Accurate assessment of the Hirakud smelter aluminium reduction cell thermal balance using only temperature measurements

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Plan of the Presentation

- Introduction
- The cell heat balance
- Cell heat losses measurement methods
- Fundamental heat flux equations
- Measurement campaign
- Analysis of the results
- Conclusions

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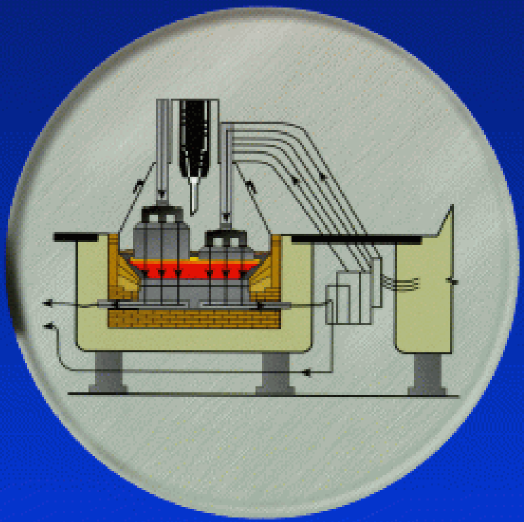
Introduction



The power consumption of the Hall-Héroult cell being one of the major operating costs, the aluminium industry is constantly trying to reduce the specific power consumption of smelters expressed in kWh/kg of aluminium produced.

Today, best results are:

12.9 - 13.0 kWh/kg for high amperage PBF cells
14.0 - 14.5 kWh/kg for best VSS cells

Older smelters still operating at 17 - 18 kWh/kg are feeling an increasing pressure from their more efficient competitors. They have essentially two options:

1) Retrofit their cell design in order to improve their power consumption and hence reduce their production costs
2) Be run out of business

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Introduction

The first priorities of the Hirakud smelter cell retrofit program has been to measure the cell heat balance and to develop reliable mathematical models.

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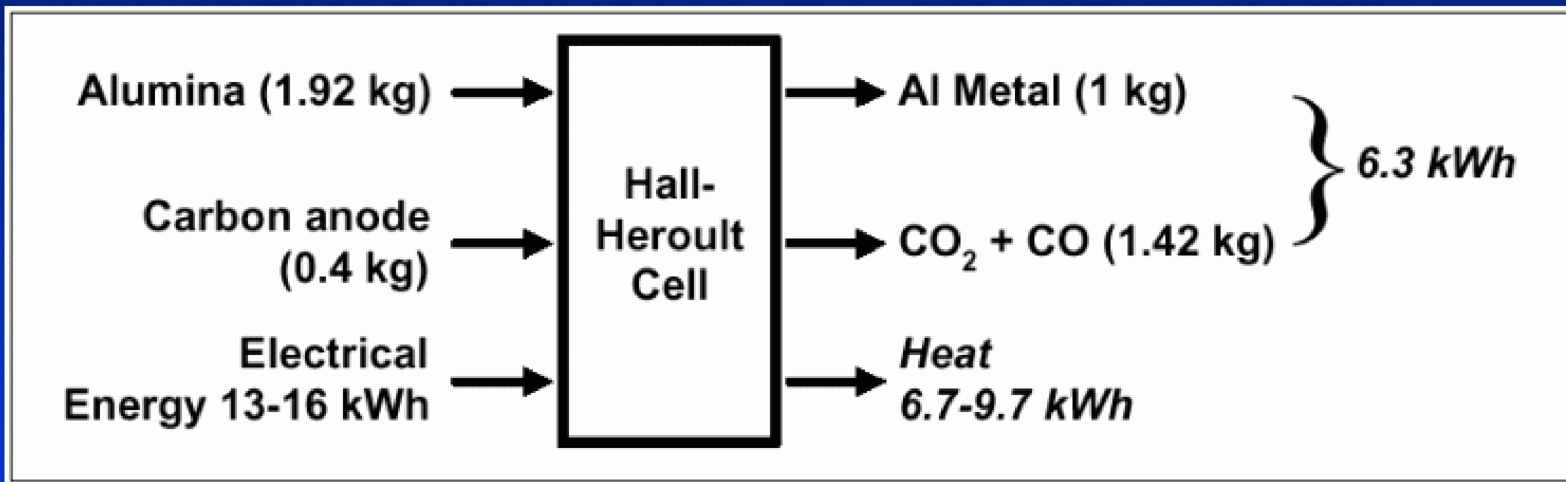
The cell heat balance



The concept of the cell heat balance is quite simple: of the total electrical power fed to the cell, less than half is actually used to produce aluminium, the remaining part must be dissipated as heat losses in order for it to maintain its thermal equilibrium.

