 have been analyzed for power outages of 7 hours. The temperature profiles of Case – 1 at different time intervals were compared. For further analysis of Case – 2 through 7, the temperature at few locations such as cathode top corner, steel shell sidewall, and anode cover top surface were tracked and compared with the results obtained for Case – 1.

#### 3.1 Case – 1

The temperature variation with time has been tracked for bath, metal, steel shell, anode cover top surface and cathode at different time intervals. The isotherms in bath and metal region were plotted with time for an interval of 0 to 7 hours as shown in Figure 3. Since rate of cooling is overpredicted, it can be concluded that complete solidification of bath volume will take at least 6 hours as shown in Figure 3. It can also be observed that metal volume will remain liquid even after 7 hours.

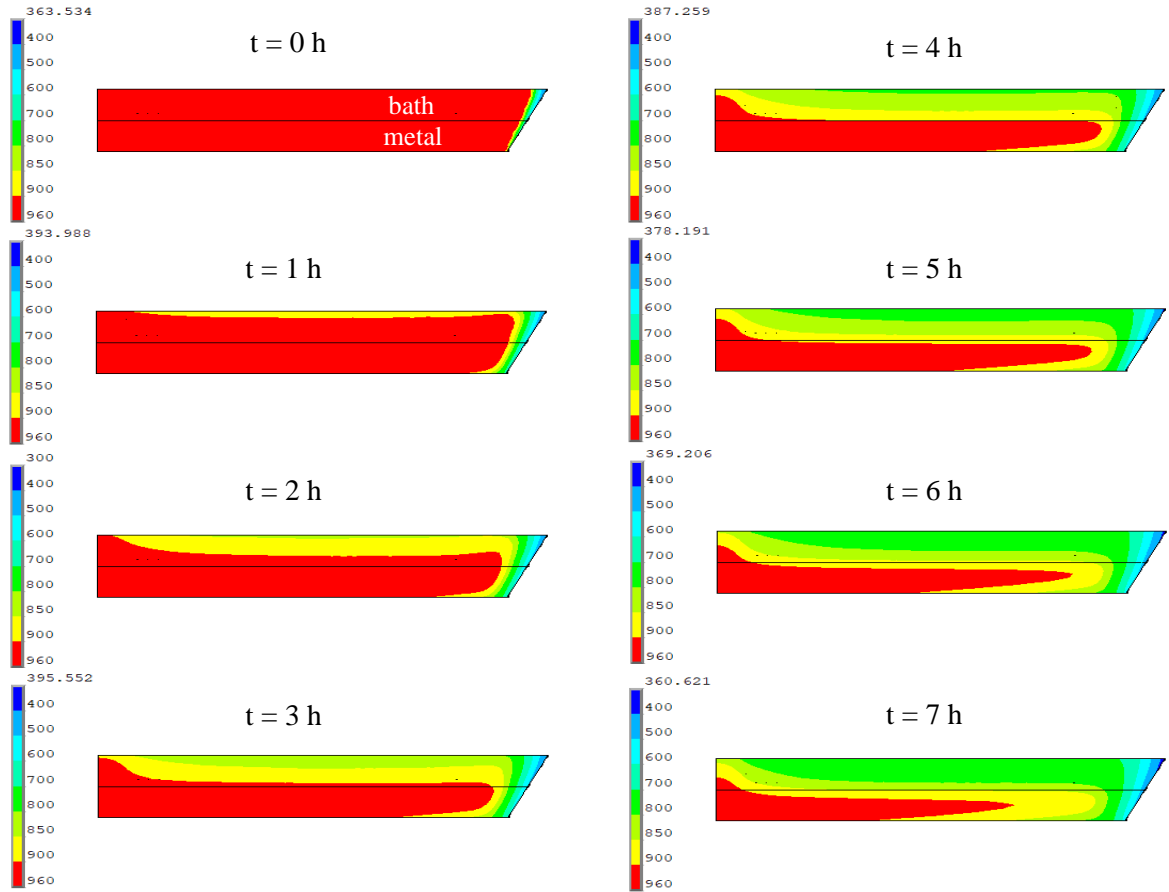


Figure 3. Isotherm locations at different time intervals.

Shell temperature increases during the initial ~2 hours of a power outage before declining, as shown in Figure 4. The rise in shell temperature is attributed to stoppage of FCN during outage. After outage cooling is due to natural convection, hence initially temperature should increase.

