

EARLY FAILURE MECHANISMS IN ALUMINIUM CELL CATHODES

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ABSTRACT

The present paper gives examples of early failure mechanisms as revealed by detailed autopsies of cells at Elkem Aluminium. When more emphasis was put on planned and thorough autopsies back in 1984 the average pot life was approximately 1000 days. At present it is approaching 2000 days and still increasing, mainly as a consequence of a significant reduction in early failures. This paper will concentrate on the actual examples, underlying causes, mechanisms and remedies. For a more detailed theoretical discussion it is referred to the book by Sørli and Øye [1].

INTRODUCTION

Ideally, an aluminium reduction cell cathode should last as long as it takes the natural erosive and corrosive forces to wear the carbon lining evenly down to the level of the current collector bars. In practice, this will not take place and industrial cathodes fail in a far shorter period for a number of other reasons. Determined efforts, through design and relining practices as well as increased quality of lining materials and better understanding of the basic thermomechanical and chemical processes that takes place in the cathode lining during heating and operation, have increased pot lives at most smelters around the world.

UNEVEN HEATING AND THERMAL SHOCK

The cathode carbon lining has an open porosity through which bath components can percolate. Liquid metal, however, do normally not penetrate this porous structure. The various carbon qualities that are used in industrial cells, having different porosity, permeability, structure, etc., may only influence the rate of percolation, not the end result [2]. Since this bath penetration is normal in the cathode, a proper lining is designed in such a way that part of the refractory materials underneath the carbon bottom blocks will have time to absorb and react with the penetrating fluorides, thus converting it into a denser, often glass-like, barrier that stops or significantly retards further percolation. Since such reactions should proceed evenly and slowly after start-up of the cell, it is of utmost importance that larger cracks or gaps in the lining, through which uncontrolled amounts of bath and metal may drain in a short time, are avoided. Such early crack or gap formation in the carbon lining are most often caused by thermal shock or thermal displacement of lining materials during preheating and/or start-up of the cell.

The thermal gradients that are introduced in the carbon bottom during preheating of the cathode are a major contribution to thermal

shock cracking of the bottom blocks. Other important parameters are materials properties associated with the structure of the carbon, such as the coefficient of thermal expansion, thermal conductivity and strength parameters.

The gentlest possible preheating of the cathode is probably achieved with gas burners. The temperature increase and the temperature distribution in the carbon bottom pane can be closely monitored and controlled and no cracking or displacement of the bottom blocks is likely if such a flame preheating is performed satisfactory. The philosophy regarding the final preheating temperature setpoint may be different at different smelters using this method, but it seems that 600-700°C top temperature and an even temperature distribution is sufficient [3], resulting in an even cathodic current distribution during start-up.

Resistor baking of pots, using a coke bed as resistor material between anode and cathode, is probably the most common preheating method, especially in prebaked anode cells. Poorly executed this method can, however, subject the bottom blocks to severe thermal shocks, with temperatures up to 1500°C and thermal gradients of 1100°C/m at the carbon surface of the cathode [4]. Poor anodic current distribution during preheating may often be seen directly as red studs or anode cracking, but the condition of the underlying bottom block can be equally poor, although often not spotted due to the coke cover. Such preheating cracks (Figure 1) in

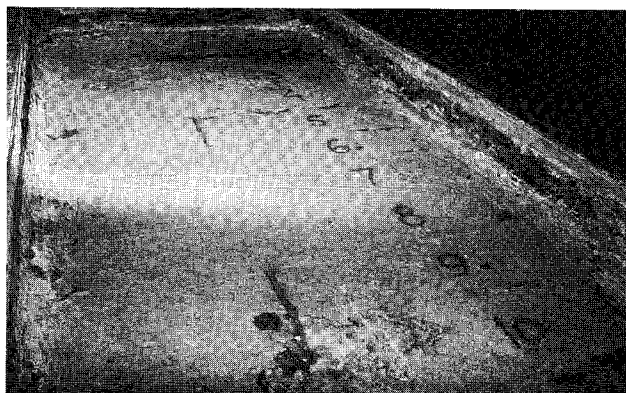


Figure 1. Preheating cracks (in bottom blocks no. 5 and 9) in failed cathode. Cracks are painted in order to mark them on photograph. Coke resistive preheating on full line load. Pot life was 446 days.

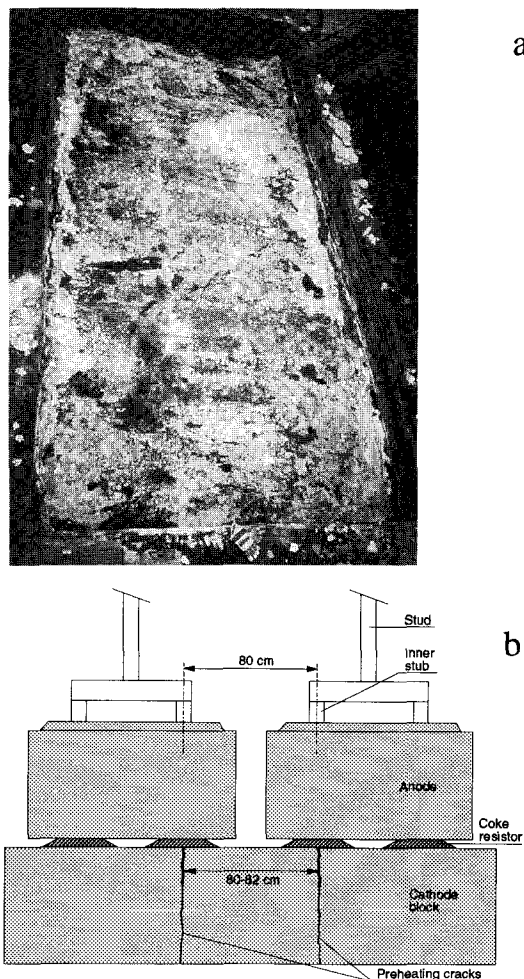


Figure 2. Photograph (a) shows cathode surface with two parallel lines of preheating cracks, spaced 80-82 cm apart, running through all bottom blocks. Cracking pattern corresponds exactly to inner stub-stub distance (b) and observation that major part of current initially passes through the inner stubs. Pot life was 1233 days.

one or more blocks is probably more a rule than a freak accident if cathodes with amorphous bottom blocks are resistor baked on full line load. Shunting or replacing amorphous block qualities with more graphitic ones will reduce or remove this problem.

