# Pot Abnormality Tracking System (PAT) for Critical Pot Detection

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## Abstract

Pot tap out is one of the most hazardous condition in an aluminum smelter, posing risk to life as well as business. During pot tap-out metal seepage takes place from the collector bar, side shell or bottom shell of pot, which determines the kind of failure. The main reason for pot tap-out is the metal penetration through cracks in cathode and side lining. Therefore, for critical pot detection, Pot Abnormality Tracking (PAT) system was developed which can aid in shutdown of pots before failure. PAT is a score-based algorithm where selected key performance indicators (KPIs) such as pot age, cathode type, bath temperature, instabilities, historic events, lining vulnerability, etc., are tracked and evaluated against a pre-decided weightage structure. The weightage for each parameter is decided on the basis of historical data and its impact leading to pot failure. PAT system generates separate scores against the possibilities of failure through collector bar and failure through side shell. On the basis of these scores, ranks are allotted to the pot which defines the criticality of pot. Pot shutdown priority can be based on PAT score and hence pot tap outs can be avoided.

**Keywords:** Pot tap-out, Pot abnormality tracking, Collector bar tap-out, Side shell tap-out.

## 1. Introduction

Aluminium is produced industrially by the Hall-Heroult process [1]. The aluminium electrolysis process consists of electrochemical decomposition of alumina dissolved in sodium cryolite based electrolyte ($Na_3AlF_6$) known as bath at 950-970 °C. Faraday's law of electrolysis governs this process. Under the influence of DC current alumina is reduced to liquid aluminium, which collects at the cathode while the oxygen reacts exothermically with anode carbon to form carbon dioxide and carbon monoxide gases [2]. The main reaction in the cell can be expressed by Equation (1):

$$2\ Al_2O_3 + 3\ C = 4\ Al + 3\ C\ O_2 \tag{1}$$

The carbon is supplied to the reaction by prebaked anode blocks made of a mixture of coke, pitch and recycled anode butts [3]. The process is carried out in reduction cells or pots as shown in Figure 1 [4].

As it can be seen from Figure 1, aluminium smelting consists of a large number of process parameters such as alumina dosage, bath temperature, cathode type, etc. Hence, aluminium smelting is a process, which involves multiple variables and highly complex mechanisms such as mass and energy balances, electrochemical reactions, the supply of reactants and the maintenance of the composition of the reaction mixture [5]. In addition, the large amount of information coming in from such a process, some in real-time and others intermittently at varying frequencies, is challenging for a human brain to process. To control this complex process to achieve high productivity and efficiency requires day to day (and sometimes minute to minute) monitoring of the variables, and a high level of deductive problem solving and decision-making.

As most of the process parameters cannot be monitored online continuously throughout the day such as sudden surge in iron percentage in the metal which may lead to pot failure through the collector bar, a system is required which could predict the criticality of pot based on the critical process parameters analysis. Therefore, a system has been made which is known as pot abnormality tracking (PAT) system. PAT is a score-based system where selected key performance indicators (KPIs) are tracked and evaluated against a pre-decided weightage structure. Separate scores are generated against possibilities of failure through a collector bar and failure through side shell. The highest of the two is considered as PAT score. The pot with the highest PAT score is considered as the most critical pot. The weightage to each parameter is decided based on root cause analysis of pot failure and based on pot autopsies report. For the efficient functioning of the system certain algorithms have been applied on KPIs considered, which enables to predict the correct PAT score.