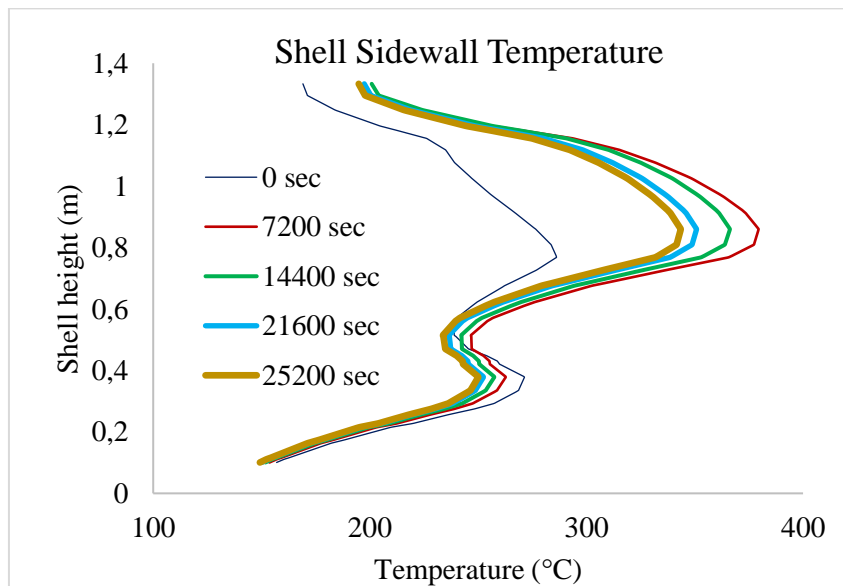
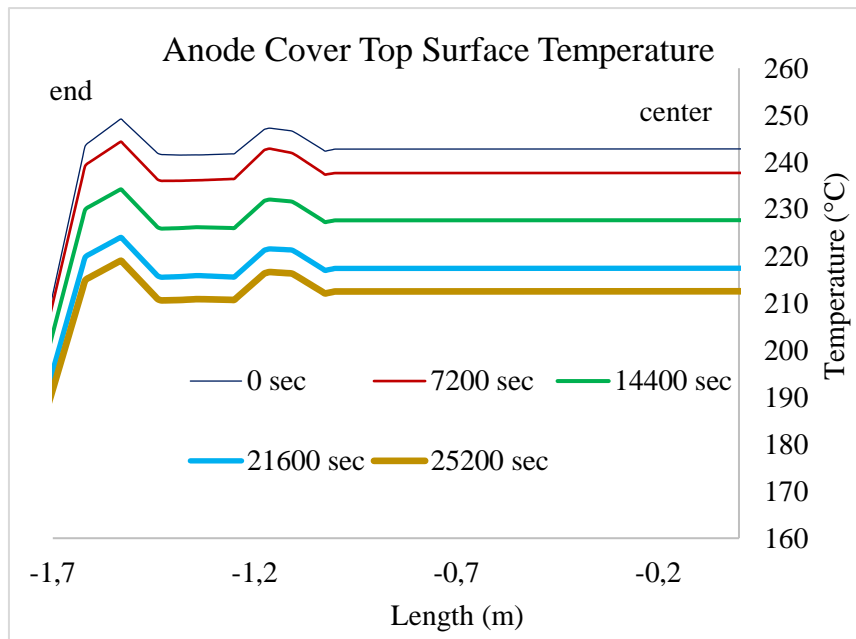
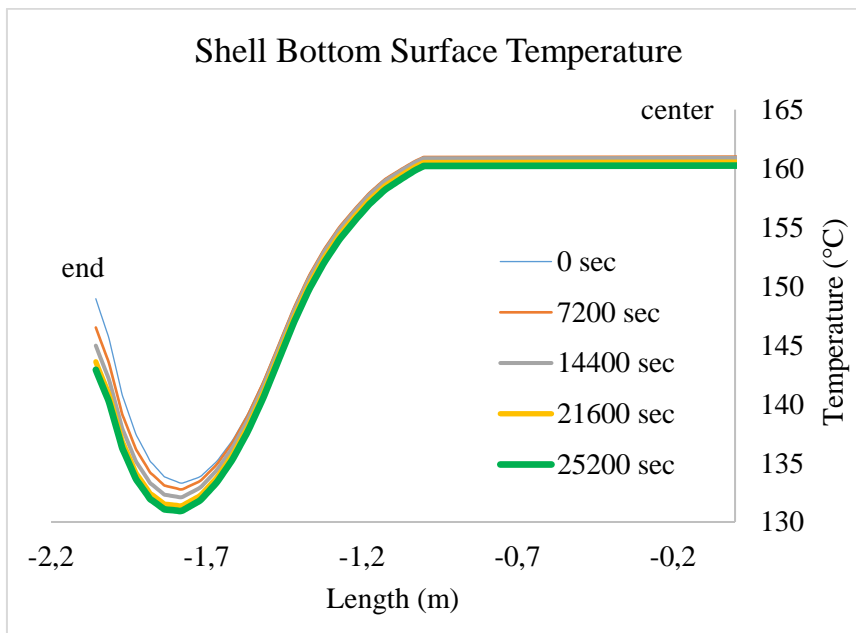