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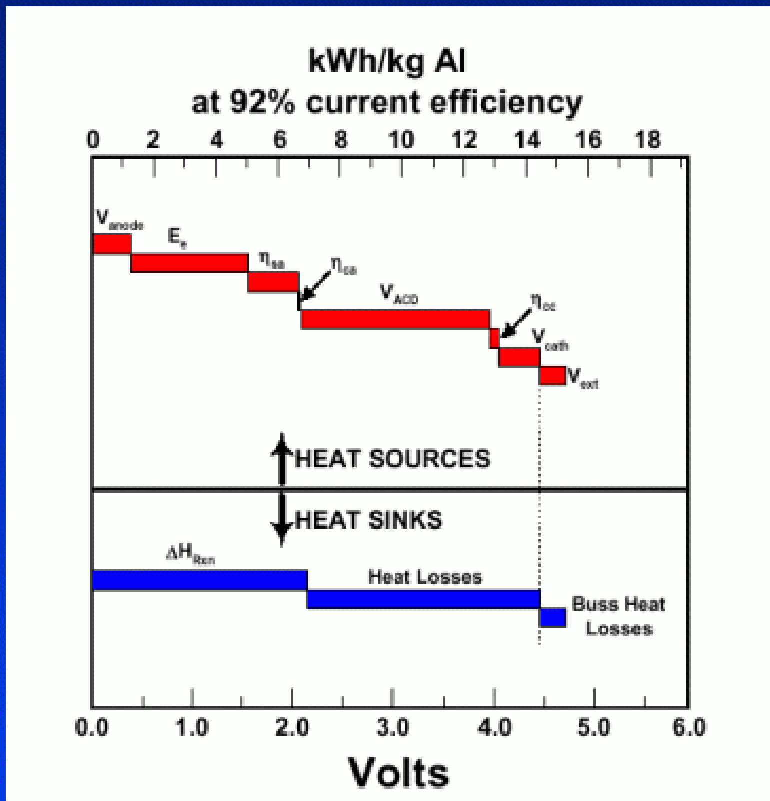
The cell heat balance



Experimentally, a cell voltage break down is required in order to calculate the cell internal heat: the heat that the cell needs to dissipate to maintain its thermal equilibrium.

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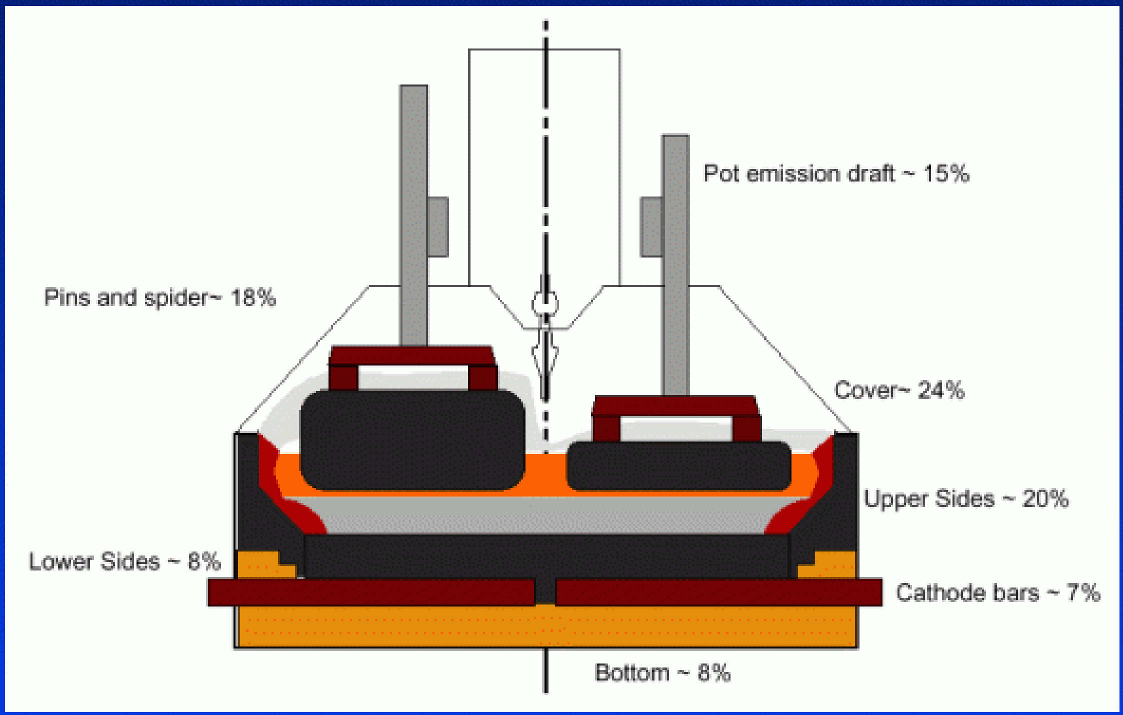
The cell heat balance



