ENERGY ASPECTS OF PRIMARY ALUMINUM PRODUCTION

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INTRODUCTION -
– energy consumption

The aluminum reduction by electrolysis in the presence of a carbon anode

$$2Al_2O_3 + 3C = 4Al + 3CO_2$$

$$\mathbf{1.89kg}\ \boldsymbol{Al_2O_3} + \mathbf{0.33kg}\ \boldsymbol{C} + \mathbf{6.38kWh} \rightarrow \mathbf{1kg}\ \boldsymbol{Al} + \mathbf{1.22kg}\ \boldsymbol{CO_2}$$

Electrical energy consumption:

- theoretically required : 6.38 kWh/kg_{Al}
- industry average : 15 kWh/kg_{Al}
- best reported : 11-12 kWh/kg_{Al}

efficiency < 50%

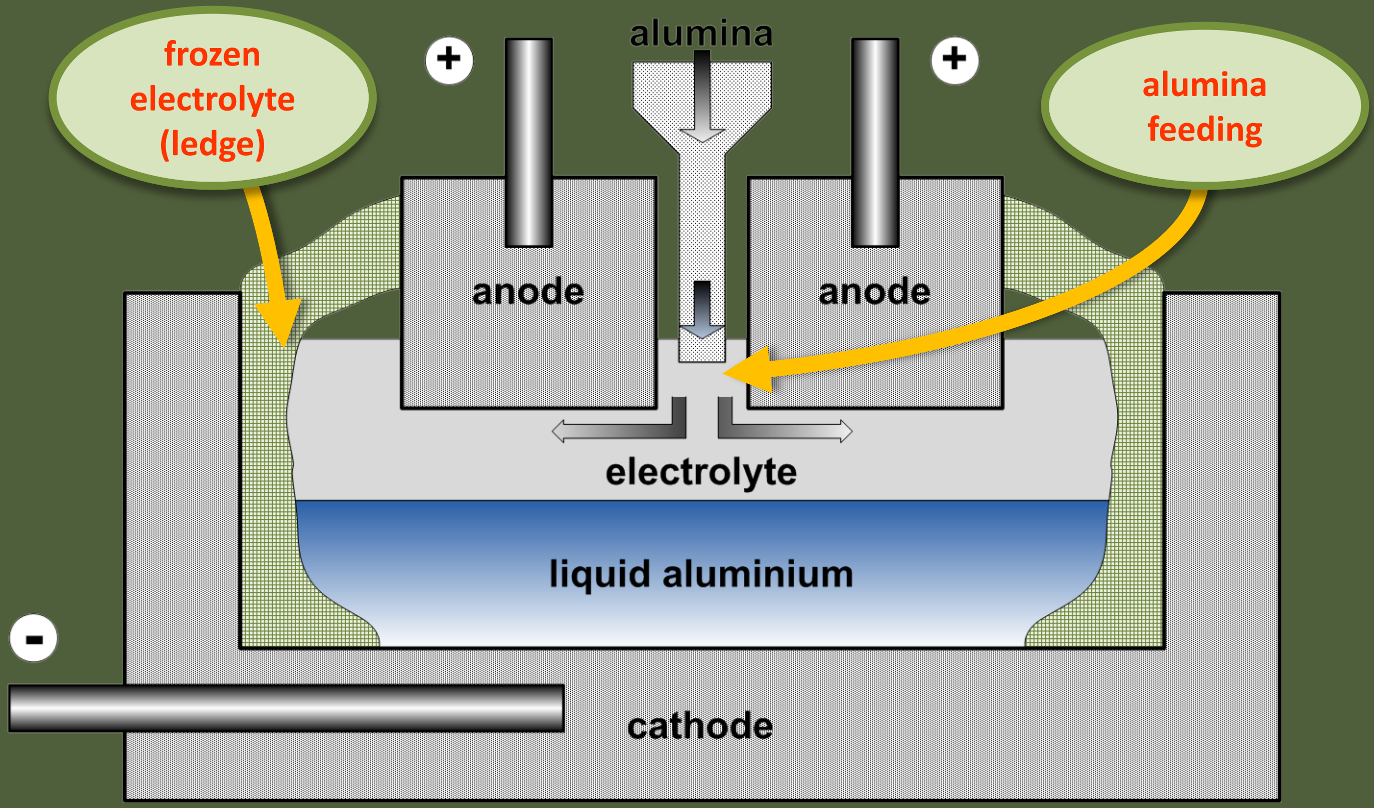
Why is energy efficiency less than 50% ?

$$\frac{\textit{theoretically required electrical energy}}{\textit{actually used electrical energy}}$$

The so-called current efficiency is about 95% !