Figure 4. Temperature tracking on the shell sidewall at time intervals.

Figure 5 and Figure 6 shows that temperature profiles of both anode cover and bottom surface of steel shell respectively, which is on reducing trend, as expected. Temperature decreases at 4.3 °C/h at the top and ~ 1 °C/h at bottom of the cell during 7 hours of outage.



**Figure 5. Temperature tracking on anode cover top surface at time intervals.**



**Figure 6. Temperature tracking at shell bottom surface at time intervals.**

Cathode surface temperature near vicinity of the side wall has been tracked with respect to time as shown in Figure 7. Temperature reduces at ~ 27 °C/h during outage. This also indicates that the metal could remain in liquid state during that period.

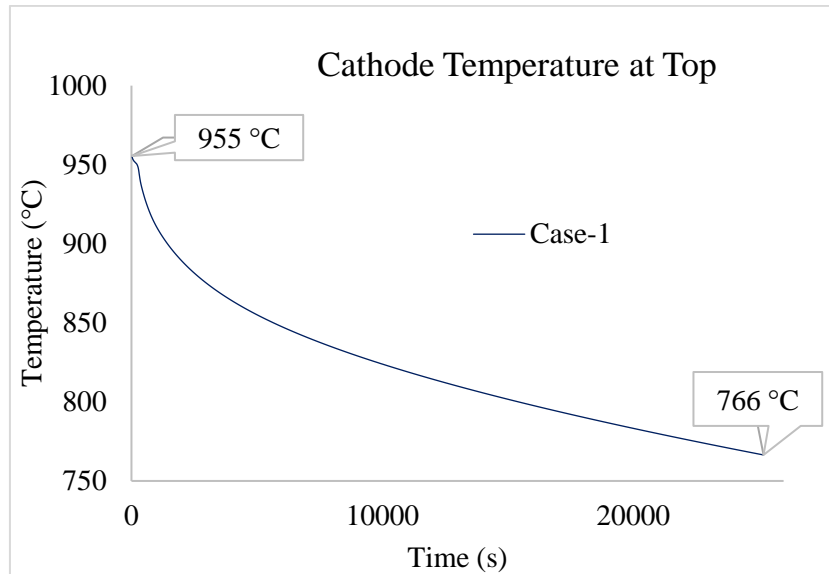


Figure 7. Cathode temperature tracking for 7 hours of a power outage.