Although one or two blocks may crack due to poor current distribution, more extensive cracking during preheating is most often due to unsatisfactory carbon quality. Figure 2a shows a photograph of a cathode surface in which every bottom block had experienced two preheating cracks, seen as two parallel lines running down the length of the cathode bottom. As the current distribution inevitably is somewhat uneven some cathode blocks are being subjected to much lower current densities than average. Normal quality blocks subjected to lower-than-average current densities should not crack, hence a cracking pattern as shown in Figure 2a is caused by inadequate thermal shock resistance of the entire bottom blocks lot. The distance between the parallel cracks was measured to 80-82 cm, corresponding almost exactly to the inner stub-stub distance of the anodes in the cell (Figure 2b) and in agreement with the observations that the major part of the current is passing through the inner anode stubs during the initial preheating period.

The procedure that most effectively may reduce or avoid thermal shock cracking during resistive preheating is by shunting the pot. Other remedies can be reducing the differences in resistivity of the

coke beds underneath each anode. This is done by using flexible contacts and allowing the full weight the anodes to rest on the resistor coke bed. The evenness of the coke layer is important, both with respect to height, contact area and granulometry.

Coke resistive preheating may also be used for Söderberg pots, but a requisite for avoiding thermal shock cracking is that the anode surface is milled flat. Since the working surface of the anode adjusts to the shape of the metal pad surface, it is virtually impossible to obtain even contact with the resistor coke over a sufficiently large cathode surface area. The result of such a preheating may be catastrophic, in extreme cases the unevenness of the cathodic current distribution has been found to melt steel collector bars in their slots and almost instantly graphitize parts of amorphous cathode blocks, a thermal process that need temperatures well above 2000°C.

STRATIFICATION OF RAMMED PARTS

Virtually all modern cathode designs use a combination of prebaked blocks and a carbonaceous ramming paste in the construction of the carbon lining. Such paste is almost always used in the peripheral seam between bottom blocks and sidewall carbon and also normally between bottom blocks, although in some designs these blocks can be glued together. The ramming paste itself do normally not act as a glue and show poor bonding properties. The use of rammed parts in the pot serves several purposes. Its most important purpose is to fill the voids between the prebaked bottom blocks and between blocks and sidewall materials, thus preventing liquid metal and bath from penetrating rapidly into the interior of the lining. Another important purpose is to absorb some of the thermal expansion of the bottom blocks during cell preheating. The need for peripheral paste-filled seams also result from the practical problem of fitting bottom blocks with mounted current collector bars into the pot shell if the shell has a permanent deckplate. Special high electrical conductivity carbonaceous pastes, glues or cements are also used at some smelters to make the seal between current collector bars and bottom blocks.

Autopsies of failed cathodes have shown that a disproportionate number of early failures, *i.e.* pot lives less than 2-3 years, are caused by weaknesses in the rammed parts of the carbon lining [5]. Such failures are either caused by improper paste installation, bake-out or cell operation, in addition to poor thermomechanical characteristics of the paste itself.

Possibilities for later pot failures introduced during installation may be caused by improper ramming procedures as well as poor paste properties. Unsuccessful compaction will yield baked parts with low mechanical strength and excessive amounts of coarse porosity,

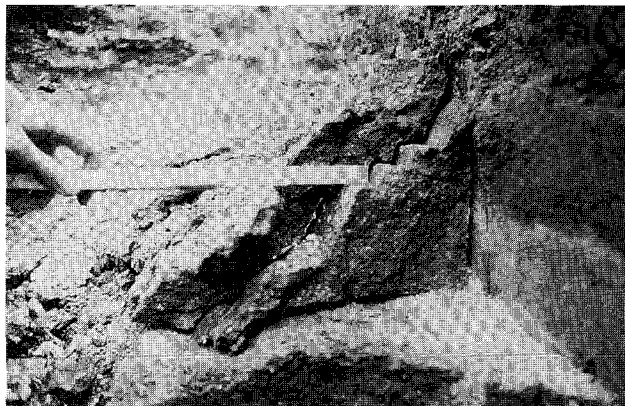


Figure 3. Photograph of peripheral paste incline shows stratification and lack of binding between paste layers caused by extensive crushing of paste surface particles during compaction (grooves from serrated wheel of compaction machine). Pot life was 314 days.

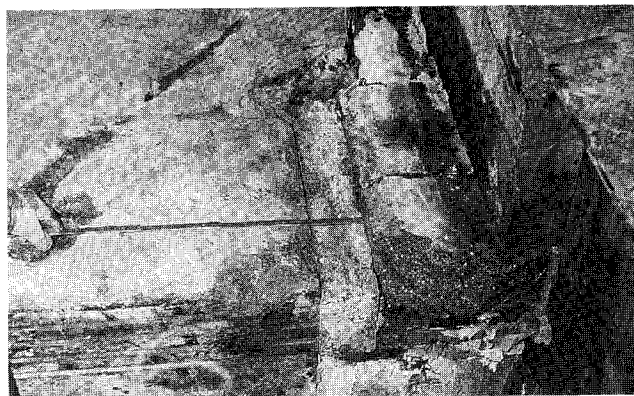


Figure 4. Loss of parts of the peripheral seam incline caused by stratification in upper part of seam. The photograph also illustrates the poor bonding between prebaked carbon (filler block and sidewall block) and rammed parts. Pot life was 9 days.

being subject to wear and pot-hole formation. Over-compaction, on the other hand, may segregate the surface layer or crush surface aggregate, resulting in poor green and/or baked binding properties to the next rammed layer. Figure 3 and Figure 4 show examples of stratification failures in the peripheral seam. It is important to know the compaction characteristics of a given paste and its temperature window [6], since a good standard installation practice for one may be unsatisfactory or, in worst case, completely destroy another brand [7].