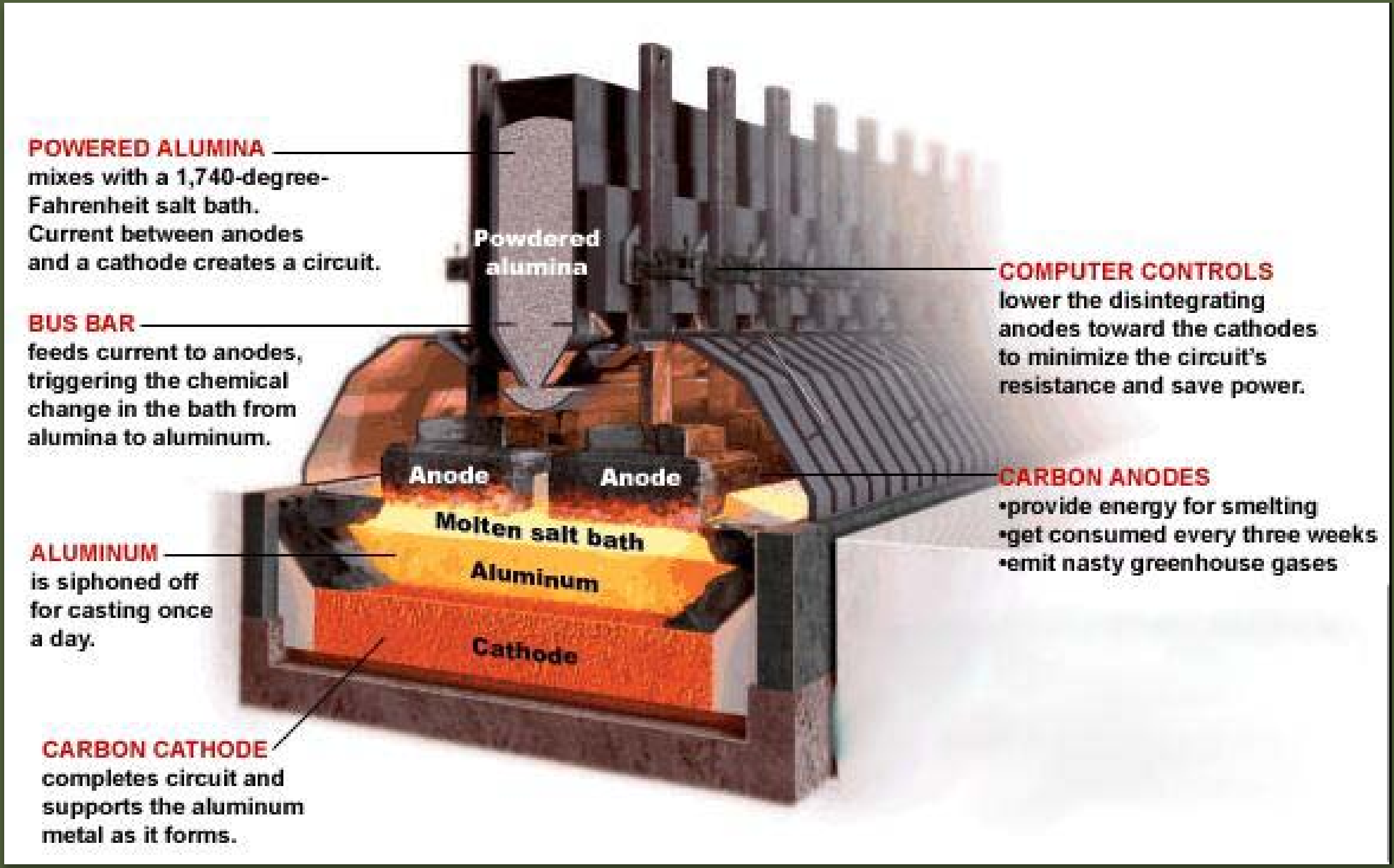
$$\frac{\textit{actually produced metal}}{\textit{metal corresponding to the electrical charge passing through the cell}}$$

The process



frozen electrolyte (ledge)
alumina
alumina feeding
+
+
anode
anode
electrolyte
liquid aluminium
-
cathode

Schema of a modern industrial cell



amperage : 200 to 500 kiloamperes

power consumption per cell : 1-2 MW/cell

number of cells in a potroom : 160- 280

production of a cell : 1.5-4.0 ton/day

Aluminium smelter -potroom

Tapping (syphoning)

The process – temperature level

The solvent of the alumina, Al_2O_3 , is the cryolite Na_3AlF_6

melting point of pure cryolite is ----- 1100°C
melting point of industrial electrolytic bath
(cryolite+alumina+additives) -------------- 960°C