### 3.2 Case – 2

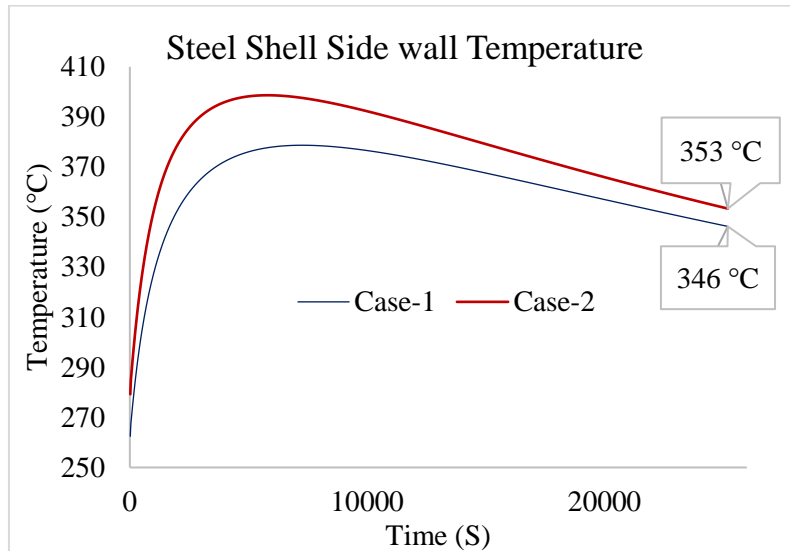
In normal practice, increasing anode cover thickness could be the best way to extend the pot survival time, as this will reduce heat dissipation during a power outage. Either an increase in anode cover thickness or the inclusion of a layer of insulation material immediately after power outage may lead to an initial cooling of the cell since these newly added materials would be at room temperature and would extract some heat from the pot. However, such operational measures may be highly beneficial to extend the pot survival time.

Based on analytical calculations, adding a 3 cm thick layer of anode cover would take about 0.01% of total heat content of normal operating pot, before it starts retarding the heat loss. The initial heat requirement which is very less or insignificant. Hence for ease of computation, impact of increased insulation was considered in obtaining steady state results, which were used as initial condition for transient simulations. To quantify the increase in survival time, temperature at locations of steel shell sidewall, anode cover, steel shell bottom, and cathode have been tracked with time and compared with the results shown obtained for Case – 1.

The impact of anode cover increment on shell sidewall and anode cover top temperatures at different intervals is shown in Table 2. The temperature at a point on shell sidewall bath-metal interface has been tracked and observed that for up to ~ 2 hours, the temperature at shell sidewall shown in an increasing trend. After ~ 2 hours, shell sidewall temperature starts reducing. After 7 hours, shell temperature for Case – 2 was found to be over 7 °C higher than that of Case – 1 as shown in Figure 8. Temperature of anode cover top surface initially increases for 1 hour before going towards a downward trend. In Case – 2, The temperature at anode cover top surface has increased from ~ 216 °C to 223.3 °C in the first 1 hour and then it has started decreasing at 4.55 °C/h up to a minimum of 196 °C. Lower values of top surface temperature for Case – 2 as compared to those from Case – 1, indicates that the increase in anode cover thickness leads to lesser heat losses from anode cover top. The temperature at bottom of the cell for Case – 2 decreases with very slow rate between 0.03 to 0.075 °C/h.

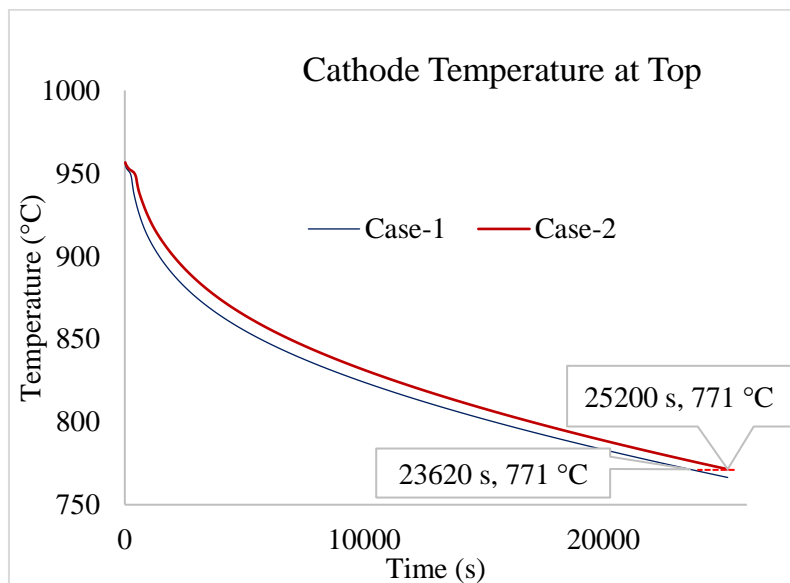
**Table 2. Impact of increased anode cover thickness on both shell sidewall and anode cover temperature.**

	Shell temperature, (°C)			Anode cover top surface temperature, (°C)		
	t = 0 h	t = 2 h	t = 7 h	t = 0 h	t = 1 h	t = 7 h
Case – 1	262.5	378.5	346.0	249.7	248.9	222.0
Case – 2	279.2	398.5	353.4	216.1	223.3	196.0



**Figure 8. Impact of anode cover thickness on steel shell sidewall temperature.**

In Case – 2, the cathode top corner point temperature was found to be 5 °C higher after 7 hours as compared to that of Case – 1. This high cathode temperature could give an additional buffer of ~ 26 minutes (time required to decrease 5 °C) as shown in Figure 9. Higher thermal resistance by anode cover diverts heat flux towards bottom and sides, ultimately increasing the temperature along both the boundaries.