SHRINKAGE OF RAMMING PASTE

While baked carbon materials displays a positive coefficient of thermal expansion at all temperatures they are likely to experience in the cell, carbonaceous ramming pastes will normally shrink within a certain temperature range, caused by carbonization reactions in the binder. A pitch-based binder will remain in a liquid or plastic stage up to 500°C where it carbonizes to a brittle solid. This temperature can be lowered if thermosetting additives are used. Below the hardening temperature the rammed parts may expand (or slump) but will absorb thermal expansion of the bottom blocks and other construction parts by plastic deformation. Above this temperature the paste will shrink, the magnitude will mainly depend on the granulometric composition of the paste and to a lesser extent the binder content [5]. The compaction density of the paste will normally not have any large influence on its shrinkage behaviour. The calcined paste aggregate will expand over the entire temperature range and as the binder carbonization reactions goes towards completion, usually in the temperature range 750-900°C, the bulk paste starts to expand again. The net shrinkage of the paste will be the net thermal movement from the temperature it solidifies to the temperature expansion starts again.

High paste shrinkage, especially in the more bulky peripheral joint, can result in vertical crack opening and be detrimental to pot life. For pastes with very poor shrinkage characteristics such shrinkage cracks have been found with less than 1 meter spacing almost along the entire periphery of the cell. Assuming a paste with 0.4 % net shrinkage, which is quite normal but far in excess of what should be tolerated, the total crack width for each running meter could amount to as much as 4 mm. Figure 5 shows a photograph of such a shrinkage crack in the peripheral seam.

The rammed peripheral seam has often been found to be the weakest part of the lining, through which massive amounts of bath and metal can drain into the interior in early life. Figure 6 shows an autopsied cathode where the fatal failure, a typical vertical shrinkage crack in the peripheral seam, had developed. A massive cone of solidified aluminium metal can be seen below the crack, among reacted and

collapsed refractory and insulation materials. Several tons of metal and bath had flowed further down into the cathode, destroying more bottom insulation on its way.

The rammed joints between the bottom blocks do usually not develop these shrinkage cracks. These joints are only a few centimeters wide and the frictional forces between the paste and the prebaked blocks are high enough to distribute the shrinkage stresses in such a way that rather a large number of microcracks will develop than a few major cracks. In addition to choosing ramming pastes with more acceptable shrinkage characteristics, similar narrow peripheral seams could be used to minimize the possible development of fatal shrinkage cracks.

COLLECTOR BAR INDUCED FAILURES

The steel collector bar in aluminium cell cathodes is normally sealed to the bottom block by cast iron, carbonaceous ramming paste, glues or cements. Since the thermal expansion coefficient of the current collector bar can be several times that of carbon, severe

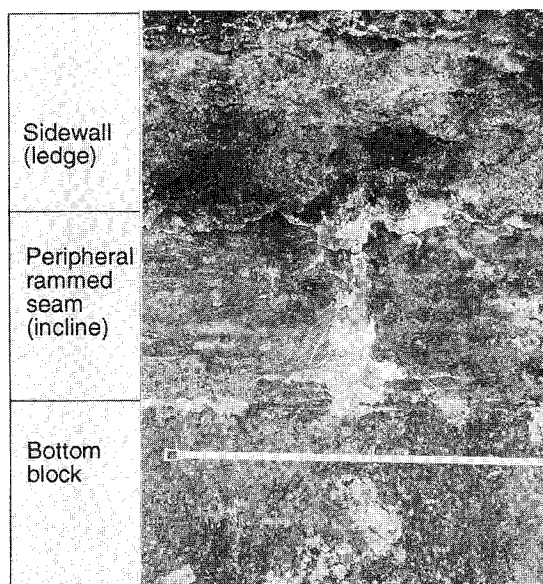


Figure 5. Vertical crack in peripheral seam filled with bath and metal. Pot life was 350 days.



Figure 6. Cathode failure caused by massive bath and metal penetration through shrinkage crack (surface covered with frozen bath and metal) in peripheral seam. Pot life was 5 days.

thermomechanical stresses can develop when the assembly is heated. Unless taken into consideration and reduced by design or sealing practices such stresses can lead to crack formation that may completely destroy the cathode bottom or severely increase the cathodic voltage drop.

Cast iron sealing is known to initiate bottom block cracks if not performed properly [1]. These are normally wing cracks and corner cracks caused by thermal shocks and differences in thermal expansion. These cracks may seem to close again when the assembly is cooled after sealing, but will remain weak spots in the block that may initiate further crack formation and fatal failures may develop when the cell is started and the expanding collector bar exerts pressure, both transversely and longitudinally, on the wings of the bottom blocks. Such initial cracking may be reduced by several means, such as geometry of slot and bar (volume to be filled with cast iron and radius of slot corners) preheating temperature and temperature distribution of block and collector bar, temperature and composition of cast iron poured, *etc.* The preheating procedures during sealing will also reduce the resultant stresses during preheating and start-up.

When ramming paste or glue is used for sealing purposes the differential thermal stresses can not be reduced by any preheating measures of the block or collector bar. A carbonaceous paste, glue or cement will remain plastic up to its hardening temperature and contract during the baking process. The baked carbon, and thus the slot, will expand over the entire temperature range while the steel collector bar will expand up to about 750°C, then contract and expand again. The steel expansion-contraction-expansion is caused by the ferrite-austenite phase transformation in the steel. Assuming that there is zero stress in the bar-paste-block assembly as long as the paste remain plastic, it is the relative thermal movements of the parts after hardening that generates the critical stresses [8,9].

