Power failure, restart and repair

Power outage may be partial or total, planned or unplanned. Time is an important parameter. Total loss of power for half an hour due to change of cathodes or minor repairs are no problem. Stop for two to four hours are manageable while five hours or more causes large problems with loss of cell life.

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All power interruptions will affect the operation of aluminium cells, from adapting modified operational procedures during routine power modulations to full shutdown of a power line or rectifier failure. Due to limited power or grid capacity several smelters have to live with power modulation in periods of peak power demand and have worked out routines to deal with that.

Primary aluminium producers must have an emergency programme to deal with all kinds of power failures. Such situations can occur without warning and a power failure of more than a few hours may severely damage prebaked anode potlines.

In this situation it is difficult to minimise the damage. However, most power outages are not that dramatic, but it is necessary to have worked out emergency programmes and have foremen and operators drilled in these. Temporary shut-downs of potlines or groups of pots may also be caused by seasonal power shortages, economic considerations or industrial disputes [1,2]. All shutdowns may result in some irreversible damage to the pots and will likely reduce pot life.

Most smelters will have auxiliary power. However, if auxiliary power is lost during a full power failure, there is little one can do other than rapidly evacuate the potrooms. Since the fans will not operate, carbon monoxide poisoning will be a real danger to personnel not wearing suitable respiratory protection.

If line load only falls out and loss of power is assumed to be over the critical length of time, ie the time it takes for the bath to freeze, the anodes should be let down into the metal but pulled up again in the interval between bath and metal freeze. With some power available it would be preferable, but not always possible, to run the pots on a lower load.

Alternatively only part of the line would need to shut down. If the power is restored within the critical time period, pot operation is resumed, possibly at a lower load to give the rectifiers a necessary margin to handle increased pot voltage for rapidly getting back to normal pot operating temperature and conditions, as well as handling the large number of anode effects that are likely to occur.

In the event of an unplanned power failure the cells will quickly lose temperature and the electrolyte begin to freeze. There are, however, considerable differences between the reaction of cells to power loss depending upon technology, size, design and cell condition [3]. Søderberg pots will cool slower than prebake cells.

Due to the high heat capacity of the Søderberg anode this type of cell can tolerate larger power modulations and longer power failure periods than a similar size prebaked cell without irreversible consequences. A pot in poor condition, eg running high voltage due to partial destruction of thermal insulation, will cool faster than a similar cell with intact thermal insulation. In general modern prebake cells (300-400kA) will be most vulnerable and have a significantly higher risk of damages if power interruptions should occur.

These high amperage cells are deliberately designed to have a high heat loss from the cathode and sidelining. They are built with high thermal conductivity materials such as graphite bottom blocks and graphite and/or silicon carbide sides. Their sidewall blocks may be thinner and they may have enhanced shell cooling, eg fins, fans or forced air cooling.

Cell Cooling

Potline power interruptions of 10-30 minutes are commonly carried out in many smelters to change cathodes and perform other necessary repairs.

A prebaked cell can normally tolerate short power interruptions without too many adverse effects. Operational side effects of a full power interruption up to an hour will normally be cooling of the electrolyte to about 940˚C, increased anode effect frequency, excess muck, more bottom ridge and an increase in ledge thickness. When the period reaches one to two hours more serious problems occur.

The bath may cool to about 900˚C, and the cell will begin to freeze in and muck up. When power returns, a lot of anode effects will occur and the possibility of

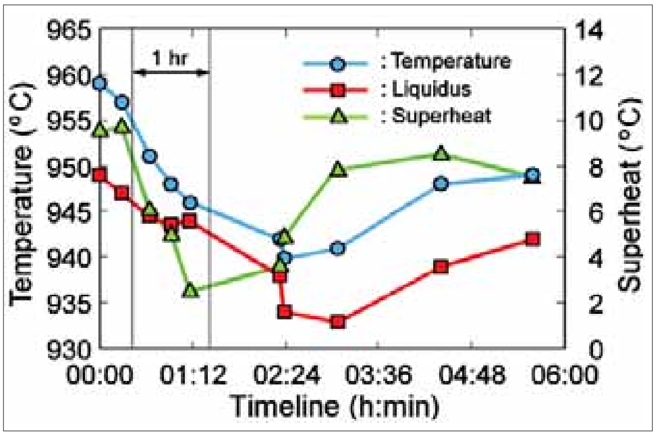

Fig 1 The development of bath temperature, liquidus temperature and superheat during and after a 1 hour shutdown. Source (5)

