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REDUCTION CELL RESTART METHOD INFLUENCE ON CELL LIFE EVOLUTION

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Abstract

Low market conditions, power supply limitations, and interruptions in raw material deliveries might cause aluminium smelters to shut down in full or partially, and restart the capacities later. Shutdown circumstances and, more probably, methods of restart have further affect on operational performance and cell life.

In the present paper potential mechanisms of cell lining damage caused by different restart techniques are discussed and analysis of restart technique influence on future cell life is made using data from several restarted cell lines.

The paper also includes financial assessment of benefits and disadvantages of different restart techniques on a long-term smelter economy.

Introduction

From 1995 and up until mid-2008 the global aluminium industry was going through continuous growth and improvement, practically doubling production by the end of this period. Currently market conditions remain unstable, while energy price is continuously climbing up being stimulated by energy consumption increases in the high-tech industry and on the consumer market. For instance, Russian energy system reforms have increased energy prices 250% from 2005 until 2012 while metal price and demand stayed at relatively low levels since Q4 2008. The European energy market is under strong influence of the nuclear power generation decrease in Germany, as well as CO_2-trading legislation. Under these circumstances a lot of primary metal producers have had to stop production on some cell lines. Some of them were restarted recently using different techniques.

Technical problems, like power supply interruptions caused by weather conditions, rectifier-transformer problems, key raw material supply interruptions caused by infrastructural problems also force producers to shut even profitable capacities down, and restart after problems are fixed.

It is well known that cell linings are damaged through restart to a certain extent [1, 2, 3], decreasing average cell population life and sometimes even driving to cell failure. Cell relining has a significant impact on smelter economics, productivity and environment, and creates hazardous waste – spent pot lining (SPL). It raises the decision of which technique to use for cell restart to minimize risks and losses.

This paper analyses the magnitude of particular restart technique influence on cell life, using data from seven cell lines. Potential cell lining damage mechanisms are also discussed. Based on cell life evolution data, 7-year financial evaluation of the restart techniques is made, helping to make better decision related to cell restart techniques and cost.

Restart Method Influence on cell life

Analysis on cell life evolution after restart was done based on the data from seven recently restarted cell lines (see Table I). Three methods of cell restart were discussed – crash start, metal reheat and conventional restart with metal pad removal. Techniques are described in [4, 5].

Table I. Cell line data available for analysis

Line#	Technology-arrangement-Amperage	# of cells restarted	Method of restart
1	PB-ete-160	122	Metal
2	PB-sbs-300	179	No metal pad
3	PB-ete-60	82	Crash restarts
4	HSS-ete-105	245	Metal
5	HSS-ete-85	76	Metal
6	PB-ete-90	80	Metal
7	HSS-ete-95	147	Metal

* ete- end-to-end, sbs –side-by-side arrangements

The accuracy of cell life prediction methods after a major disturbance such as cell restart has been a subject of discussion in the industry. Since the restarted cells amount to the majority of the cell lines population, actual mean cell life could not be used for the analysis. Instead, prediction through Weibull distribution was employed for the analysis [6, 7]. The convergence of the method is described below.

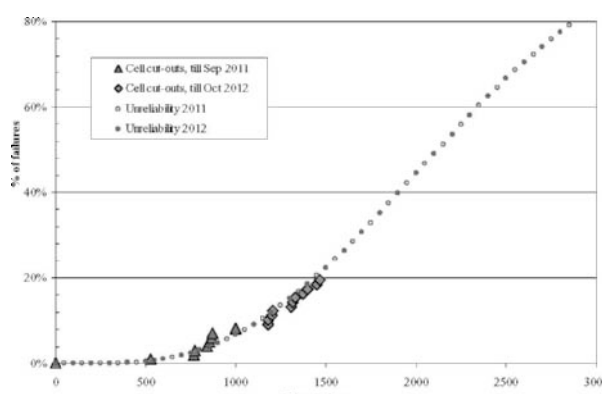

Figure 1. Shifted 13 months Weibull cell life prediction.

Fig. 1 shows two Weibull-based integral unreliability (proportion of cells disconnected) curves for an existing cell line, identical to Line 1 listed above, consisting of 100 cells. Curve "Unreliability 2011" was calculated based on 8.2 % cell failures while curve "Unreliability 2012" - one year later based- is based on 20.4% cell failures. Mean time to cell failure was 2176 days and 2161 days respectively. Therefore Weibull prediction accuracy was considered acceptable.