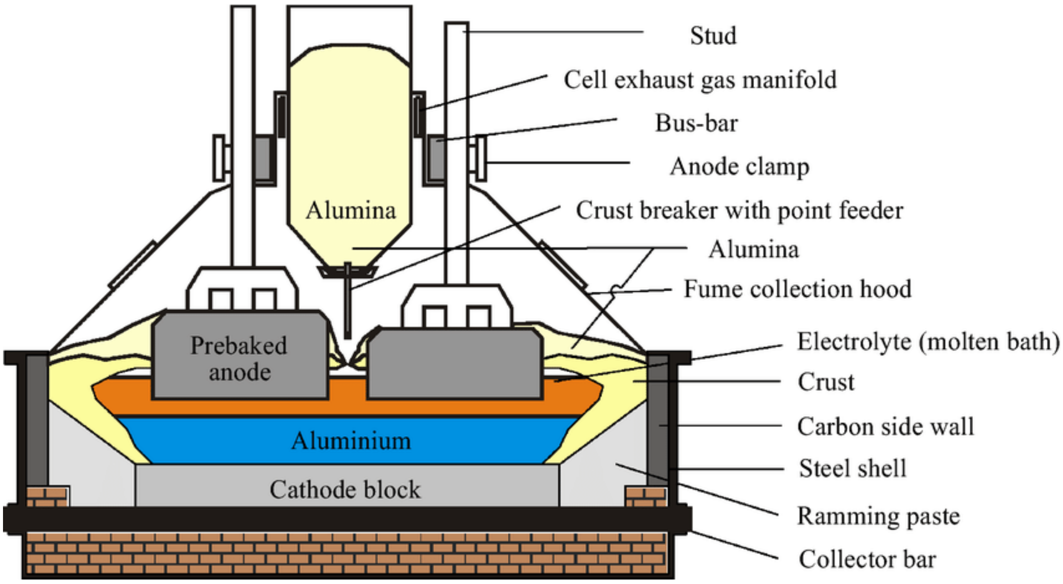



**Figure 1. Front view of Prebaked Electrolytic Cell [4].**

## 2. PAT Parameters and Model

Several critical process parameters are considered for developing the PAT System. Selection of correct parameters remains crucial for developing any kind of model; for PAT some known basic process parameters were taken into consideration. Apart from which autopsies of failed pots and shutdown reports of schedule-stopped pots were studied. Root cause analysis (RCA) study was done over all these stopped pots and a set of parameters were finalized along with their contribution (weightage) leading to pot failure.

The major parameters, which play a role in pot tap out are cathode age, iron and silicon increment in metal as an indicator of metal penetration, bath temperature deviation, side ledge melting due to high superheat, anode effect frequency, and critical measurements such as collector bar temperature and side shell temperature. Apart from these parameters information like iron increase due to anodic issue have also been considered to factor-in false metal penetration signals from Fe increase.

As any pot can fail either through sidewall or collector bar, all these parameters were divided into two sets of collector bat temperature (CBT) and hell sidewall temperature (SST). The following is discussion over factors considered in both CBT/SST parameter sets and rationale behind their inclusion.

### 2.1 Cathode Age and Type

Different types of cathodes are used in an aluminum smelter. Cathodes are broadly classified as 30 % graphitic, 50 % graphitic and 100 % graphitic. The average cathode age is considered 1800 days. The higher the cathode age, the greater is the risk of metal penetration through the cathode cracks as the cathode erosion takes place over the whole life of the pot. Based on this assessment and historic data, higher weightage is given to the pots, which have crossed their threshold age (here 1800 days). However, for 30 % and 50 % graphitic cathodes maximum weightage is given to pots with age over 1500 days as these pots had the history of early failures.

### 2.2 Fe and Si Deviation

Hot metal analysis provides the amount of iron and silicon percentage in metal. An increment of iron or silicon percentage in metal is an indicator of metal penetration through cathode cracks to collector bars in the pot or through the SiC side lining. To determine the intensity of penetration, the change in iron % as well as the rate of change is considered, hence the last five iron values are tracked, inclusive of scheduled and unscheduled metal sampling. Historically it was observed that rate of change of iron increase provides more reliable signal than the absolute difference between two iron % values, hence more weightage has been given to it.

Similarly, increment in silicon % in metal indicates side ledge melting and direct contact of bath with the sidewall SiC brick, hence change in silica is considered as a prominent factor. However, in many instances silicon increase lagged the actual side ledge melting. For this reason, apart from silicon increase, other factors that directly or indirectly lead to ledge failure have been taken into consideration. These additional factors could be higher operating pot voltage, higher anode effect rate, high superheat, etc.