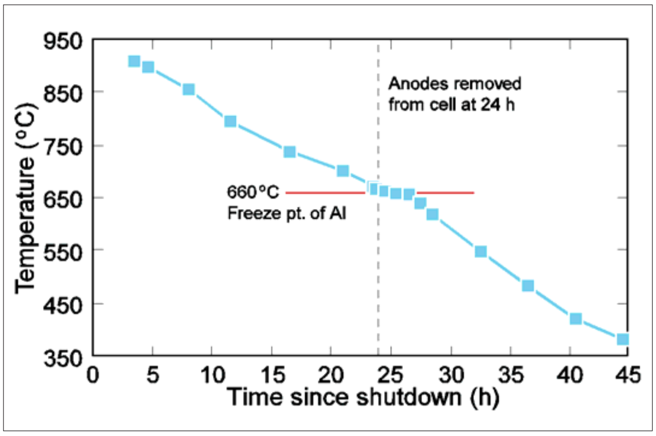

Fig 2 Aluminium temperatures measured in a cell after shutdown. The intersection of metal freezing and removal of anodes was coincidental. Source (6)

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having to shut down some cells is high. A shutdown period stretched towards three hours will, after power is restored, cause extreme difficulty in pot operations [4].

Non-planned prebake cell power interruptions of more than three hours can be catastrophic. This can result in complete freezing of the bath and the forced shutdown of all cells in a potline. Based on their experience Stam and Schaafsma [5] claim that full power loss periods with a maximum duration of about two hours is manageable for repeated current interruptions.

A time limit of three to four hours is applicable but recovery time increases substantially. **Fig 1** shows the development of bath temperature, liquidus temperature and superheat before, under and after a one hour full current interruption. The initial reaction is an instantaneous decrease of both bath temperature and electrolyte-liquidus temperature due to continuous heat losses without energy input.

During this period the energy balance causes a shift in the material balance due to excessive freezing of bath (ie cryolite), which results in an enrichment of AlF_3 (and Al_2O_3). After restart the superheat reacts immediately with an increase and stabilises at approximately its original value, while bath and liquidus temperature continue to drop for a while due to the change in bath chemistry.

The electrolyte freezes at about 900°C after four to five hours. The metal takes a considerably longer time to freeze, and is dependent on the depth of bath and metal pad [6]. In a small prebake cell with about 1600kg metal present, complete freezing of the metal took about 27 hours.

Anode removal after 24 hours may have a minor influence (**Fig 2**). Modeling results for a large prebake cell with about 2½ cm of remaining bath and 7½ cm metal showed that it took more than 24 hours for all the metal to solidify, while a similar size pot with about 20cm bath and 36cm metal needed more than three full days for the aluminium pad to turn 100% solid, provided that anodes were not removed in the meantime.

Due to the large heat capacity of the Søderberg anode, this type of cell can survive a power interruption for a considerable time. Tørklep [7] used computer simulations to calculate the time it would take for the metal in a 116kA Søderberg cell to freeze in the event of a complete power cut. The result was 33 hours, assuming that no extra oxide cover or other insulation against heat losses was provided.

If a power interruption is anticipated some specific steps may be taken to minimise problems and reduce the risk of freezing the bath in the pots [4]:

- Increased pot voltage and/or amperage prior to the event.
- Increased alumina feed control setting prior to event.
- If possible tap metal from cells.
- Increase bath levels in pots with low bath levels.
- Adjust bath chemistry to lower excess AlF_3 (higher ratio).
- Increase anode cover depth.

After the power is cut the suction power of the fans to the pot gas removal system can be reduced to lower the heat transfer from the anode tops.

If short-term power interruptions occur and/or extended power reductions should become necessary there are some modifications to work practices that can be done to reduce heat losses [4]:

- Disable automatic alumina control and resistance regulation.
- Stop changing anodes.
- Inspect and manually cover open holes in pots.
- Reduce fan suction.
- Stop forced cooling of cathode sides (where they exist).
- Close basement shutters (where they exist).
- Kill anode effects as soon as possible.
- Select a group of pots to stop (if necessary) to provide sufficient power to remaining majority of pots.