This can be experimentally confirmed by directly measuring the cell heat losses.

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The cell heat balance

Measurement of the complete heat balance requires that all heat losses be measured such that the sum of the measurements is equal to what is called the theoretical heat loss. The theoretical heat loss is calculated from the voltages and line current. The heat balance closure, then, is defined as the % of the theoretical heat that is actually measured:

$$\%\ \text{Closure} = \frac{Q_{measured}}{\left(V_{pot} - E_{\Delta H} - V_{ext}\right) \bullet I} (100\%)$$

Thorough and careful measurements usually close the heat balance between 93% and 105% of the theoretical heat loss.

If the cell heat losses correspond to the calculated cell internal heat, those measurements can be used with confidence in order to calibrate the mathematical models of the cell.

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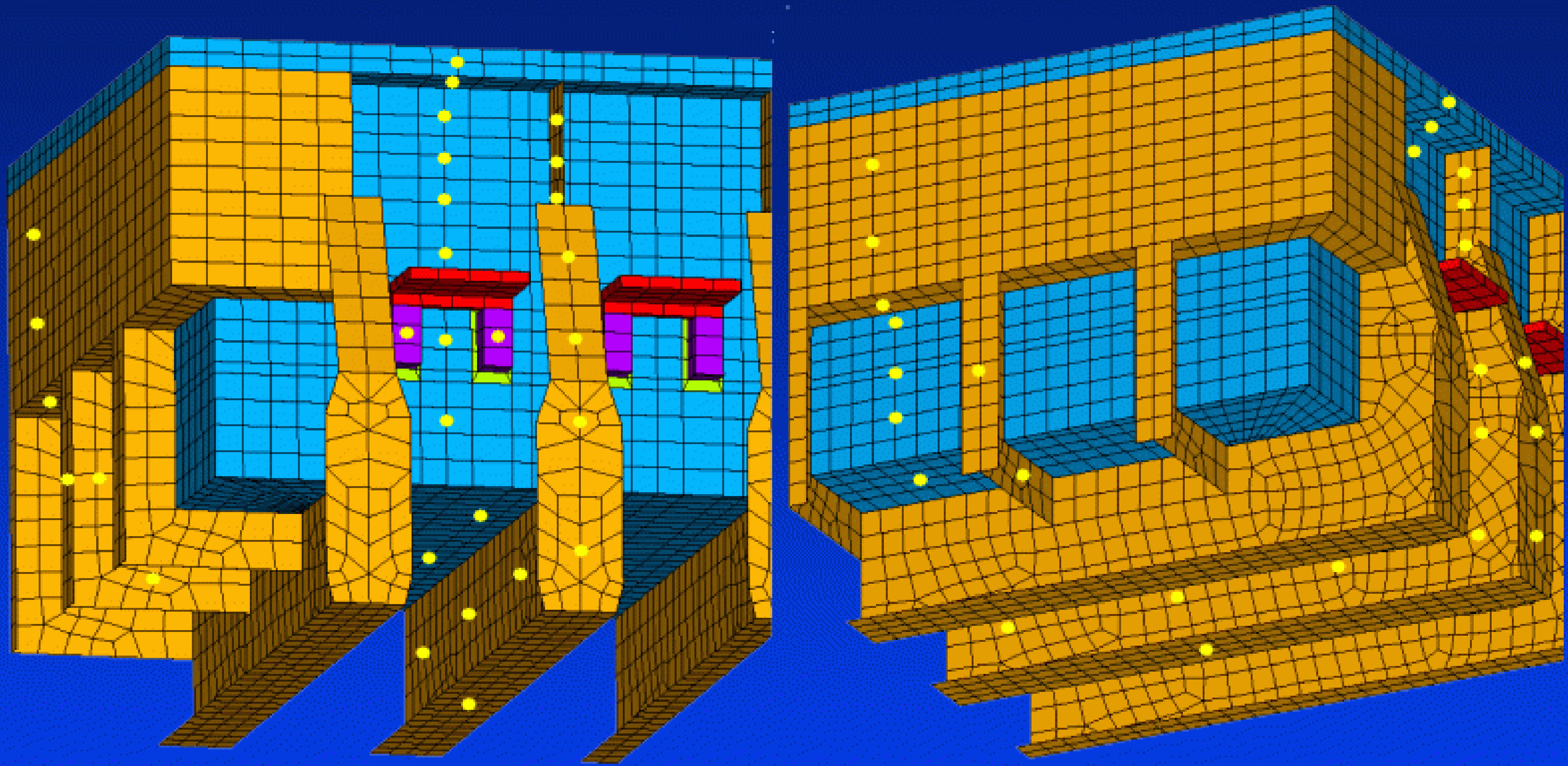
Cell heat losses measurement methods