**Figure 9. Impact of anode cover thickness on cathode temperature.**

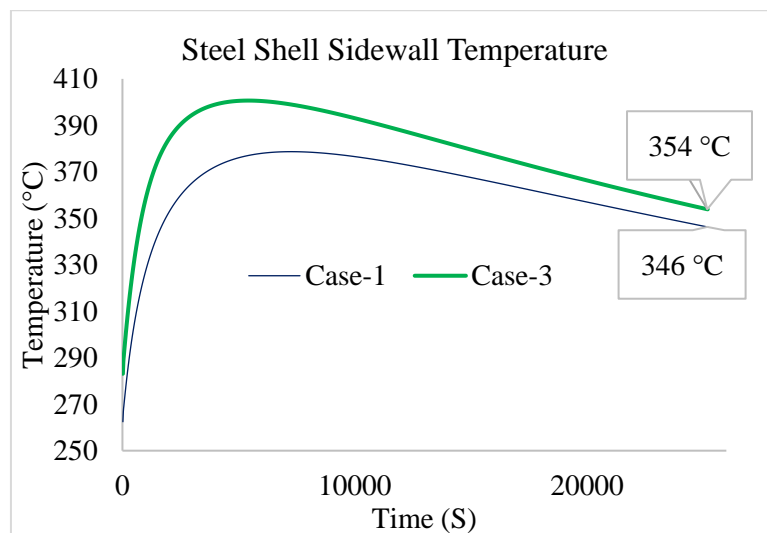
### 3.3 Case – 3

To increase the pot survival time, changes to the cell lining design were introduced. Insulation material with lower thermal conductivity replaced the light insulating bricks in the lining along with change in the brick arrangement. Rest of the operational parameters were maintained same as Case – 1.

The evolution of temperature at shell sidewall may be seen in Figure 10, while Table 3 compares predicted anode cover and sidewall temperature to those obtained for Case – 1. Steel shell sidewall temperatures were similar to Case – 2 after 2 and 7 hours (Table 2). Since, anode cover thickness remains unchanged, predicted temperature at anode cover top surface remained essentially unchanged with respect to Case – 1. Bottom shell temperature remains almost unchanged.

**Table 3. Impact of change in cell lining on both shell sidewall and anode cover temperature.**

	Shell temperature (°C)			Anode cover top temperature (°C)		
	t = 0 h	t = 2 h	t = 7 h	t = 0 h	t = 2 h	t = 7 h
Case – 1	262.5	378.5	346.0	249.7	249.1	221.7
Case – 3	288.3	398.8	354.0	249.7	249.1	221.9



**Figure 10. Impact of low thermal conductivity lining material on steel shell side wall temperature.**

In Case – 3, the cathode temperature was observed to be 15 °C higher as compared to Case – 1 after 7 hours, as shown in Figure 11. Higher temperature avails an additional buffer time of ~ 1 hour 18 minutes, thus, increasing the period for which pots may survive during the power outage.

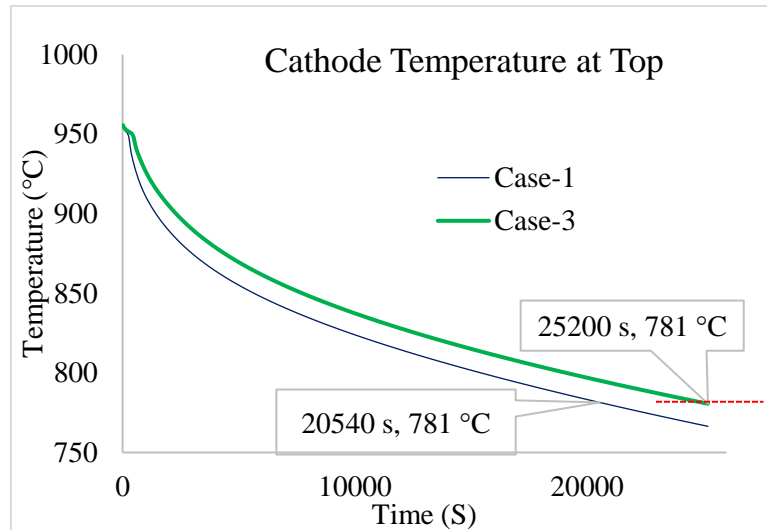


Figure 11. Impact of low thermal conductivity lining material on cathode temperature.