Wing cracks can often be observed in autopsied cathodes and are sometimes the direct cause for failure. Depending upon slot and block geometry, resulting forces and movement restraints in the carbon bottom pane, the crack propagation paths may take a variety of directions from the slot corners, from more usual angled cracks *via* near vertical tensile failures to near horizontal shear failures. Even if such cracks not necessarily leads to a rapid failure the cell

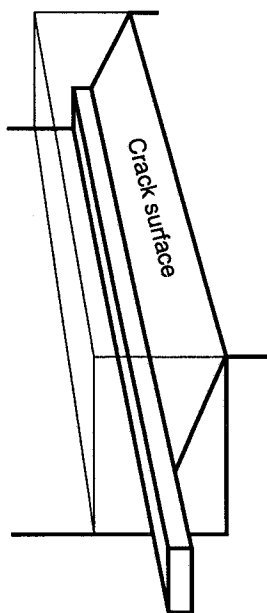
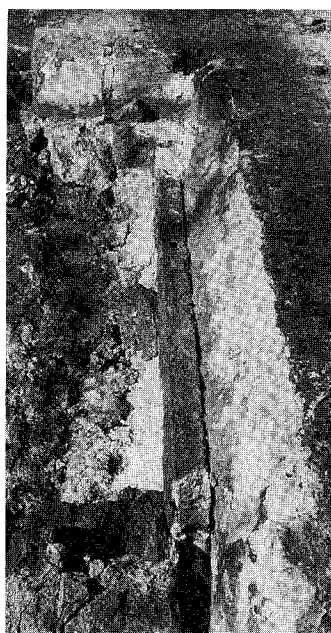


Figure 7. Cathode failure caused by angled crack in bottom block. Top of bottom block removed to expose crack surface. Partially dissolved collector bar in foreground. Pot life was 1032 days.

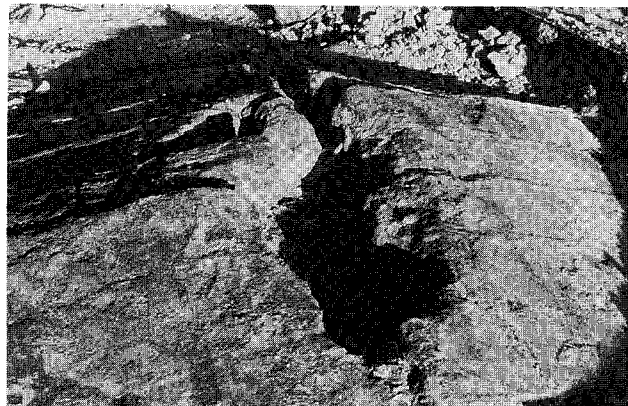
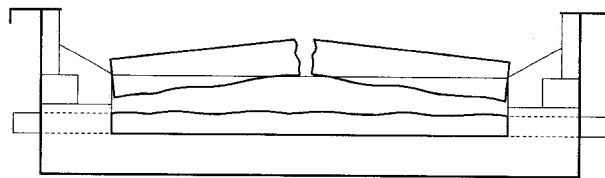


Figure 8. Buoyancy displacement of large parts of carbon bottom caused by extensive horizontal shear failures in bottom block wings. Pot life was 21 days.

will experience an excessively high cathodic voltage drop and high energy consumption. Figure 7 shows a crack running along the entire length of a bottom block from the top of the collector bar to the cathode surface. The top of the block has been removed and a typical crack surface, covered with aluminium carbide and fluorides is seen. Part of the collector bar has been dissolved and replaced with frozen bath.

More extensive wing failures, especially of the shear type failure may have dramatic consequences. Figure 8 shows the cleaned surface of a failed cathode where large parts of the carbon bottom pane above collector bar level became detached and floated to the anode working surface.

The best remedy for avoiding a fatal wing crack failure is to adjust the geometries of the slot and collector bar to the combined thermomechanical movements of the sealant, bottom block and bar. While the contact pressure during early operation should be large enough to minimize cathodic voltage drop and to avoid the possibility of any early bath or aluminium metal penetration, it should not exceed the critical of the carbon block. If cast iron is used to seal the bar proper preheating of collector bar and block prior to sealing is also very important.

TRANSIENT HIGH TEMPERATURES

Inadequate start-up procedures and operational difficulties, such as prolonged anode effects, "sick" pot or alumina feed problems, may sometimes lead to exceedingly high temperatures in the cell, lasting from a few hours to days. The results of such incidents are not only poor pot operation results and high fluorine losses, but fatal and irreparable damage to the cathode lining may also take place. Increased temperature gives increased expansion of the carbon lining, an expansion which is ultimately absorbed in the peripheral crushable insulation (if any) or by the steel shell. Ideally, the steel shell and its supporting structure should absorb these strains elastically. Some non-elastic deformations are, however, likely to occur, especially if the shell is old, the supporting structure weak, or the operational problem is not rapidly diagnosed and attended to.

When the temperature is brought back to normal again the carbon lining contracts accordingly and any non-elastic deformations of the

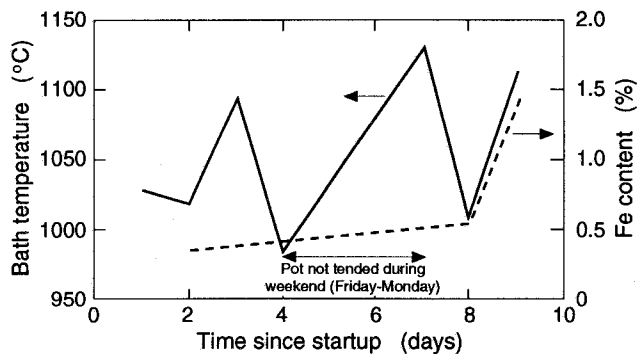


Figure 9. Recorded temperature and iron contamination in a pot that failed only 9 days after start-up. High transient temperatures had led to gap opening between bottom blocks and peripheral rammed paste.

steel shell or crushing/deformation of lining materials will lead to gap opening in the lining. Depending on where the failure occurs the cathode may experience rapid failure from metal penetration in bottom block-peripheral seam area, or permanently changed cathodic heat balance from insulating gaps formed at the steel shell-lining interface.

The development of temperature and metal iron content in a pot that failed after only 9 days is shown in Figure 9. After an transient high temperature three days after start-up the pot was brought back to normal conditions before a week-end. Lack of proper attention during the week-end brought the temperature up to $\approx 1130^{\circ}\text{C}$, leading to pot failure from excess iron contamination when brought down again. A later autopsy of the cathode revealed that gaps had opened between bottom blocks and the peripheral rammed seam along one side of the pot, thus giving aluminium metal rapid access to the current collector bars.