In order to calculate the global cell heat losses, approximately 200 surfaces must be established around the cell.

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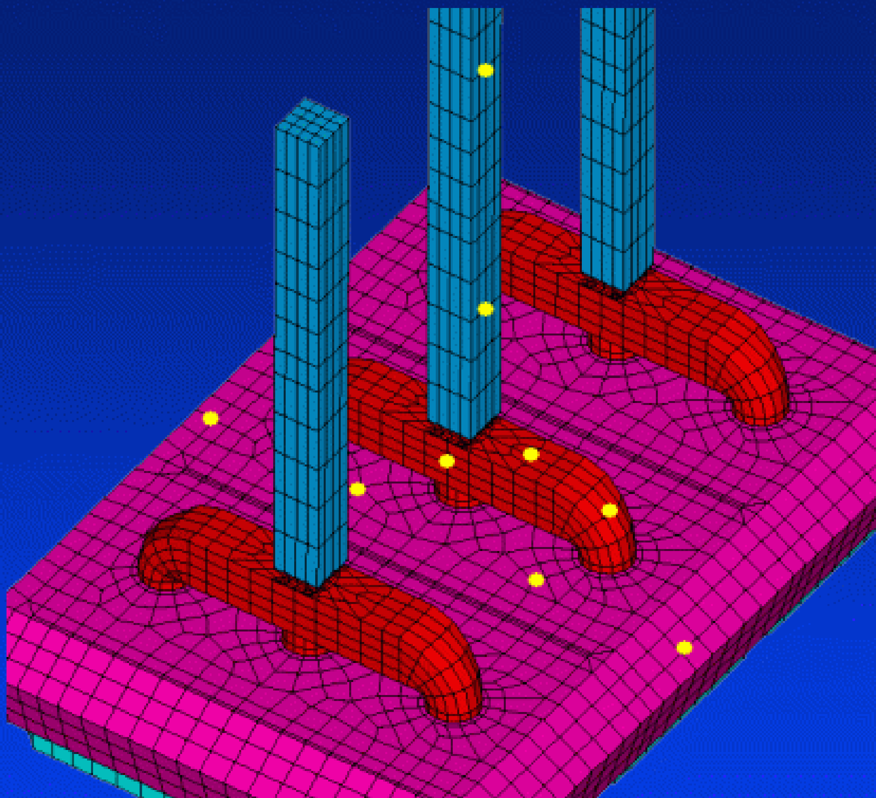
Cell heat losses measurement methods



The area of each of those surfaces must be calculated in order to be able to, in turn, calculate the heat dissipated by each of them.