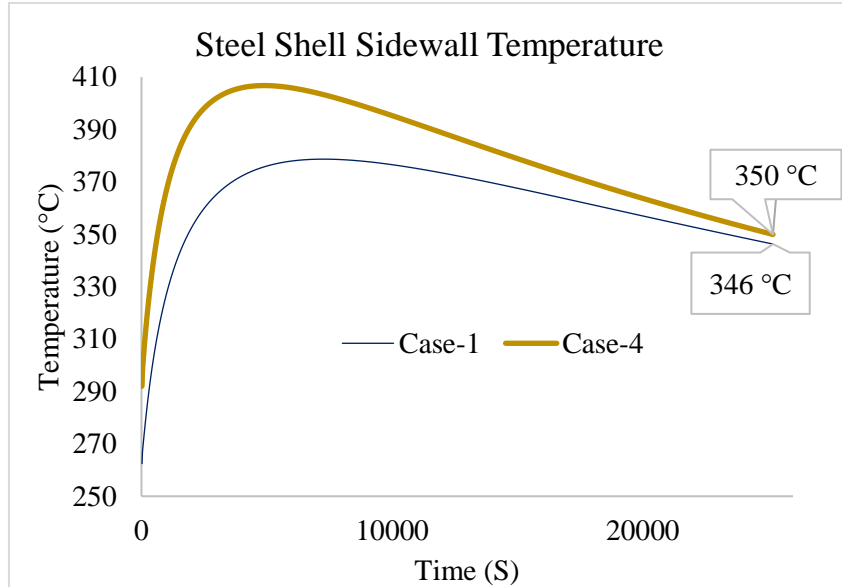
### 3.4 Case – 4

External insulation material like rockwool or any other material with an in-duty performance can be placed over anode cover to reduce the heat loss from top of the cell. As thermal resistance at top will increase, heat flux will divert partly towards sidewalls & bottom, which would lead to higher temperature of steel shell and cathode.

Shell temperature was found to be higher than that of Case – 1, as shown in Table 4 and Figure 12. Lower temperature at top surface of an external indicates lower heat flux from the cell top.

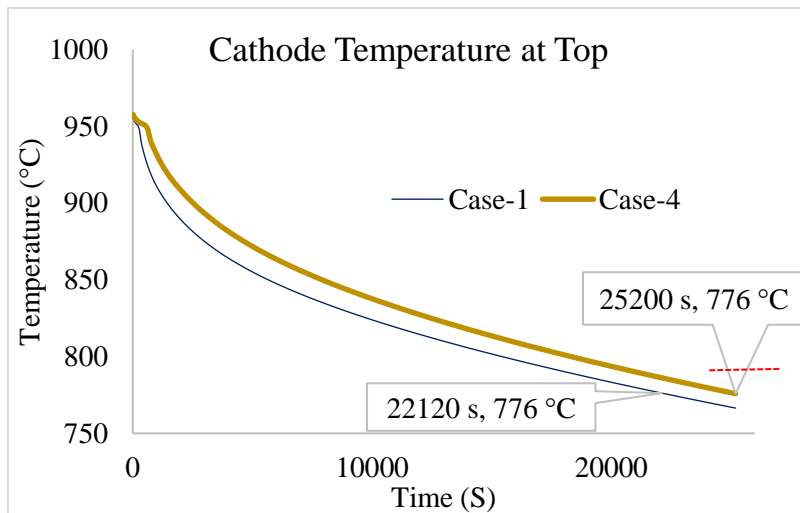
Table 4. Impact of external insulation on both shell sidewall and anode cover temperature.