### 2.3 Bath Temperature

Bath temperature above 970 °C can lead to severe damage to the side ledge of the pot and can even melt the side ledge of a pot. Due to side ledge failure, metal penetration may take place from the side walls, which can eventually lead to pot, tap out. Hence, in PAT system last measured bath temperature as well instances of higher bath temperature in last 10 days have been considered as an indicators of eroded side ledge.

### 2.4 Anode Effect

Anode effect is a phenomenon, which occurs when alumina concentration is low in the electrolyte and eventually increases the resistance in the pot, making the pot unstable. If anode effect occurs for a longer period, it can make the pot noisy and create heat imbalance in the pot. Thus, both anode effect frequency and anode effect duration are given the priority in the PAT system. An anode effect that lasts for more than 6 minutes is given the maximum weightage.

### 2.5 Critical Measurements

Pot thermal measurements such as collector bar temperature and side shell temperature provide an idea of metal penetration through the cathode cracks and the sidewalls. If the collector bar temperature is greater than 280 °C and if the side shell temperature is greater than 450 °C then there is a possibility of metal penetration through the cathodes and sidewalls. Therefore, in the PAT system maximum weightage is given to the collector bar and side shell temperatures over 280 °C and 450 °C, respectively.

### 2.6 Historical Sensitivity and Miscellaneous KPIs

Leveraging on the fact that whenever any high CBT or SST is observed in any pot it either indicates metal penetration through cathode/side ramming or sidewall erosion. Where metal penetration is an irreversible change (but controllable) and sidewall erosion can be recovered with process stability, we considered historical observations as weak spots in a pot. Historical data for high CBT and SST was mapped against each pot, live measurement we evaluated against the mapped observations. Any coinciding measurement or observation were given higher weightage, considering higher probability of pot failures through these identified weak points.

PAT system also considers current physical vulnerabilities of pot, i.e., the number of air-cooling points installed in pot (indicator of identified weak collector bars), side shell repaired locations, busbar or anode riser damage/bypass, damaged side lining location, sudden aluminium fluoride dump in the pot, leading to high superheat, etc. These KPIs are being tracked under miscellaneous KPI category.

These parameters are critical in predicting the pot failure and are given certain weightage according to the learnings from autopsies of previous pot failures.

## 2.7 Leakage Patterns and Factors Impacting Pot Health

As discussed earlier, factors affecting pot health were classified into two categories, namely factors impacting collector bar failure and side shell failure as shown in Figure 2 and Figure 3. Based on root cause analysis of failed pot autopsies, the corelations of various contributing factors were derived. Regression analysis was also carried out, and based on the best fit values weightage was decided. These weightages were then used to create an algorithm which evaluates live process data and generates scores (feedback) for the two categories separately. This exercise is done for all pots in the smelter. Higher score indicates higher probability of pot failure.

Collector bar and side shell leakage pattern analysis was done for PAT system as shown in Figures 4 and 5. The data in Figures 4 and Figure 5 indicate failure of collector bar and side shells from different positions for last one year. It was observed that pot failures (tap out) followed a certain pattern, be it the failure through the side wall or through the collector bar. These leakage-prone areas were correlated with high side shell temperature and high collector bar temperature locations. The purpose is to give more than normal weightage to any SST/CBT measurement, which coincides with leakage prone locations in a pot.