Using the Weibull method, mean-time-to-failure predictions were done for the cell lines before and after restart. Results are listed in Table II.

Table II. Cell life prediction after the restart.

Line	Initial mean cell life, days	Predicted cell life, days	Cell life loss, days	Restart tempo, cells/day	% of cells failed in 30 days after restart	% of cells failed in 360 days after restart
1	2 900	2 854	-46	2	1.6	4.1
2	2 514	2 197	-317	3	5.1	24.2
3	1 576	1 306*	-270*	6	0	48.9
4	2 254	2 184	-80	3.5	1.5	12.1
5	2 825	2 803	-35	3	0	4.3
6	2 493	2 368	-38	2.6	0	1.3
7	1 830	1 773	-57	4.1	1.8	17.5

*cell life loss after two restarts

Line 3 life prediction includes two restarts, as successful restart with no early failures was followed by a six-hour power outage two months later. The high failure rate within 360 days was driven only by high cell population age. Since there was no way to draw statistically significant line between the influences of each restart, the authors concluded equal cell life loss, or 135 days per restart.

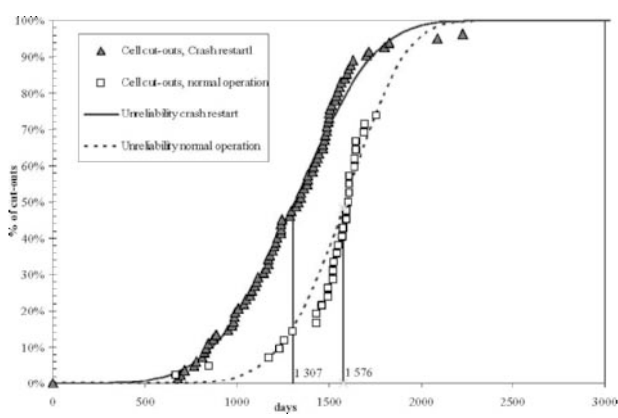

Figure 2. Line 3 cell failure. Predicted cell life without restart 1576 days, after the 2 crash starts 1307 days.

As seen from Table II, the metal restart technique gives 30-80 days of cell life loss. Crash start method has more impact. Failure rate of 24% for metal pad removal technique within first year after restart explains highest loss of cell life for this technique. It corresponds well with industry available experience of approximately 70% cell survival [8].

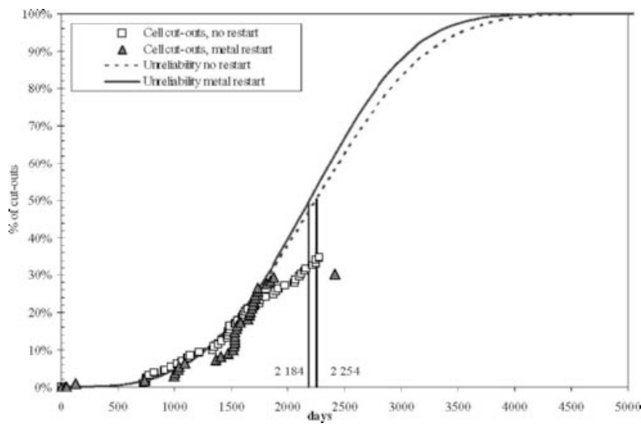

Figure 3. Line 4 cell failure. Predicted cell life without restart 2254 days, after the metal restart 2184 days.

Discussion on restarted cells failure mode

In the absence of failure caused by material defects or poor construction practices, cell failure happens when no more than 30-50 mm of carbon block is left over the collector bars, and every minor crack can result in direct aluminum contact with collector bars. Usually a cell is disconnected if iron content increases significantly due to direct contact with a collector bar or after metal tap-out through the bar.

Different restart techniques, discussed in [5], cause additional major disturbances to cell structural stability and can speed up cathode block disintegration, driving to a cell failure.

Metal Restart

Since the metal pad is kept in the disconnected cell, direct mechanical damage to the cell lining caused by pad extraction does not happen. Minor cracks due to cathode block cooling are possible, but at 660 °C, where the metal pad becomes liquid, most of them are already sealed off through bottom block thermal expansion and cannot cause direct metal contact with the collector bars. Minor amounts of metal, penetrated into the cathode panel, will form aluminum carbide, sealing minor cracks through metal substitution by Al_4C_3 with respective product volume expansion.