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Cell heat losses measurement methods

Heat Balance Results

date: 12-Aug-03 Cell: "VAW" 300

Cathode Heat Losses	W / m2	kW	%
Shell side wall above bath level	2002	11.53	1.83
Shell side wall opposite to bath	5616	32.35	5.14
Shell side wall opposite to metal	7617	43.87	6.97
Shell side wall opposite to block above bar	6041	48.71	7.74
Shell side wall opposite to block between bars	1505	6.50	1.03
Collector bars to air	3035	17.48	2.78
Collector bars to flexible		57.42	9.12
Shell side wall opposite to brick	990	11.40	1.81
Shell floor close to corner	504	12.65	2.01
Shell floor quarter point region	499	10.42	1.65
Shell floor centerline region	498	8.31	1.32
Cradle above bath level	882	6.04	0.96
Cradle opposite to bath	1906	13.04	2.07
Cradle opposite to metal	2360	16.14	2.56
Cradle opposite to block above bar	854	8.18	1.30
Cradle opposite to block between bars	355	2.43	0.39
Cradle opposite to brick	130	1.78	0.28
Cradle corner	89	1.53	0.24
Cradle below floor close to corner	100	2.75	0.44
Cradle below floor quarter point region	101	2.77	0.44
Cradle below floor centerline region	102	2.80	0.45
Shell end wall opposite to metal	1503	2.62	0.42
Shell end wall opposite to block above bar	3050	7.43	1.18
Shell end wall opposite to block below top of bar	4034	7.02	1.11
Shell end wall opposite to brick	2931	10.20	1.62
Shell coverplate in the ends	490	1.49	0.24
Shell horizontal strip in the ends	1112	27.59	4.38
Shell vertical stiffeners in the ends	837	5.65	0.90
Shell horizontal stiffeners in the ends	100	0.45	0.07
Total for the cathode part		**380.56**	**60.43**

Anode Heat Losses	W / m2	kW	%
Crust in side channels	1713	21.65	3.44
Crust above anodes	1798	81.80	12.99
Crust in center channel	1740	3.58	0.57
Studs	4002	27.16	4.31
Yoke	3682	84.83	13.47
Aluminum rod	818	30.14	4.79
Total for the anode part		**249.2**	**39.57**
Total for the cell		**629.7**	**100.00**

For each surfaces, the average heat flux is multiply by the surface area in order to obtain the surface heat loss.

The summation of all the surfaces heat losses gives the total cell heat loss.

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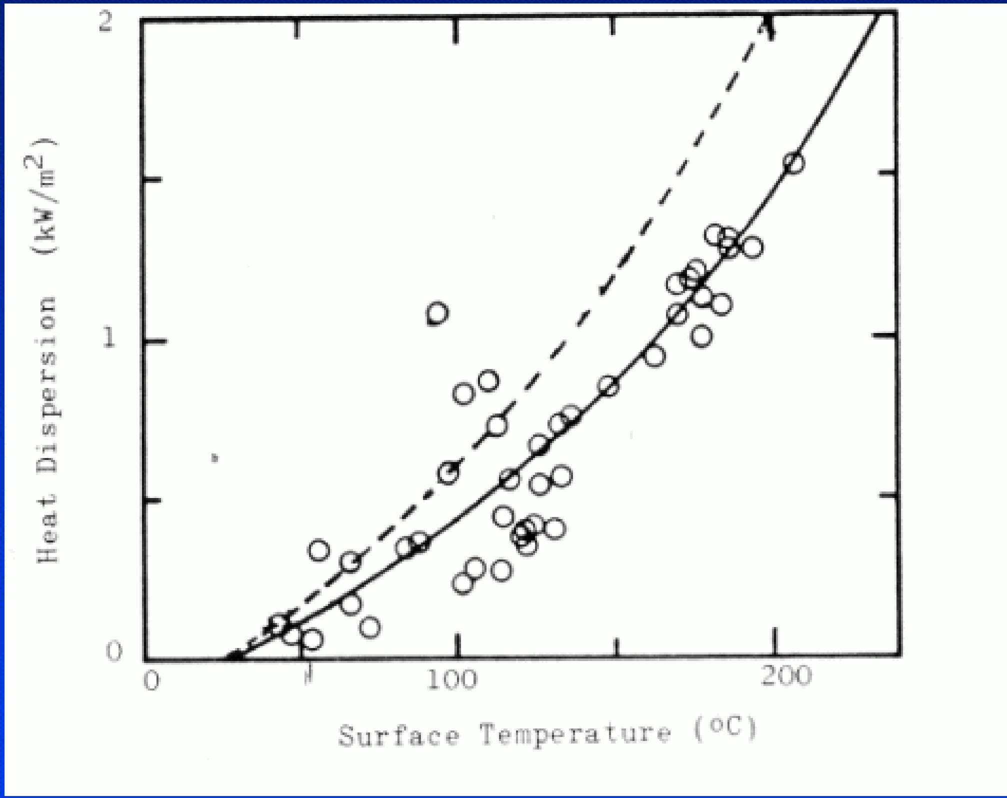
Cell heat losses measurement methods