	Shell temperature (°C)			External sheet top temperature (°C)		
	t = 0 h	t = 2 h	t = 7 h	t = 0 h	t = 2 h	t = 7 h
Case – 1	262.5	378.5	346.0	249.7	245.8	221.7
Case – 4	292.0	403.5	350.0	165.0	169.2	155.0



**Figure 12. Impact of external insulation on steel shell side wall.**

The inclusion of said insulating sheets helps in buying an additional buffer of ~ 51 minutes, as cathode temperature after 7 hours was 10 °C higher as that of Case – 1, as shown in Figure 13.



**Figure 13. Impact of external insulation on cathode temperature.**

### 3.5 Case – 5

Impact of changes in cell lining and additional anode cover thickness has been studied in Case – 2 & 3, respectively. Case – 5 includes the combined effect of both Case -2 & 3, reducing the heat losses from all the boundaries of the cell. Increased anode cover thickness reduces the heat loss from the cell top and replacement of lining material resists the heat loss from the side and bottom of the cell. The lining material with low thermal conductivity and high heat capacity should be considered during lining process, which helps to resist the heat loss from side and bottom of the cell and extends the pot survival time during power outage.

The results of case-1 and case-5 have been compared and it was observed that, cathode, bath and metal temperature for Case – 5 are higher as shown in Figure 14.

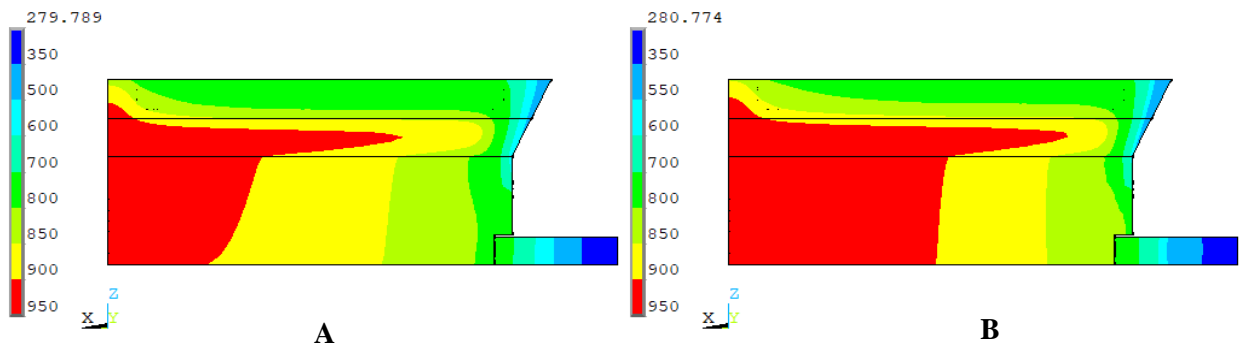


Figure 14. Isotherms, (°C), after 7 hours of a power outage. A) Case – 1, B) Case – 5.

Figure 15 and Table 5 show that the shell sidewall temperature has increased initially for 2 hours, then decreased to 346 °C, similarly to Case – 1. The cell anode cover top surface temperature was in a decreasing trend at 7.26 °C/h for 2 hours, then decreased to 194 °C at 1.6 °C/h, as shown in Table 5.

Table 5. Combined impact of increased anode cover thickness and change in cell lining on both shell sidewall and anode cover temperature.

	Shell temperature (°C)			Anode cover top temperature (°C)		
	t = 0 h	t = 2 h	t = 7 h	t = 0 h	t = 2 h	t = 7 h
Case – 1	262.5	378.5	346.0	249.7	245.8	221.7
Case – 5	291.2	397.4	346.0	216.6	202.0	194.0