Several prebake cells from Line 1 disconnected under controlled conditions, but failed in 5-7 days after being metal restarted, were investigated.

Fig. 4 shows anode current distribution during the restart. Anodes 4, 12 and 13 were drawing double the average current, while cell corners (anodes 1-3, 7-10, 15, 16) remained relatively "unloaded".

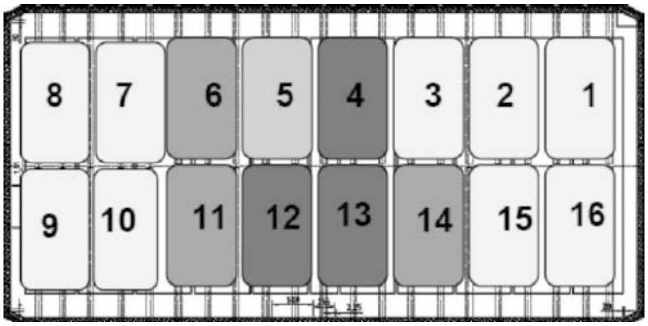

Figure 4. Anode current distribution on cell 447 failed in 5 days after metal restart.

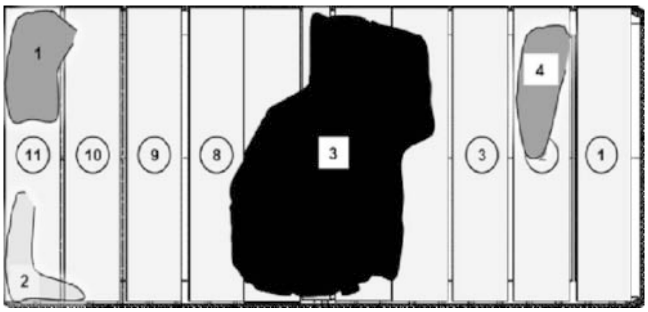

Figure 5. Fatal lining damage (area 3) on cell 447 failed 5 days after metal restart.

Figure 5 shows cathode damages, where area 3 in the center of the bottom lining cracked apart and heaved 150-200 mm from design level, allowing aluminum to contact the collector bars and refractory materials. Figures 4 and 5 show a good match between areas of high anode and therefore cathode current densities on one side, and fatal cathode damage position on the other side. It was identified that high currents drawn by particular anodes were due to uneven cathode current distribution, in turn caused by presence of bottom muck before the cell disconnection.

Current with density of even 1.8 A/cm^2 cannot damage itself the carbon material, therefore the authors believe the failure was provoked by a high temperature gradient between top and bottom, center and side parts of the cathode blocks. Warm top central part expansion is practically twice that of the cold bottom or side parts, creating significant bending/heaving forces which exceed the bending strength of the blocks. Figure 6 shows visible cathode panel heave of the failed cell.

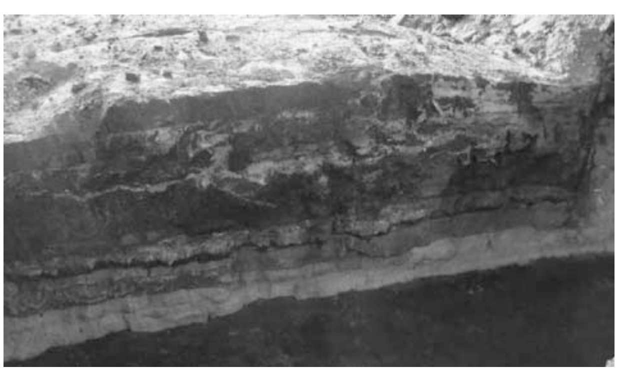
Figure 6. Cathode panel heave and cathode block destruction on cell failed in 5 days after metal restart.

This failure mechanism can be also supported by the fact that cells, disconnected in good shape, planned and without sludge on the bottom, very rarely experience such failures. Statistics on early-after-restart failures from HSS Line 4 or PB Line 6 also support it.

<u>Crash Start</u>

The method, utilizing the liquid bath resistance to generate heat, also can not cause direct mechanical damage. However, uneven current distribution in the metal pad due to muck presence or uneven metal pad contact with cathode panel, especially in the beginning of a cell restart can start the same mechanism as described for metal restart technique.