Less dramatic gap openings and metal penetrations, but in the end often detrimental to pot life, are sometimes experienced shortly after start-up of a cell through a sudden an transient increase of the iron content in the metal (Figure 10). Normally this means that parts of the collector bars have been exposed to molten aluminium and that the gap or crack that were created was big enough to transport iron up into the metal pad. These gaps often close again due to thermomechanical and chemical processes taking place in the lining, resulting in a rapidly decreasing contamination level. However, fatal damage may already have been initiated since metal has penetrated the lining and been sealed off in the interior of the cathode. This early metal penetration will increase the possibility for slow but damaging chemical reactions to take place in the lining. Such early transient metal leaks are often caused by inadequate preheating and start-up practices or from relining of old and deformed shells.

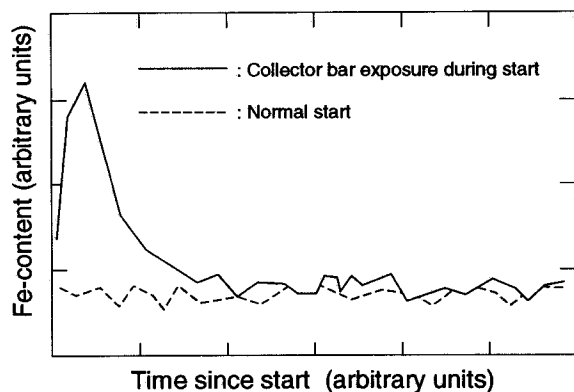


Figure 10. A transient increase of the iron content in the aluminium metal after start-up is an early warning signal that a metal leak into the interior of the lining has taken place (from [1]).

SODIUM INDUCED EXFOLIATION

Intercalation is a process where atoms or molecules (intercalants) are free to move through the carbon (host) lattice to occupy fixed positions between the graphitic basal planes. Such intercalation reactions may, if run to their final stages, result in stoichiometric carbon-intercalant compounds that have physical and chemical properties very different from the original carbon or graphite. This leads to an expansion of the carbon lattice perpendicular to the basal planes as well as a rearrangement of the stacking order of the planes. Sodium, which always is present at the cathode carbon-metal interface in aluminium reduction cells, will readily penetrate the carbon lattice. Furthermore, sodium will have a higher affinity the more disordered (amorphous) the carbon is, the driving force being electron transfer from the sodium atom to the π -electron system of carbon [10]. Such changes on the atomistic scale can have dramatic consequences for the macroscopic behaviour of amorphous carbon blocks. An isothermal sodium induced expansion of a given cathode carbon block may be far larger than its normal thermal expansion up to operating temperatures and give rise to local strains on the grain level and below that may completely disintegrate the baked carbon.

Different carbon materials have different resistivity towards sodium expansion and deterioration. A general rule is that the more graphitic a material is the less affected it is by sodium and the greater its sodium resistance. Only cathodes made from electrically calcined anthracite, ECA (possibly GCA + graphite) or better should be used in the cathode lining, and there appears to be a trend in the aluminium industry to move towards more graphitic bottom blocks.

Apart from minor sodium-induced surface spalling (Figure 11) it is often hard to point to fatal failures that directly can be related to the sodium expansion of the carbon materials since other types of materials degradation and failure may shroud the failure sequence. However, there are examples of almost complete disruption of most of the carbon bottom (amorphous blocks above current collector bar level) by enormous amounts of minor horizontal exfoliation-like cracks that it is difficult to explain otherwise.

Contrary to the thermal expansion of the carbon, it seems that it is possible to partially restrain the sodium induced expansion by applying an external load [11], a situation that might apply to modern strong potshells. It is, however, possible that the microfailures that sodium intercalation can introduce will reduce the



Figure 11. Sodium-induced surface exfoliation of amorphous sidewall carbon. Pot life was 111 days.

strength and integrity of individual grains and the binder matrix, thus making the carbon more susceptible to failure by other mechanisms in the longer run.

BOTTOM HEAVE

Pot failure by bottom heave sometimes takes place in young pots, and the pot is normally taken out either after a sudden increase in the iron content of the metal or following a tap-out through a collector bar. However, the initiation of this type of failure occurred most probably during preheating or start-up of the cell through crack or gap formation followed by rapid bath and/or metal penetration into the interior of the cathode.

Metal leaks through the insulating parts of the lining will act as heat sinks and reduce the temperature in the interior of the cathode while increasing the temperature on the steel shell. Any metal penetration into the interior of the lining is potentially harmful. A disturbed heat balance may influence the operation and energy efficiency of the pot, resulting in excess bottom ledge formation, increased ohmic set-point and higher energy consumption. More serious for the pot life expectancy are the reactions that slowly but steadily proceeds in the interior of the cathode, especially if the freezing, or critical, isotherms are pushed up into the carbon bottom blocks. In these surroundings, lenses of columnar fluoride may start to grow within the carbon body. This "salt lens" formation is fed by bath components percolating through the open porous structure of the bottom blocks and the preferential growth of crystals in the larger pores on the expense of the smaller. It should be noted that the forces that develop are directional, not merely upward because of less resistance to expansion and material displacement, but perpendicular to the isotherm and in direction of crystal growth.

Considerable amounts of aluminium carbide may also be formed by reaction between aluminium metal and the lower parts of the cathode block. This reaction can be especially damaging if metal leaks forces the critical isotherms up into the carbon block and a slow feed of aluminium metal and fluorides is maintained. The last requisite is almost self fulfilling, since bottom heave generates leaks that generates more bottom heave, and so on in a vicious circle. The pressure that forces the bottom blocks up will also tend to flex them, ultimately resulting in fatal crack formation and exposure of current collector bars to the metal pad (Figure 12).



Figure 12. Failed cathode with extensive cracking pattern in carbon lining caused by bottom heave. Pot life was 501 days.

BOTTOM HEAVE - POT SHELL INTERACTIONS

The pressure that forces the bottom blocks upwards results in a counterpressure of similar magnitude directed downwards. The deckplate around the periphery of the pot and the strength and stiffness of the casing itself and supporting structure will counteract these vertical movements. Weak pot shells with no or inadequate supporting structure can be badly deformed in the bottom heave process. The photograph in Figure 13 shows the deformation of the peripheral parts of the steel shell bottom, caused by the resulting forces of an upward pressure acting on the deckplate and a downward counterpressure acting under the carbon bottom pane.