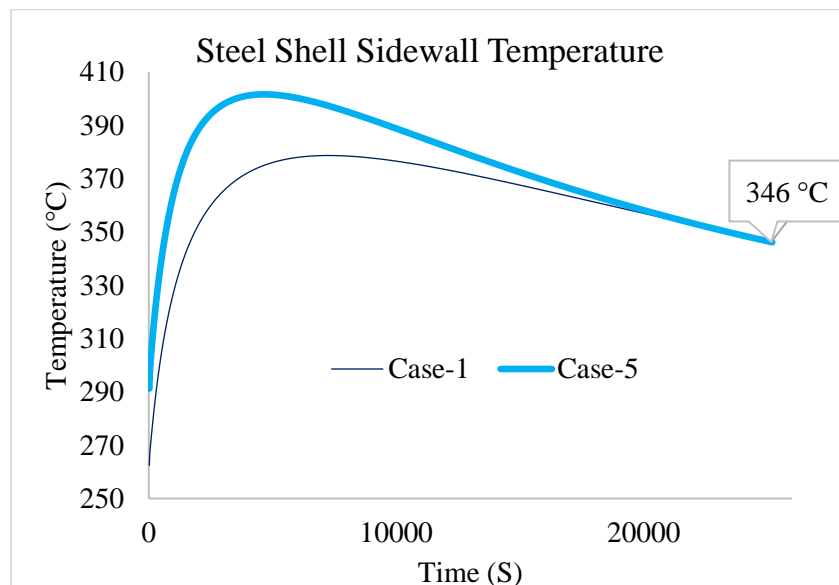
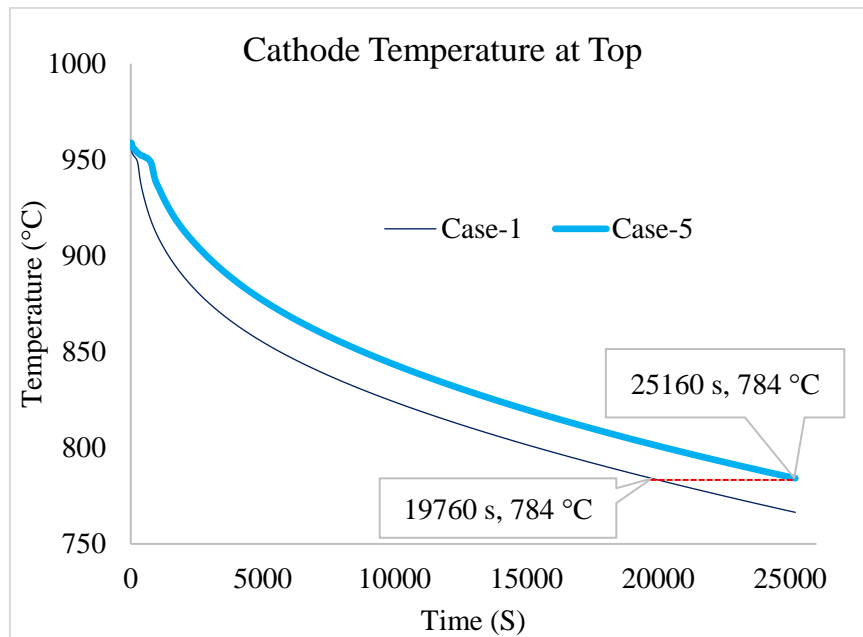


Figure 15. Combined impact of increased anode cover thickness and change in cell lining on shell side wall temperature.

The temperature at the cathode top corner was relatively higher than remaining cases, reaching 784 °C after 7 hours, as shown in Figure 16. High cathode temperature, in this case, would be due to the thermal arrest at boundaries by both thicker anode cover and modified lining design. These changes extend the pot survival time by ~ 1 hour 30 minutes of over Case – 1.



**Figure 16. Combined impact of increased anode cover thickness and change in cell lining on cathode temperature.**

#### 4 Conclusions

Based on the heat dissipation study and time-variant computational simulations for a 7-hour power outage scenario, the temporal evolution of temperature at particular locations (such as steel shell sidewall, anode cover top surface, the bottom of the cell, and cathode top corner) was tracked for all considered cases and compared with the results obtained for the existing lining design (Case – 1). The following observations were formulated:

1. Using dynamic model, the variation of liquidus temperature with outage time was obtained. Liquidus temperature of bath drops at average rate of 9 – 10 °C/hour.
2. Increase of anode cover thickness by 3 cm with an existing lining helps in keeping the cathode at high temperature for additional 25–30 minutes
3. Changes in cell lining design as well as using low thermal conductivity material gives an additional survival time of well over an hour. However, the applicability of this scenario also depends on the implications of these changes for normal pot operation, which would also have to be carefully checked (beyond the scope of this study).
4. Addition of an external insulation over anode cover before or after power outage will restrict heat loss from the top of the cell and may give an extra buffer of 50–60 minutes.
5. Considering a change in lining design and increased anode cover thickness by 3 cm has shown a good thermal arrest from cell boundaries and as compared to case-1 it provides additional survival time of 1 hour 30 minutes.

#### 5 References

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