Since bath resistance is high, heat generation inside the cell cavity during crash restart is the highest of the three techniques. This fact can increase the severity of temperature-gradient-driven cathode block heave, making restart cell failure more probable. Tabereaux [3] shows 400 days of life loss for cells above 200 kA during crash restart.

Heat generation can be regulated using line current shunts, which reduce current load and, therefore, initial carbon lining heaving during cold crash start. Smelters employing this technique with the line shunts report satisfactory results [8].

<u>Restart with Metal Pad Removal</u>

This method secures fast restart tempo and easy control procedure, being similar to new cell start-up technique. However, during solid metal pad removal from the cell cavity, mechanical destruction of cathode blocks occurs. For example, it is mentioned [5], that up to 30% of cells with removed metal pads had shallow/lamination cracks formed during the pad extraction (no Al_4C_3 was present). Depth of cracks seen in Figure 7 was measured in the range of 1-3 cm, which reduces carbon thickness above cell collector bars and for 30% graphite blocks can be recalculated into 1-3 years of cell life loss. Inspected cells were below the age of 360 days, the cathode panel erosion had not progressed significantly. No anchoring points were visible. It was noted that these cracks always appear on the side of the cell where the metal pad is first lifted from the cathode surface.

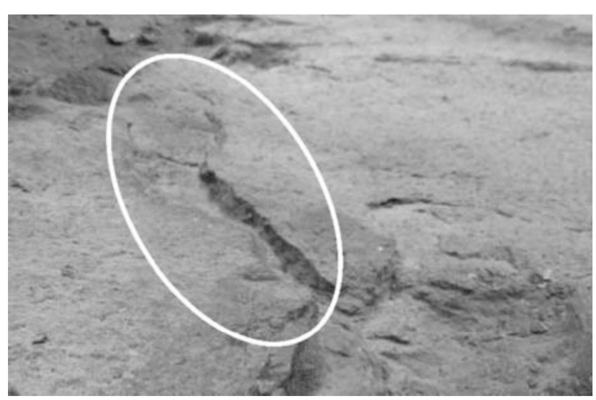
Figure 7. Shallow cracks on the cathode block surface after metal pad extraction, going 1-3 cm inside cathode panel

Carbon cathode is substantially weakened by sodium intercalation [3, 9, 10] during cell operation. Bath film is present between metal and bottom lining thus cold metal pad does not have direct contact with carbon and just adhered to the cathode blocks by the film. Therefore this type of crack may occur when both force applied during metal pad extraction and adhesion forces exceed the strength of sodium-saturated cathode block. On the other hand, it can also be caused by cathode block quality deviations.

The tendency of the cathode surface to have uneven erosion through cell life makes metal pad extraction even more destructive for aged cells. "Rat holes" and minor cracks filled with liquid metal during normal cell operation will hold solidified metal pad anchored in carbon blocks and destroy cathode panel integrity when the metal pad is pulled out. Figure 8 shows lining damages after metal pad extraction on a 1800 days old cell. Surfaces are not covered with Al_4C_3, confirming non-presence of the crack in the running cell.

Figure 8. 7 cm lining crack due to metal pad extraction.

During the restart, heaving forces driven by temperature gradients may exceed bending strength of partially cracked cathode blocks, causing early cell failure. As seen on Fig. 8, cathode block thickness in the area of the crack is reduced by 7 cm (potentially 2 -5 years of life). That means mechanically created cracks reduce cell life even if a cell survived the restart, since the cell life is limited by the thinnest part of cathode panel. Line 2 statistics demonstrate the highest cell failure rate – 24.2% of cell population within 360 days after restart, and 307 days life loss.

Another issue arises with this technique if the metal pad is removed shortly after a cell shutdown but the cell idle time is long. Reaction between aluminium carbide and moist air [2, 11] can drive to complete lining deterioration.

Cell life loss may not be significant if this technique is used for young cells where bottom erosion has not progressed significantly. Cells over 360 days old can experience significant life reduction.