In the early cell heat balance measurement campaigns, the equations that describe the physics of the two heat transfer mechanisms (natural convection and radiation) were used to correlate the different cell surface temperatures to the heat fluxes in order to reduce it to the measurement of the cell surface temperatures only.

This approach turned out not to produce very accurate results.

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Cell heat losses measurement methods

Bruggeman[1], clearly expressed the current conventional wisdom of the industry by specifying that heat flux transducer must be used to carry out cell heat loss measurement campaigns.

Cell heat losses measurement methods

He even pointed out that: "Haupin developed a heat flux transducer especially for pot measurements". Apart from Alcoa, most of the rest of the industry is rather using commercially available heat flux transducers.

Cell heat losses measurement methods

Unfortunately, commercially available heat flux transducers are fairly expensive and relatively fragile.

They are also characterized by a fairly long response time of around 10 minutes. This means that cell heat balance measurement campaigns using heat flux transducers are fairly long and expensive to carry out.

For that reason, the challenge posed to the authors was to find an accurate way to assess the Hirakud cell thermal balance using only temperature measurements.

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Fundamental heat flux equations

$$q_{tot}(W/m^2) = q_c + q_r$$

$$q_c(W/m^2) = Nu \cdot \frac{k}{L} \cdot (T_S - T_A)$$

$$q_r(W/m^2) = \varepsilon\sigma\left((T_S + 273)^4 - (T_O + 273)^4\right)$$

The equations that describe the physics of natural convection and radiation heat transfer mechanisms are well known.

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Fundamental heat flux equations

For vertical surfaces, we have:

$$Nu = 0.59 Ra^{1/4}, \text{ for } 10^4 \le Ra \le 10^9$$

$$Nu = 0.105 Ra^{1/3}, \text{ for } 10^9 \le Ra \le 10^{12}$$

For horizontal surfaces facing up we have:

$$Nu = 0.54 Ra^{1/4}, \text{ for } 10^5 \le Ra \le 2 \times 10^7$$

$$Nu = 0.141 Ra^{1/3}, \text{ for } 10^7 \le Ra \le 10^{11}$$

And finally, for horizontal surfaces facing down we have:

$$Nu = 0.27 Ra^{1/4}, \text{ for } 3 \times 10^5 \le Ra \le 3 \times 10^{10}$$

The general form of those heat transfer equations have been published multiple times[2,3].

Notice that the natural convection heat loss equations are semi-empirical.

Fundamental heat flux equations

Where:

$$Ra = \frac{g\beta L^3 (T_S - T_A)}{\upsilon^2} \cdot \Pr$$

$$k = 2.014E-15 \times T_f^4 + 1.68E-11 \times T_f^3 - 4.118E-8 \times T_f^2 + 8.051E-5 \times T_f + 0.02407$$

$$\upsilon = 1.438E-17 \times T_f^4 - 3.25E-14 \times T_f^3 + 9.095E-11 \times T_f^2 + 8.977E-8 \times T_f + 1.32E-5$$

$$\Pr = 1.937E-13 \times T_f^4 - 6.581E-10 \times T_f^3 + 7.349E-7 \times T_f^2 - 2.788E-4 \times Tf + 0.714$$

$$T_f = \frac{(T_S + T_A)}{2}$$

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Fundamental heat flux equations

$$q_{tot}(W/m^2) = F_q(T_S, T_A, T_O, \varepsilon, L, SO)$$

Where:

T_S (ºC)	is the measured surface temperature
T_A (ºC)	is the measured air temperature close to the surface
T_O (ºC)	is the measured facing radiative background temperature
ε	is the surface emissivity
L (m)	is the surface typical length
SO	is the surface orientation (V, OH or OD)

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Measurement campaign

In order to calculate the global cell heat losses, the area of each representative surfaces must be calculated in order to be able to, in turn, calculate the heat dissipated by each of them.

$$Q_i(W) = A_i \cdot F_q(T_S, T_A, T_O, \varepsilon, L, SO)_i$$

$$Q_{cell}(kW) = \sum_{1}^{N} Q_i \,/ 1000$$

It is quite easy to evaluate ahead of time A, ε, L and SO for each surface. For a given cell design, once established, the value of those items will not change.

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Measurement campaign

This leaves only three temperatures to be measured per surface T_S, T_A and T_O during the measurement campaign (instead of only T_S for "early" measurement campaign).

In comparison, in a "standard" measurement campaign using heat flux transducers, only q_{tot} is measured for each surface.

Yet, measuring T_S and T_O with a small hand held pyrometer and T_A with a thermocouple and a small hand held multimeter is far less cumbersome and requires far less time than using slow to respond heat flux transducers.

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Analysis of the results

Analysis of the initial results revealed that we were overestimating the heat flux of some very hot surfaces for which the radiation term became very large.

Of course, we knew that the radiative exchanges around a cell are very complex and that considering that each surface is only seeing one background radiative temperature could well turn out to be an unrealistic over-simplification.

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Analysis of the results

This led us to consider that those surfaces are seeing two background radiative objects that are not at the same temperature. Of course, this in turn introduce the need to calculate the view factors for each object:

$$q_r(W/m^2) = \varepsilon\sigma\Big[F\big((T_S+273)^4 - (T_O+273)^4\big) + (1-F)\big((T_S+273)^4 - (T_O^{'}+273)^4\big)\Big]$$

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Analysis of the results

Heat Balance Results

date: 5-Nov-03 Cell: Cell 265

Cathode Heat Losses	W / m2	kW	%
Shell side coverplate	821	2.26	2.00
Shell side spacer between boxes	1796	3.59	3.18
Shell side bottom box	3105	6.41	5.69
Collector bars to air	1337	7.96	7.06
Collector bars to flexible		2.40	2.13
Shell side wall collector bar level	625	0.57	0.50
Shell side wall insulation level	981	1.80	1.60
Shell side vertical boxes	918	1.97	1.75
Shell side floor perimeter section	1172	9.56	8.48
Shell side floor center section	1884	8.14	7.22
Shell end coverplate	809	2.21	1.96
Shell end spacer between boxes	1789	3.55	3.15
Shell end bottom box	3065	6.29	5.58
Shell end wall collector bar level	623	0.81	0.72
Shell end wall insulation level	969	1.82	1.61
Shell end vertical boxes	1150	2.16	1.92
Shell end floor perimeter section	1165	6.34	5.62
Total for the cathode part		67.82	60.17

Anode Heat Losses			
Crust	306	2.85	2.53
First side channel	4002	12.11	10.74
Second side channel	2037	6.16	5.47
Third side channel	1206	3.65	3.24
Forth side channel	739	2.24	1.98
Above forth side channel	554	1.70	1.51
Anode top	552	4.13	3.67
Studs		12.06	10.70
Total for the anode part		44.9	39.83
Total for the cell		112.7	100.00
Cell internal heat		117.8	
Blitz closing		95.71%	

At the second trial, the percentage of closure was in the acceptable rage.

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Conclusions

- The heat balance of the Hirakud smelter aluminium reduction cell has been accurately assessed using only a surface thermocouple and a pyrometer.
- No loss in accuracy was detected when using this approach as the cell heat balance could be closed within 5%, the level of accuracy typical of cell heat balance assessment using heat flux meter.
- Although at least three temperature measurements are required to estimate a single heat flux, it takes a lot less time to make those temperature measurements using a pyrometer than directly measuring the heat flux using an expensive heat flux meter.