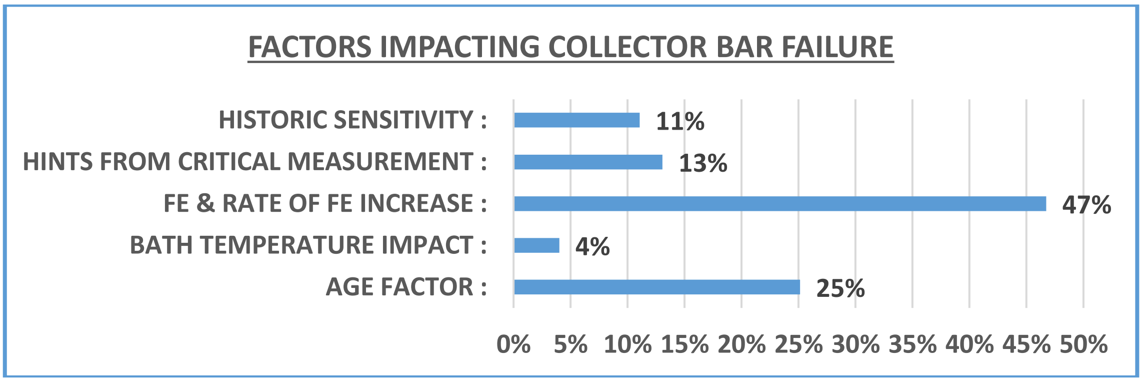



**Figure 2. Factors impacting collector bar failure.**

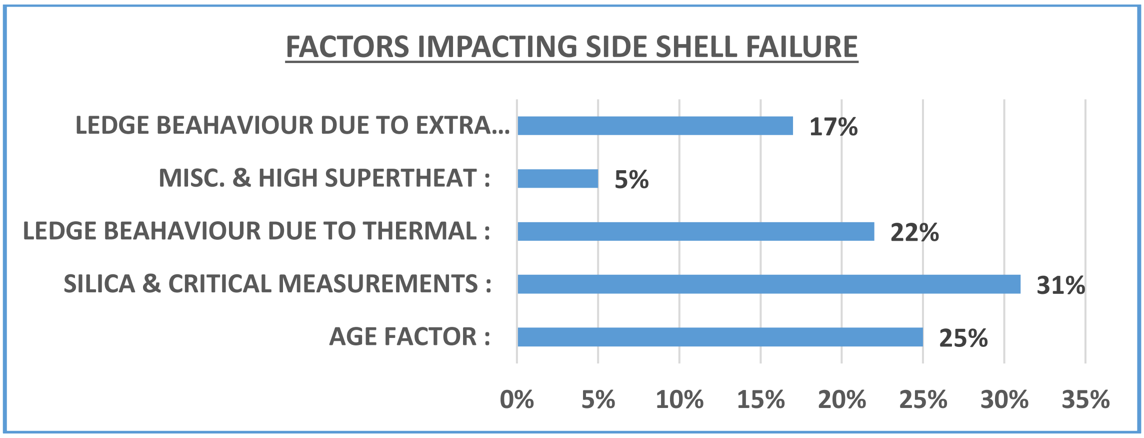



**Figure 3. Factors impacting side shell failure.**

**COLLECTOR BAR LEAK PATTERN**

| CB No. 1 | Failures | Failures | CB No. 2 |
|---|---|---|---|
| A1 | 0 | 0 | B1 |
| A2 | 0 | 1 | B2 |
| A3 | 1 | 1 | B3 |
| A4 | 1 | 1 | B4 |
| A5 | 1 | 0 | B5 |
| A6 | 1 | 0 | B6 |
| A7 | 1 | 0 | B7 |
| A8 | 1 | 0 | B8 |
| A9 | 1 | 1 | B9 |
| A10 | 2 | 0 | B10 |
| A11 | 3 | 0 | B11 |
| A12 | 1 | 1 | B12 |
| A13 | 1 | 0 | B13 |
| A14 | 4 | 0 | B14 |
| A15 | 1 | 0 | B15 |
| A16 | 2 | 0 | B16 |
| A17 | 3 | 1 | B17 |
| A18 | 3 | 1 | B18 |
| A19 | 4 | 3 | B19 |
| A20 | 2 | 2 | B20 |
| A21 | 0 | 0 | B21 |
| A22 | 3 | 0 | B22 |
| A23 | 4 | 2 | B23 |
| A24 | 4 | 0 | B24 |
| A25 | 3 | 0 | B25 |
| A26 | 4 | 3 | B26 |
| A27 | 0 | 0 | B27 |