Financial evaluation of the restart techniques

Reduction line restart is usually limited by rectifier performance and voltage, skilled manpower availability and potroom logistics. Cell size and arrangement can also have significant influence on restart technique selection and tempo of the restart. For example, crash start can be successfully employed for cells with relatively small anodes and low anode current density (which, in turn, can be lowered even more by usage of local cell shunts) but can be very challenging for smelters with 300+ kA side-by-side cells, being limited by bath solidification during bath-up. Therefore, every smelter considers its own technique, based on local constraints.

For the analysis of data collected through cell life prediction, an abstract 230 kA side-by-side PFPB line, consisting of 250 cells, with 94.5 % current efficiency, 13600 kWh/t and 2500 days normally distributed cell life is used.

Restart tempo and amperage

Actually achieved speeds of line restart were used (see Table III), despite faster tempos being reported [4, 11, 12]. Restart tempo can be affected by logistical constraints [12] i.e. anode change and covering, which may exceed full stable operational load by 30-50%, and bath addition, which in some smelters is made using metal tapping equipment, while metal production grows through the restart progress [5, 13].

Metal restart was considered the slowest case. Anode current distribution control and reheat takes a longer time due to limited manpower and heat generation in cells. The other two methods allow faster restart tempo, as anode adjustments require less workforce and more energy can be introduced into cell due to higher voltage. However, crash start method for a modern 230 kA cell might require significant work to dress cells with hot butts or to equip a cell with shunts to regulate current at restart, which was taken into account.

Table III. Different techniques restart efficiency

	Metal	Crash	Metal pad removed
Restart tempo, cell/day	3	4	4
Man-hours per restarted cell	64	71	58

During restart, line current differs significantly depending on the technique employed. Crash start requires cell line de-energizing for every cell scheduled for restart, while other techniques allow cut-in cells by groups. Early cell failures also affect this parameter, i.e. for restart with metal pad removed where early failure rate is high. Table IV presents monthly averaged amperage used for modelling.

Table IV. Monthly average line amperage during the restart

Month since restart	Metal	Crash	Metal pad removed
1	227.8	217.0	226.0
2	228.0	217.1	227.0
3	228.4	229.2	229.4
4	229.9	229.9	229.5

Raw materials, energy and current efficiency

Carbon and energy consumption also differ (See Figure 9, 10) for the discussed techniques, which is mostly driven by different time of anode exposure to airburn. Also, metal and crash restart techniques create great possibility for anode disturbances, requiring premature anode changes and additional assembly reparation.

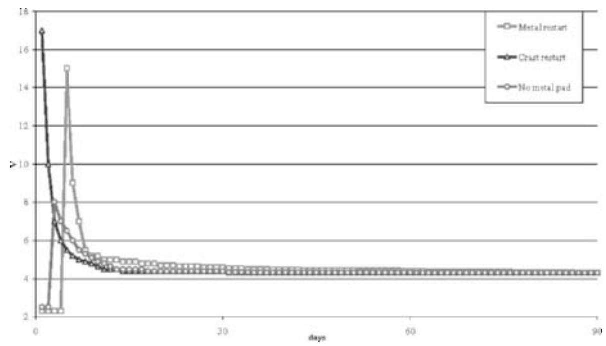

Figure 9. Voltage on cells restarted with different techniques.

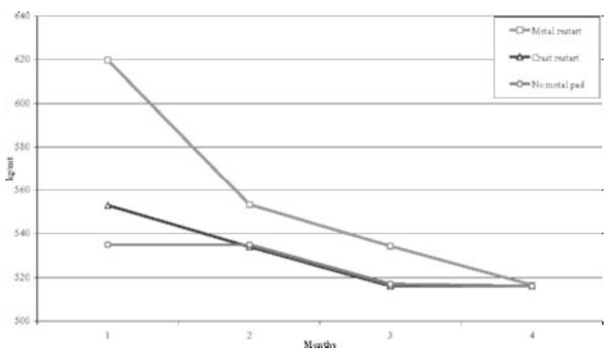

Figure 10. Gross carbon consumption for a cell restarted with different techniques

From practice it is assumed cells have lower CE (93%) the first month after restart, getting to normal conditions later. Marginal bath materials consumption difference was not considered in the model.

Relining

Early failure rates, and cell life loss for each technique was used for modeling:

Table V. Failure rate and cell life loss.