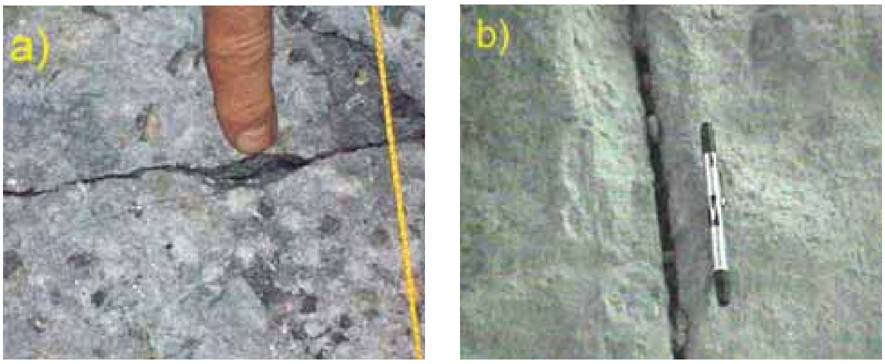

Fig 3 Cooling crack in cathode bottoms. The objects next to each crack gives an impression of crack width. Source (A-8, B-9)

Damage to Cooled Pots

Cell cut-out will always lead to cracks in the rigid carbon pane. These are called cooling cracks and are most often vertical cracks through the bottom blocks, normally perpendicular to the long axis of the bottom panel (**Fig 3**).

Cooling cracks will be visible once the metal pad is pulled as cracks with carbon only in the fracture surfaces. These cooling cracks are seldom the cause of rapid failures after restart. The cracks will be partly closed during restart once underlaying materials have reacted with the bath material making them more resistant to penetration.

Cracks already present in the bottom lining when the cell was shut down which usually fill with aluminium carbide are generally more detrimental to the life of restarted pots than the cooling cracks. These are cracks due to material failure during cell operation and are not likely to mend themselves during and after a restart. The additional thermomechanical stresses imposed during cooling and reheating will likely exacerbate the weakness already present and hasten the final shutdown.

Prolonged exposure and oxidation of already weakened sidewalls can be a major contributor to shorten the life of restarted pots. One may try to leave the side ledge intact during pot cleaning, but it is difficult to avoid patches of exposed side. Old ledge will often also be lost due to temperature excursions during restart and local oxidation and later sidewall patching may become necessary. Preferably the upper sides should be rebuilt. Only sides showing no or very little erosion oxidation damage should pass.

If a decision is taken to temporarily shut a potline, it is preferred to leave an appropriate metal level in each pot, typically about 4-12cm [10]. This solidified metal pad is left in the pot to make restart easier and to protect the underlying lining in case of a long curtailment. In other cases as much metal as possible is siphoned off from each pot, though this is dependent upon the smelters desired method of restart.

During a planned shutdown it normally takes up to a week to get the levels adjusted, perhaps with a proportion of pots shut when ready, before the power is fully cut. At this point, after the line has cooled, it is essentially mothballed, and can be left with minimum maintenance.

Among the most serious damage one may do to cathodes intended to be restarted is to clean them, including removing the metal left, and then let them be exposed to air for a prolonged time prior to restart. The warmer the climate and the higher the relative humidity, the more the damage, possibly resulting in complete destruction of an otherwise good pot. The cause of damage is the reaction of aluminium carbide with moisture in the air:

$$Al_4C_3(s) + H_2O(g) = Al_2O_3(s) + CH_4(g) \quad (1)$$

Fig 4 The result of exposing a cleaned cathode surface to air. a) Alumina powder formed by reaction between aluminium carbide and moist air. The ridges are reaction products being pushed up from the narrow joints. b) A view of the destroyed cathode surface after most of the powder has been removed

This results in a significant expansion of solids. **Fig 4a** shows the surface of a once cleaned cathode exposed to air for too long. The carbide oxidation produces a layer of very fine alumina covering the entire surface.

The parallel powder ridges seen in the photo mark the location of the narrow joints. They are likely to hold a higher carbide concentration. As the oxidation proceeds, it follows the carbide infiltration down into the joint and the fine-powdered alumina reaction product is pushed up.

In the process the carbide-infiltrated the baked ramming paste disintegrates and is pushed out of the joints together with the expanding alumina. In that process the edges of the bottom blocks are also broken off, resulting in a completely destroyed cathode (**Fig 4b**). This cathode was 468 days old and had a level surface without obvious damage when it was cleaned.

Shortened Pot Life

A pot cutout and subsequent restart will almost always lead to some damage to the lining and can, on average, decrease an otherwise obtainable pot life with up to several hundred days.

Driscoll [10] assumes a loss in life expectancy of 50-150 days for each individual pot following a line restart. Older pots with less than 10% of expected life remaining will often not be restarted, those with newly lined cathodes taking their place. This will include at least 5-10% of the population in a line (perhaps as much as 40%), requiring extra effort on the part of the potlining crew to prepare a line for restart.