In cathodes having stronger and stiffer support structures, steel shell deformations of this magnitude are seldom seen. With similar reactions taking place within the interior of the stronger cathode the resulting displacements of lining materials can be similarly damaging. Figure 14 shows the vertical tilt of a filler carbon block in the side lining of a strongly supported steel shell, caused by the upwards movement of the adjacent bottom block. The vedge-shaped gaps formed at the interfaces between the peripheral rammed seam and the prebaked filler and bottom blocks are filled with bath and aluminium carbide.

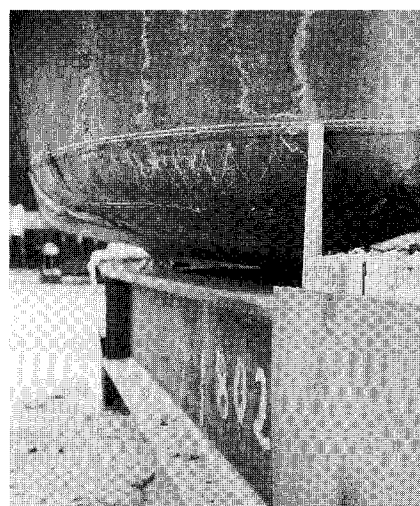


Figure 13. Bottom deformation of a weaker type self-supporting steel shell following bottom heave. Pot life was 742 days.



Figure 14. Forced tilt of carbon side lining filler block following bottom heave in cathode with strongly supported steel shell. The vertical displacement is 7.5 cm measured from bottom corners of filler block. Pot life was 1032 days.

AIR OXIDATION

Failures caused by air oxidation of carbon are normally upper sidewall failures (Figure 15), usually resulting in red-hot sides or bath tap-outs. This kind of sidewall failure is usually a function of cell operation, *i.e.* insufficient covering and sidewall protection practice, but poor lining design and bad pot shell conditions may worsen the situation. Unless a good frozen bath and alumina cover is maintained, the upper part of the sidewall carbon may be completely removed in a couple of years. Finally, only a frozen layer of bath may protect the potshell, and a prolonged anode effect may be enough to melt this ledge and cause a tap-out. Figure 16 shows a photograph of a pot that was stopped after the fourth tap-out due to sidewall removal. The first similar tap-out occurred after only ≈ 900 days in operation.

This type of failures can sometimes be temporarily repaired by cutting a hole in the deckplate and seal off the tap-out area with ramming paste. Proper covering of the top sidewall with frozen bath and oxide will reduce the rate of oxidation. One or two layers of air and fluoride resistant refractory bricks between deckplate and

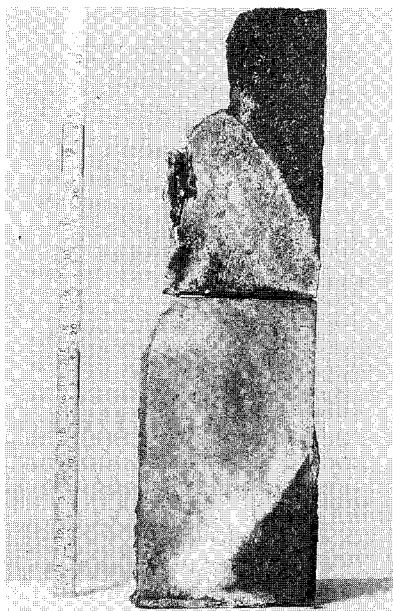


Figure 15. Oxidation (and sodium) damage of sidewall carbon after 262 days in the pot.

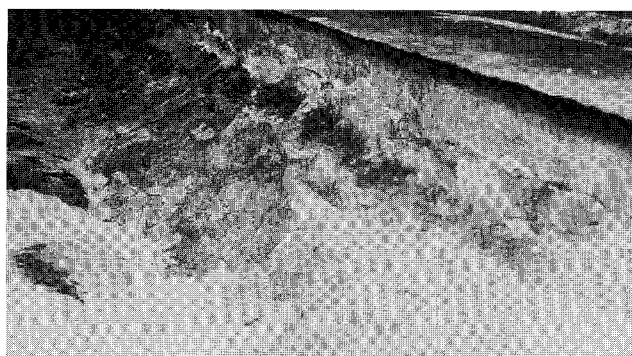


Figure 16. Almost complete removal of sidewall carbon by air oxidation. Pot was finally taken out following its 4th side tap-out after 1486 days, but first tap-out caused by sidewall oxidation took place after ≈ 900 days in operation.

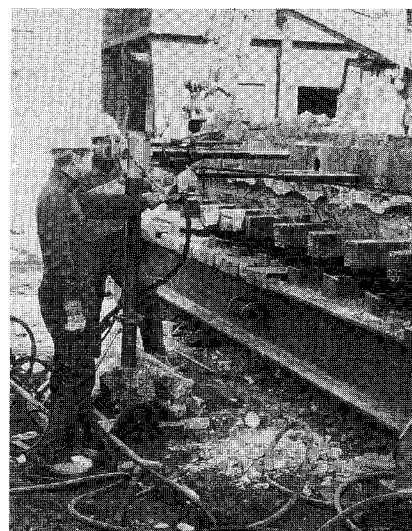


Figure 17. The steel shell side has been removed from a failed pot and an air-burn pattern characteristic of leaky seals can be seen on the carbon filler blocks above the current collector bars. Pot life was 595 days.

sidewall carbon can give an excellent, although more costly, protection of the underlying carbon. High quality silicon nitride bonded silicon carbide bricks will normally give an adequate protection. Air may also find its way behind the sidewall carbon, from the top or through leaks in the collector bar-steel shell seals (Figure 17). In addition to removing sidewall protection from places where it is not readily detectable, such air gaps that are formed between lining materials and the steel shell can result in unwanted insulation effects. As the air usually enters through the collector bar holes, an effective seal will alleviate the problem.