**Figure 4. Collector bar leakage pattern.**

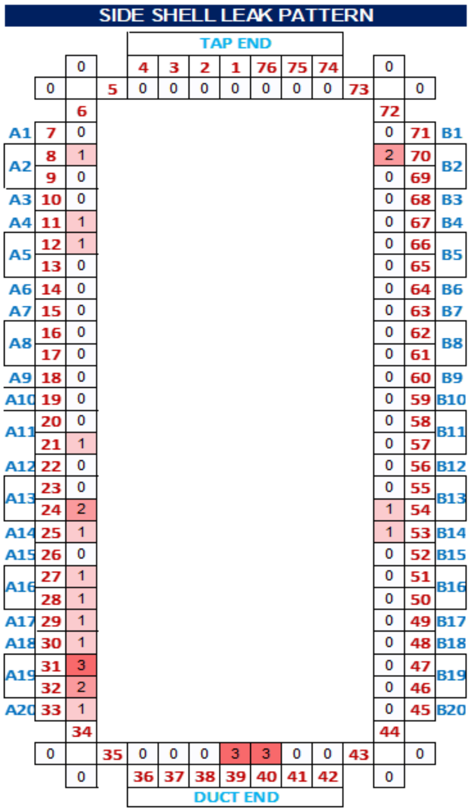



**Figure 5. Side shell leakage pattern.**

## 3. Back-test PAT Verification

After applying algorithms for various critical parameters and deciding the criteria for providing weightage to different parameters, PAT model back-testing was carried out. The data was collected for one year for various pot parameters. Back-testing was carried out for all the scheduled cut-out pots and for the unscheduled (tap-out) pots for the last year. Scheduled cut-out pots are those, which are considered as critical due to abnormal Fe and Si trend. In this case, the pot current is bypassed through the short circuit shunts by removing the insulator separating the anode risers from the short circuit shunts. This stops the current flow in anode risers of the particular cut-out pot. Unscheduled cut-out pots are those in which metal penetration occurs either from the side shell or the collector bar due to several factors, such as, high side shell temperatures, high voltage anode effect or metal penetration through the collector bars, resulting in localized increased current density through the particular pair of collector bars and high collector bar temperature.

In case of tap outs, there is always a risk of busbar damage, which may prevent current from flowing to the next pot leading to situations, such as the failure of an entire section of the potline. For scheduled cut-out pots, if the pot criticality rank came in the top three out of 1500 pots, then the algorithm logic was considered as successful. For the unscheduled cut-out pots if the pot rank came in the top 10 out of 1500 pots, then it was considered as a successful algorithm implementation. Tables 1 and 2 indicate the back-test results for scheduled and unscheduled cut-out pots, respectively, for last 12 months data.

**Table 1. Back-test summary for scheduled cutout pots.**

| S. No | Pot Number | Cathode type | Cathode age (days) | PAT rank | Did the pot come in top 3? |
|---|---|---|---|---|---|
| 1. | 12XX | 30 % graphitic | 1485 | 3 | Yes |
| 2. | 31XX | 50 % graphitic | 1525 | 10 | No |
| 3. | 41XX | 30 % graphitic | 1614 | 2 | Yes |
| 4. | 11XX | 30 % graphitic | 1587 | 1 | Yes |
| 5. | 33XX | 100 % graphitic | 1825 | 85 | No |
| 6. | 34XX | 30 % graphitic | 1423 | 3 | Yes |
| 7. | 52XX | 50 % graphitic | 1680 | 1 | Yes |
| 8. | 56XX | 30 % graphitic | 1248 | 1 | Yes |
| 9. | 48XX | 50 % graphitic | 1398 | 56 | No |
| 10. | 55XX | 30 % graphitic | 1485 | 2 | Yes |
| 11. | 51XX | 30 % graphitic | 1571 | 3 | Yes |
| 12 | 23XX | 100 % graphitic | 1896 | 21 | No |
| 13 | 37XX | 50 % graphitic | 1567 | 8 | No |
| 14 | 48XX | 30 % graphitic | 1438 | 1 | Yes |
| 15 | 35XX | 100 % graphitic | 1955 | 3 | Yes |
| 16 | 46XX | 50 % graphitic | 1824 | 5 | No |
| 17 | 57XX | 30 % graphitic | 1317 | 1 | Yes |
| 18 | 53XX | 100 % graphitic | 1896 | 3 | Yes |
| 19 | 58XX | 30 % graphitic | 1853 | 2 | Yes |
| 20 | 46XX | 50 % graphitic | 1925 | 1 | Yes |