Welch and Grjotheim [1] found that cells only continued to operate from 400 to 580 days after a restart. Based on pot age at restart, cathode design and cell operational practice, the pot life expectancy can be either longer or shorter. The pot life can suffer badly if several shutdowns are experienced.

According to Rao [2], the average pot life was reduced to 17 months and the average cathodic voltage drop increased from 11 to 16 mV, when the number of restarts was increased from one to two for a given potline.

Each restart resulted in a drop in current efficiency of 1-2% which could not be pinpointed to any particular cause. By taking into account the condition and age of each individual cell and estimation of the average reduction in pot life for a particular cell design, it should be possible to calculate if it is economically feasible to restart a given pot.

Another way of assessing reduced pot life is in % of remaining life. Losses of 50-30% of remaining life are probable figures. Again the loss will be dependent on how the pots are stopped. For a potline with an average life of 2500 days, loss of 30% of remaining life = 2500 x 30 / 2 = 375 days.

For 16 different potlines at 10 different prebake smelters Tabereaux [8] reported an average loss in pot life due to shutdown and restart of 279 days with a typical variation from 100 to 400 days depending on specific circumstances particular to each smelter. Some of the major factors that influenced pot life were pot age distribution, cathode sidewall and bottom block materials, pot operational conditions prior to shutdown, cell restart methods and potline startup amperage.

The loss in pot life distribution emerged as follows:

- A low loss in pot life (100-200 days) and low number of premature failures (0-2%) were obtained in potlines that had a low to normal age distribution of cells, controlled shutdown, slow restart practices and control of pot temperatures after the restart.
- An average loss in pot life (200-300 days) and normal number of premature failures (2.5-5%) were obtained in potlines that had a normal pot age distribution, controlled shutdown, improved restart practices and good control of pot temperatures after restart.
- A high loss in pot life (300-400 days) and a high number of premature failures (>5%) were obtained with potlines that had one or more of the following:
  - High pot age distribution.
  - Long extended cooling periods prior to shutdown.
  - Uncontrolled shutdown.
  - Rapid restart practices with marginal control of pot temperatures after restart.

There are several reports of shut-down and restarts which give useful information

Albras 2002 [9]

Had to shut a group of pots due to power shortage. The cells were covered with electrolyte during the stop but some oxidation still occurred. The cells were cleaned, checked and patched before start-up and covered with a plastic sheet to minimise oxidation.

Due to capacity reasons both hot and cold restart were used. There were some operational difficulties such as joint failures, high burn-off rates, anode cracking and hot pots.

Alumar 2003 [11]

Had a rectifier blow up which affected 247 pots. Anodes were raised above bath level. Some pots were tapped some not. Anode and superstructure were removed and bath removed. They tried to keep the side ledge. Butts selection was critical.

The anode sidewall channel was filled with crushed bath to protect the sidelining and give heat insulation. Start-up was by the crash method, ie the bridges were lowered until contact with the solid metal pad, liquid bath poured in and the current cut in. The ACD during restart was kept higher to melt the metal pad and heat the cathode. Enough bath should be poured in to allow the higher ACD. No liquid metal should be added with the bath. A lowering of the line load may be necessary if the number of anode effect became high. Increase of metal pad depth may help with ledge formation and pot stability.

Additional liquid metal should not be added before the bath is completely melted. The bath ratio was kept above target to compensate for sodium absorption. Alumina feed was turned on when pot noise reached a low level. The restart of the 247 pots took 32 days. (Shorter than first anticipated).

Elkem Aluminium, Mosjøen 1982 [13]

An arctic hurricane hit and line II lost power for 7.5 hours and ${}^{1}/_{3}$ power for an additional 6 ¾ hours. Auxiliary power was available. The anodes were lowered into the metal pad and covered with extra crushed bath. The gas cleaning system was run on ${}^{1}/_{3}$ capacity.

A hole in the frozen bath was chiseled

out in the middle of the aisle side for inspection and possible bath addition. The pots were on normal load and 1.5 – 2 volts with anodes in the metal pad with temperature 875°C - 925°C.

The anodes were lifted to the top of the metal pad to give 4 – 7 volts and left for preheating for 6 – 8 hours. The anodes were lifted further to give an unstable voltage of 5 – 30 volts. Bath started to melt out from the sides, and after some bath production the voltage stabilised at 15 – 25V.