SIDEWALL AND BOTTOM EROSION

Although bottom wear and lower sidewall failures often are referred to as erosion, a more correct term would be corrosion, since the major part of the carbon is removed by chemical [1] or electrochemical [12] mechanisms. The reaction between aluminium metal and carbon to aluminium carbide is thermodynamically favoured at all relevant temperatures, and is found at all metal-carbon interfaces in the cell, although not in the quantities suggested by the favourable thermodynamics.

Aluminium carbide has a much higher solubility in the electrolyte than in the metal, and any carbide formed will rapidly dissolve again if exposed to the molten electrolyte. Through loss of protective side ledge the exposed carbon at the metal-bath interface area may rapidly be eaten away by this mechanism due to the normal metal level fluctuations caused by periodically metal tapping of the cell. This carbon consumption has been found to be independent of carbon type and structure [13]. If no side ledge formation takes place a tap-out through the side may be experienced within a couple of months. Figure 18 illustrates the carbon wear caused by the insufficient formation of side ledge by too much insulation between the sidewall blocks and the steel shell (end of pot).

During normal operation the carbon surface underneath the metal pad experiences a slow but steady wear during the life of the cell. This normal dissolution rate is of the magnitude > 1 to 2 cm/year for amorphous bottom blocks, depending on magnetic compensation and metal inventory. For reference purposes a bottom wear of 1 cm/year can be used unless experience with particular types of cells and bottom block qualities should suggest otherwise. However, operational disturbances, such as metal tapping, can increase the bottom wear locally. This is a particular problem in prebake cells

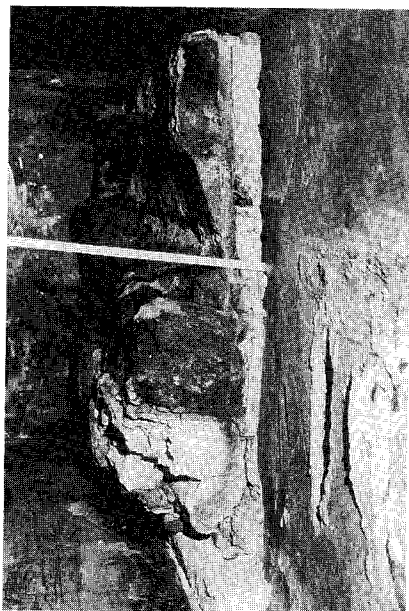


Figure 18. Profile of sidewall carbon block (pot end) that is heavily eroded at metal level and metal bath interface. All bottom and sidewall lining in foreground have been removed. Pot life was 373 days.

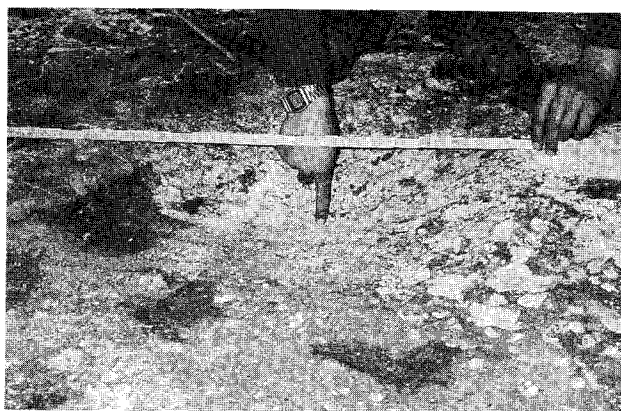


Figure 19. Photograph of cavity under tapping hole in 155 kA prebake cell. Pot was taken out after 1233 days for unrelated reasons.

where the tapping often has to be done at a fixed location and there is no bottom ledge to protect the carbon surface.

The photograph in Figure 19 shows an example of surface erosion in the tap-hole area after 1233 days of operation. The cavity shown is much wider than the tapping spout can access. The increased surface wear is probably related to an increased rate of aluminium carbide dissolution from bath that is sucked down and washed over the cathode surface during tapping, and not to any mechanical abrasion and chipping action from rough handling of the tapping equipment.

Such erosion of exposed sidewall carbon and cathode bottom surface can also be explained by the electrochemical cathodic carbon dissolution mechanism [12]. There have, however, been observed certain kinds of carbon wear in cathodes that is hard to fully explain due to electrochemical dissolution. It is common in prebake pots, which normally do not build up the kind of bottom ledge that is found in Søderberg pots, that the inclined peripheral rammed paste

is worn away to be level with the bottom block surface (Figure 20). Since an excess electrochemical dissolution rate of carbon is explained by local higher-than-normal current density or by cathodic carbon exposed to bath, the excess carbon wear in this part of the cell appears not to fit the electrochemical model. The eroded area has always been covered with aluminium metal during operation and the current density has been low. Low current density in this area is the result of several factors: This part of the bottom is outside the anode shadow, there are electrically non-conductive layers of refractories and insulation directly underneath these parts and the electrical conductivity of the ramming paste is much lower than in the prebaked bottom block. More probably the excess wear is due to a higher rate of bath exchange in the fluoride film between the carbon bottom and the metal pad in this area due to higher metal velocities.

A similar wear mechanism has been observed if the pot has been allowed to run on very low metal levels for extended periods of time. Due to the magnetic forces the metal pad will tend to have a curved surface profile, with a higher metal level in the central part of the cell and reduced thickness closer to the ends. If the total metal inventory is reduced beyond a critical level, depending on operation parameters and magnetic compensation, one of the observed effects is an increased bottom wear towards the ends of the pot. Such excess bottom wear can be explained by an increased rate of aluminium carbide dissolution caused by the increased agitation and rate of bath transport underneath the lower metal pad level towards the ends, but hardly by electrochemical dissolution since the carbon is always covered by the metal pad and there is no increase in current density towards the ends. Figure 21 shows the bottom profile measured along the long central axis of a prebake prototype



Figure 20. Horizontal extension of carbon bottom (bottom blocks in foreground) due to erosion of ramming paste incline. Pot life was 262 days.