From Table 1, it can be implied that 14 pots came in the top 3 rank out of 20 back-tested pots. Therefore, the back-test accuracy for scheduled cut-out pots is 70 %. From Table 2, it can be implied that 10 pots came in top 10 rank out of 18 back-tested pots. Therefore, the back-test accuracy for unscheduled cut-out pots is 55 %.

## 4. PAT Integration into Manufacturing Execution System (MES)

After successful verification of PAT logic, PAT system was implemented in the MES server of Vedanta. The algorithm of the complete PAT file was coded in Python and all the data was obtained from the cloud system of Vedanta. Around 30 KPIs of the pot were taken into consideration and new screens were developed for critical pot parameters to reduce manual data entry. This system provides important data of all critical pots. It is helpful for the people working in the potroom to track the critical parameters of the pot and take necessary actions according to the pot criticality. This system provides the rank of all critical pots and makes the decision making easy for the process in-charges to cut-out the pots before tap out. All the top 10 critical pots (out of 1500 pots) can be monitored continuously with the help of this system. Figure 6 indicates the parameters by the PAT report in MES system.

**Table 2. Back-test summary for unscheduled (tap-out) pots.**

| S. No | Pot Number | Cathode type | Cathode age | PAT rank | Did the pot come in top 10? |
|---|---|---|---|---|---|
| 1 | 43XX | 30 % graphitic | 1286 | 9 | Yes |
| 2 | 51XX | 50 % graphitic | 971 | 71 | No |
| 3 | 58XX | 50 % graphitic | 1271 | 26 | No |
| 4 | 32XX | 30 % graphitic | 1171 | 6 | Yes |
| 5 | 51XX | 50 % graphitic | 1095 | 32 | No |
| 6 | 34XX | 30 % graphitic | 1485 | 58 | No |
| 7 | 47XX | 100 % graphitic | 1512 | 7 | Yes |
| 8 | 48XX | 50 % graphitic | 1193 | 27 | No |
| 9 | 37XX | 30 % graphitic | 1466 | 5 | Yes |
| 10 | 46XX | 100 % graphitic | 1053 | 9 | Yes |
| 11 | 56XX | 50 % graphitic | 2299 | 185 | No |
| 12 | 31XX | 30 % graphitic | 1328 | 2 | Yes |
| 13 | 34XX | 50 % graphitic | 1285 | 26 | No |
| 14 | 33XX | 50 % graphitic | 2241 | 2 | Yes |
| 15 | 31XX | 30 % graphitic | 2376 | 6 | Yes |
| 16 | 52XX | 50 % graphitic | 1346 | 71 | No |
| 17 | 45XX | 100 % graphitic | 1601 | 3 | Yes |
| 18 | 35XX | 30 % graphitic | 1326 | 5 | Yes |