After an hour sufficient bath had melted and the cell was operated with wooden poles. The voltage dropped to 7 – 9 volts. The pot was operated manually for 12 – 16 hours and then set to 'auto' with a set point 3m higher than normal for 24 hours. Two days after restart the average bath temperature was ≈ 1010°C and went down to normal a week after restart.

The cryolite ratio was stabilised after two weeks. Two pots were lost at the end of the month probably due to the accident. No anode problems were encountered.

Rusal, Novokuznetsk 2009 [14]

Two properly functioning 140kA vs. Søberberg pots were stopped (age 33.8 and 32.1months). The cathode surface was cleaned by increasing the cryolite ratio and temperature. Metal was tapped to two levels, A: 3 – 5cm, B: 17 – 19cm. As much bath as possible was siphoned off by temporarily lowering the anode into the metal. The anode was raised out of the molten aluminium after all bath contents had solidified. The cell was left for 20 days for complete cooling.

The pots were then resistance preheated on liquid aluminium. The ramp-up speed was determined by the time it took to reach maximum pot voltage. Cryolite was added to the side channels to reduce heat loss. Both pots were preheated for three days with metal temperatures reaching 855°C in pot A and 893°C in pot B. The cells were then started by adding bath and raising the anodes.

Pot Repair

Complete relining or partial repair of failed pots is an economic decision that has to be taken on a case to case basis. The extent of the damage and the age of the pot are important parameters.

A repair that presupposes a complete cell shut-down and subsequent cooling of the cathode will reduce the pot life by several hundred days. This will therefore be uneconomical for cathodes above a certain age. If the repair can be performed without a major interruption in production or metal quality, it is generally performed regardless of cell age.

Most cathode failures, however, are so extensive that it is neither technically nor economically feasible to do anything but a full pot relining. Among the failures that sometimes can be subject to temporary repairs without a major interruption in production are bath tap-out through the sidewall, metal leak through a collector bar and sudden iron contamination caused by pothole formation. Red-hot sides, often followed by bath tap-outs through the sidewall, are generally caused by air oxidation of the sidewall carbon. A local failure generally can be repaired by temporarily reduction of the bath level in the pot, cleaning the failure area and tamping cold or hot ramming paste towards the steel side. Sometimes a hole has to be cut through the deckplate to accommodate this.

The cathode life can in some instances be extended several years by this repair method, until finally the entire sidewall lining and steel shell have reached an irreparable condition. Red sides alone are no reason to cut the pot. Cool the affected area using air pipes but determine the root cause of the problem.

If the cause of metal tap-out through a collector bar can be localized to a crack or pothole through the carbon lining near to the bar, it might be possible to seal it by packing the pothole/crack with lump or flake (recrystallised) alumina.

The strap to that particular current collector bar may have to be cut in order to reduce the temperature and current density in the failed area and let the alumina-cryolite form a hard sludge that may seal the crack. If the tapout is due to a specific block failure and not from the collector bar exposure but by general bottom wear caused by old age, the pot can be cut and repaired by removing a few blocks, or in some instances only part of a block.

Core drilling around the damage area will make it possible to remove a part of the bottom carbon lining without disturbing the remainder too much.

Local bottom surface wear under the tap-hole can be repaired in the same way by filling the depression with recrystallised alumina. However, the tapping point should be moved to another location, which can be impossible in some cell designs. Otherwise it will be impossible to form a stable alumina-bottom sludge protective cover.

If iron contaminates the aluminium through a greater number of minor cracks, which sometimes are formed in the peripheral paste seam due to excessive paste shrinkage, the metal contamination may sometimes be kept at an acceptable level for some period by breaking the top crust along the sides of the cell. If this procedure is repeated at regular intervals, a ledge of frozen bath and alumina may cover the lower side and bottom periphery and help seal off the failed areas.

Once serious metal infiltration through the ring joint followed by bottom heave has occurred further cathode deterioration is impossible to stop. The cell will have to be cut when the iron contamination reaches an unacceptable level or the pot no longer can be operated due to excessive noise or instability.

If the cell has to be shut down due to local damage in a bottom block or the peripheral paste seam, the full extent of the damage should be accessed before the decision to repair or not is taken.

This will often imply the removal of a section of the bottom lining. If the cell age is low and the damage only local, it may be worthwhile economically to replace the failed block(s) or repair the border. If there has been a metal tap-out through a collector bar and only the border is repaired, the strap to the failed collector bar should be cut in order to reduce the possibilities of a new tap-out at this weak spot. ■

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