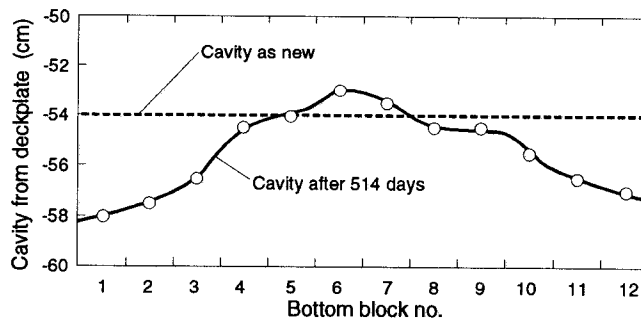


Figure 21. Bottom profile measured along the long axis of a cathode. The pot was shut down after 514 days. The cell had been run on only 5-6 cm metal height the last 6 months before shut-down.

pot that had been run on only 5-6 cm metal height for an extended period.

A stable frozen side lege will yield the most effective protection of the sidewall carbon while excessive bottom wear will have to be counteracted by adjusting metal inventory or better magnetic compensation.

POT HOLE FORMATION

Under certain circumstances the carbon wear can be very rapid and the cell fail due to very localized erosion of the carbon lining. This type of erosion is termed pot hole formation since the fatal failure area often has the form of a narrow depression or hole through the carbon lining. Such holes can sometimes have the form of an irregular inverted cone but can also have more irregular shapes. The hole can sometimes go right through the middle of the block but have a preference for the weaker rammed joint between the bottom blocks.



Figure 22. Aluminium filled pot hole in cathode showing a tiny crack that extends from the bottom of the hole further down into the carbon block. Pot life was 207 days.

The initial phase of a pot hole formation is probably a small stationary area of local high current density at the cathode carbon surface. This may be due to a local weakness at the surface that allows a minor amount of aluminium metal to penetrate (Figure 22). The higher electrical conductivity of the metal compared to carbon will increase current density and give rise to a localized magnetodynamic disturbance in the metal, leading to a faster exchange rate of the bath film under the metal pad and more rapid dissolution of the aluminium carbide that is being formed. Most minor metal penetrations into the carbon lining will not lead to pot hole formation since the metal is rapidly converted to non-conducting aluminium carbide. If this, for some reason or other, does not take place and good electrical conductivity is maintained, the erosive action will accelerate as the bottom of the depression moves closer to the current collector bar and the local current density continues to increase. The pot may then fail in a very short time.

Local high current densities caused by other circumstances may also lead to increased erosive action that may ultimately lead to pot hole formation and early failure. One is hard muck formation between the metal pad and carbon bottom. The current density through the muck will be reduced, leading to other areas under the metal pad with

increased current density and where hard muck will not form due to the local turbulence of the metal pad. These areas will, once formed and stabilized, tend to stay muck-free through a vicious circle of enhanced carbon dissolution and increased current density until the cell fails from iron contamination or a tap-out through collector bars.

A pot hole may, from the formation and enlargement mechanism described above, extend for the whole width of a bottom block or the length of several meters through erosion of existing cracks and gaps in the carbon lining. Figure 23 shows a fatal pot hole that was initiated from a preheating crack through a bottom block while Figure 24 shows similar pot hole (or crack widening) mechanism having worked on bottom heave cracks in a carbon lining surface.

Erosive enlargement of rammed joints takes place by the same mechanism. Ideally, the joints between the bottom blocks should be indistinguishable from the bottom blocks but thermal displacements during preheating and start-up tend to disturb the joint block interface so that minor amounts of metal of can penetrate, which in

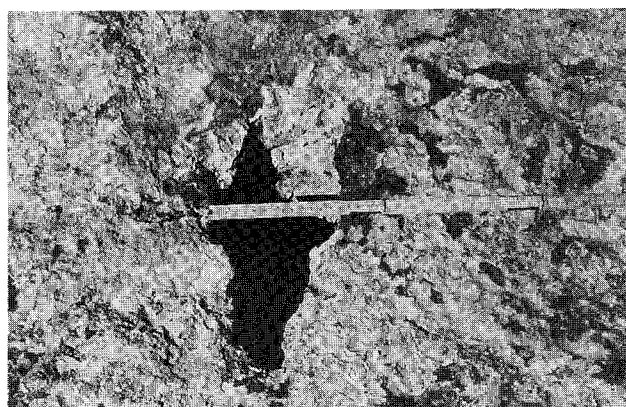


Figure 23. A pot hole covering the entire width of a bottom block was initiated from a preheating crack through the block. Pot life was 856 days.



Figure 24. Erosive enlargement of bottom heave cracks in cathode is similar to pot hole formation mechanism. Pot life was 501 days.



Figure 25. Erosion of the central joint in a cathode with split bottom blocks. Pot life was 595 days.

turn may lead to excessive carbon wear through the same local current density-metal turbulence-carbide dissolution mechanism described above.

Cathodes with split bottom blocks (and split current collector bars) and a central rammed joint running down the long axis of the cell are particularly exposed to joint erosion (Figure 25). Since any bottom heave in such a lining is likely to result in gap opening at the central block-joint interfaces, a continued metal penetration and unfavourable local current densities will tend to go on through the entire life of the cell and in some cases be the direct cause of failure.

FINAL REMARKS

Autopsies of failed cathodes, especially early failures, have proved to be an invaluable tool in diagnosing failure mechanisms and improving pot life. At Elkem Aluminium a more systematic approach to autopsies started back in 1984, with a special focus on early and unexpected failures. The average pot life was then approximately 1000 days. At present it is approaching 2000 days and still increasing, mainly as a consequence of a significant reduction in early failures.

The apparent final failure, experienced through a tap-out or a sudden rise in the metal iron level, is often only the final stage in a series of events that may have been triggered several months or years in the past. At the time of failure the lining and lining materials are often destroyed or in a state of decay that makes it difficult to obtain sufficient information to determine where the failure started and what event or lining detail that originally triggered it. However, a carefully performed autopsy of the failed cathode together with a good knowledge of the chemical and physical changes that are likely to occur in the lining during operation, will in many cases be sufficient to determine the underlying failure mechanisms and may give invaluable input for corrective action.

The present paper does not give a complete account of failure mechanisms but illustrate the multitude. Pot life is not increased by an easy and rapid solution, but by knowledge and care in materials selection, design, installation, start and operation.

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