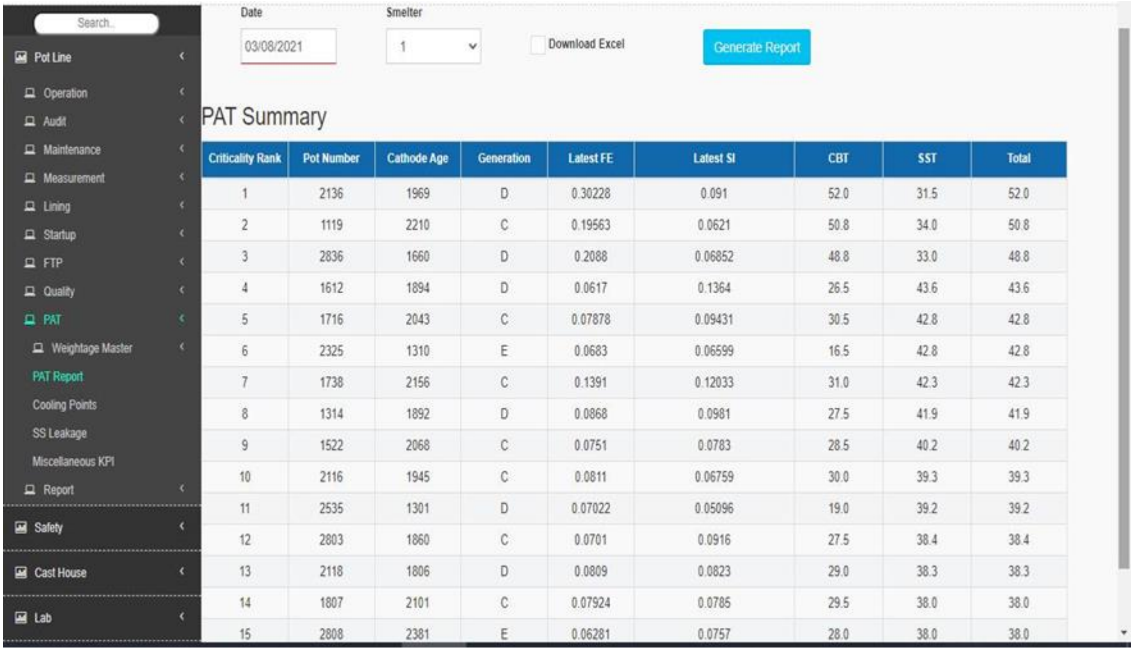
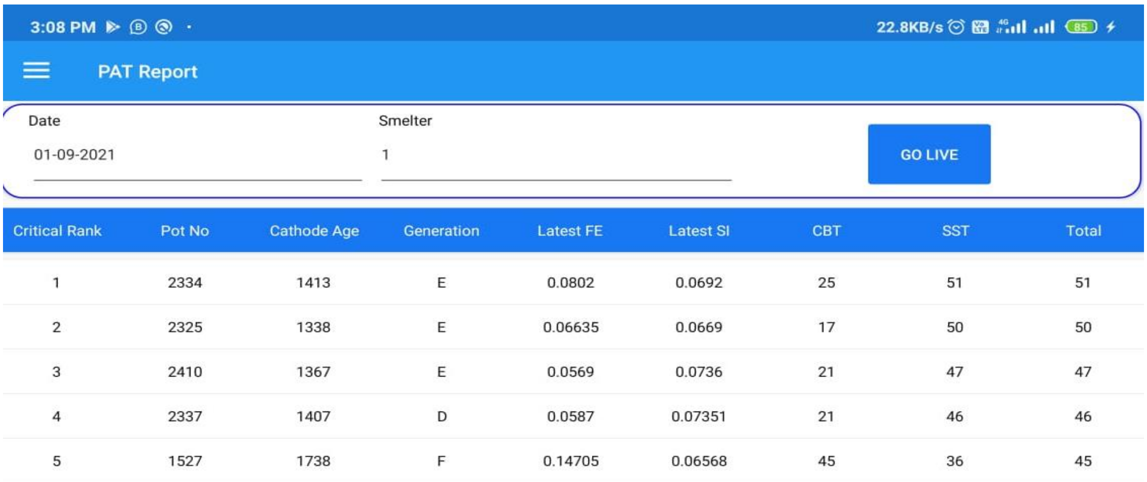