	Metal	Crash	Metal pad removed
% of cells failed in 30 days after restart	1.0	1.0	5.5
% of cells failed in 360 days after restart	5.5	5.5	24
Cell life loss, day	52	135	320

Practically, cells disconnected with the remaining life less than one year usually are not subject to restart [2, 3, 14]. Nevertheless, for the economical modelling every cell restart assumption is taken, to highlight cell life evolution and early failures influence on smelter economical performance. Cell life reduction was evenly spread through cell population lifetime.

Financial assessment

Cell line operational Net Present Value (NPV) for 12 months and seven years (potential cell life length) periods were calculated to evaluate pros and cons of every restart technique. To separate cell line performance itself, any plant overhead cost was excluded from the assessment. Long term analysis was done on a comparative basis using the same abstract 230 kA cell line described above, with no restart and no potlife loss cost.

The model assumes aluminium price at $2100/mt, energy at $50/MWh and alternative capital cost at 15% per year. Relining cost for a cell is taken at $210 000, and 100 mt of SPL generation per fully disconnected cell, with $120/mt utilization cost.

Results

Technique with metal pad removal gives the fastest financial benefit, along with the crash start: cell line gets positive cash flow (CF) on the third month. The cell line restarted with metal becomes CF positive one month later. However, life reduction of cells restarted with metal pad extraction brings significant relining cost, and in 7 months after the restart the other techniques begin to prevail. By the end of the first year results of "non-destructive" techniques are very similar, while the cell line restarted with metal pad extraction has $3.5 mln less NPV (see Fig. 11).

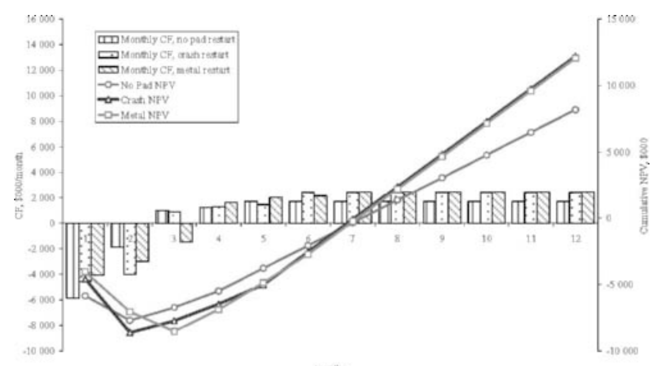

Figure 11. Restarted cell line monthly CF and 12 months NPV.

Progressing to the next 6 years, metal restart and crash restart techniques are still giving better results (see Fig. 12). The difference of $1.6 mln can be mitigated by the other cell line performance parameters.

On the other hand, cell life loss caused by restart with metal pad removal becomes more crucial. The $8 mln. NPV reduction compared to the metal-restarted cell line (see Fig. 12) is driven by additional cell relining, SPL handling and production loss due to cell turn-around.

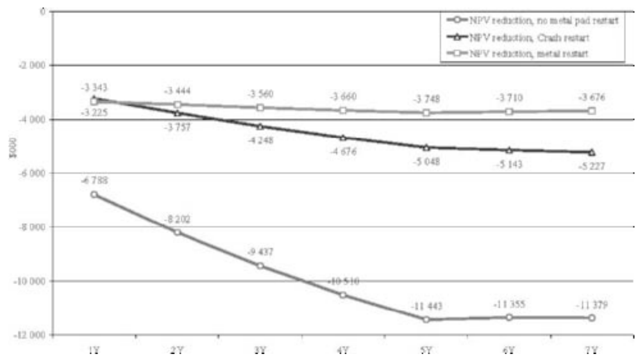

Figure 12. Restarted cell line 7 year NPV reduction, compare to normally operated cell line.

At the year 6 and 7 after metal pad removal restart, NPV-loss stops as the restarted cell generation is fully replaced with new ones.

Conclusion

Different restart techniques influence cell life. The reduction can amount to up to 300-400 days. Mechanical damage to cell lining during metal pad extraction is more crucial to cell population life than possible lining thermal instabilities from metal and crash restarts. The restart technique with metal pad extraction is recommended to use if any other method cannot be employed, or for young cells with age below 1-1.5 years.

Restart with metal pads removal saves anode and energy cost, but may results in significant cell life reduction. Despite quick financial benefits in the first months after a cell line restart, overall operational result can be below expected one for "non-destructive" restart techniques. This fact has to be considered during preparation for cell line restart.

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