**Figure 6. PAT integration into MES server of Vedanta.**

## 5. PAT Mobile App Development

For accessing the critical pots from any location in the plant, PAT mobile app has been developed. This app provides the complete access of the PAT file, which has been integrated with MES server of Vedanta. This app generates the list of top 30 critical pots of the complete location as shown in Figure 7. It plays a vital role in taking a decision for the scheduled cut-out of the pots and improves the overall working efficiency.




| Critical Rank | Pot No | Cathode Age | Generation | Latest FE | Latest SI | CBT | SST | Total |
|---|---|---|---|---|---|---|---|---|
| 1 | 2334 | 1413 | E | 0.0802 | 0.0692 | 25 | 51 | 51 |
| 2 | 2325 | 1338 | E | 0.06635 | 0.0669 | 17 | 50 | 50 |
| 3 | 2410 | 1367 | E | 0.0569 | 0.0736 | 21 | 47 | 47 |
| 4 | 2337 | 1407 | D | 0.0587 | 0.07351 | 21 | 46 | 46 |
| 5 | 1527 | 1738 | F | 0.14705 | 0.06568 | 45 | 36 | 45 |

**Figure 7. PAT mobile app working dashboard.**

## 6. Results and Discussions

The back-test model accuracy for scheduled pots came out to be 70 %, whereas for unscheduled (tap-out) pots came to be 55 %. For further improvement of model efficiency, gap analysis was carried out, which helps to understand the parameters, which can be added in the system to further improve model efficiency. Gap analysis was done for both collector bar parameters and side shell parameters as shown in Figure 8.

The model has difficulty to provide correct feedback of critical pots if some of the following information is not available in the system. This can be due unavailability of historical CBT/SST records, eroded side-lining mapping (as it is a physical audit of all pots), feedback from physical red-spot audits with roof lights off, flexible disconnect location mapping, unscheduled metal analysis update in system, correct CBT frequency based of measurement criteria.

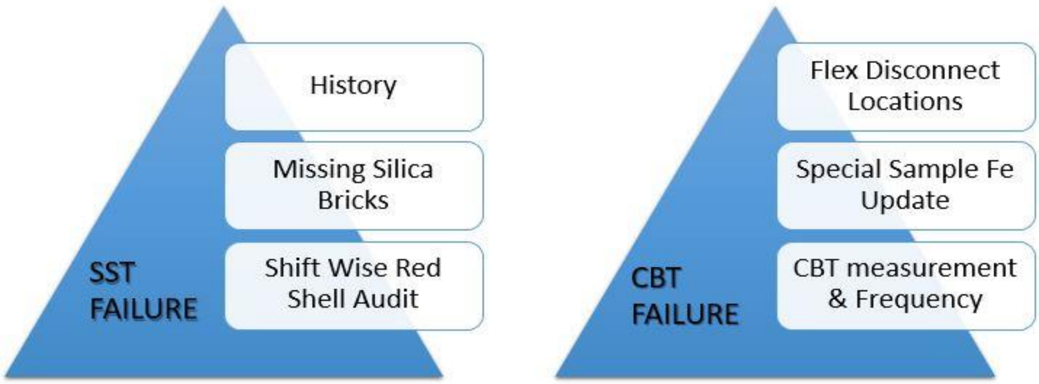



**Figure 8. Gap analysis for CBT and SST failures.**

## 7. Conclusions

This model provides good feedback regarding the probability of pot failure through the side shell or a collector bar. It was observed that collector bar failure prediction correctness is better than of the side shell failure. Having said that surprise is always there in both kinds of failure. Hence, it is imperative to understand that this model is in an ever-evolving state. Either additional parameters or the same parameters with different weightage have to be incorporated over time to see the PAT efficiency improvement. It is necessary to carry out correct autopsy of failed pots and determine correct cause and condition of pot failure. These conditions and real cause can change from smelter to smelter and even cathode type to cathode type.

## 8. Acknowledgement

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