Temperature control –

- there is no direct method available

- the heating is the consequence of the production of aluminum (no independent heater)

The process – temperature level

Electrolysis cell - heat flux driven system

process temperature → result of a balance
between the
internal heat generation
and
heat losses through the envelope of the cell

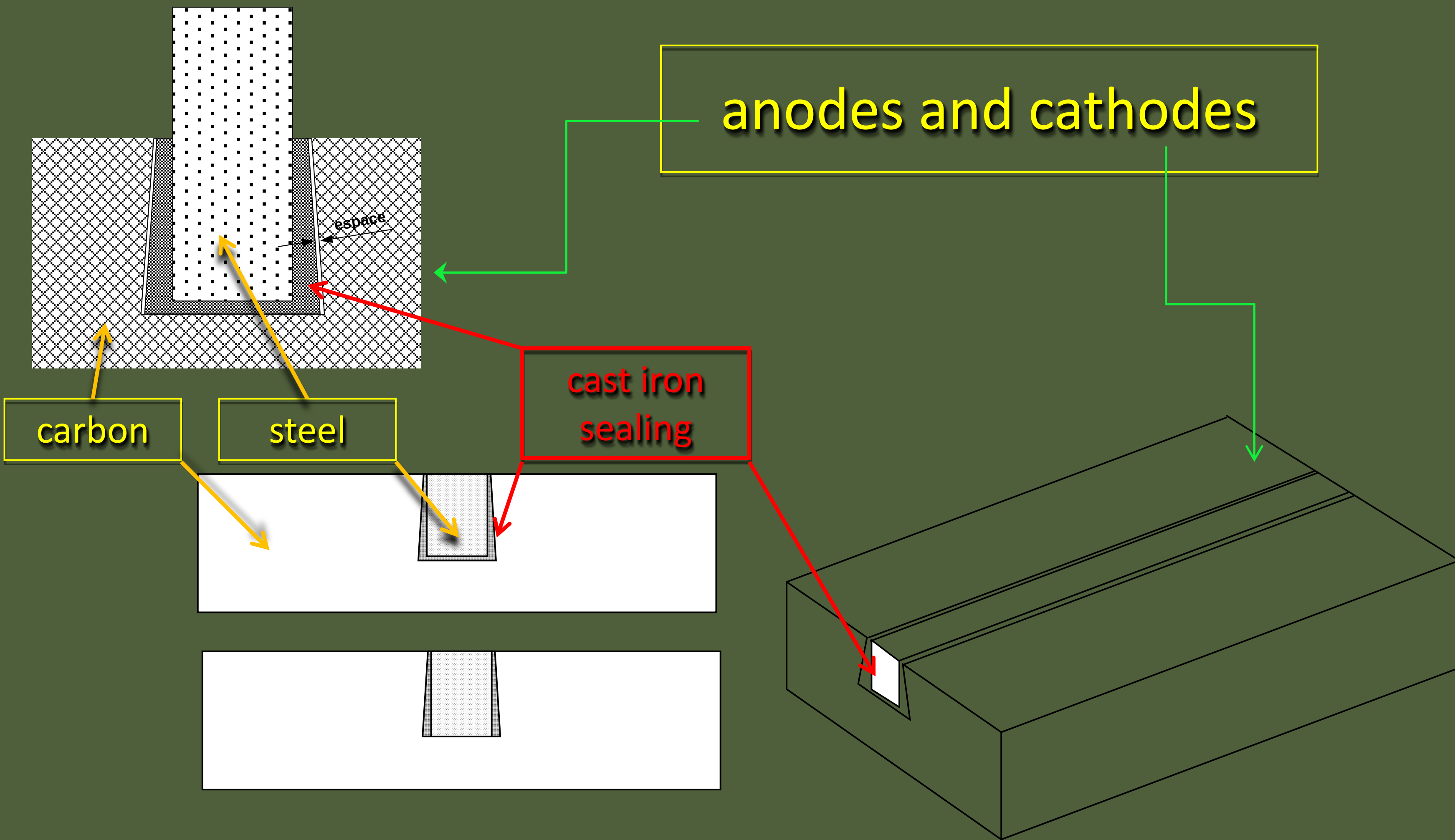
Internal heat generation inside the cell

Parasite heating by Joule effect – part of the electrical energy that does not produce metal

- bath resistance (electrical resistivity of the bath)
- bubble layer – additional resistance (voids)
- electrodes
    - bulk resistance of solids (carbon, steel, aluminum)
    - interfaces, contacts

Reversible ("splitting") voltage drop ≈ 1.9 V
Total voltage drop of a cell ≈ 4-4.5 V

Connection of electrical conductors



elevated temperatures, aggressive environment

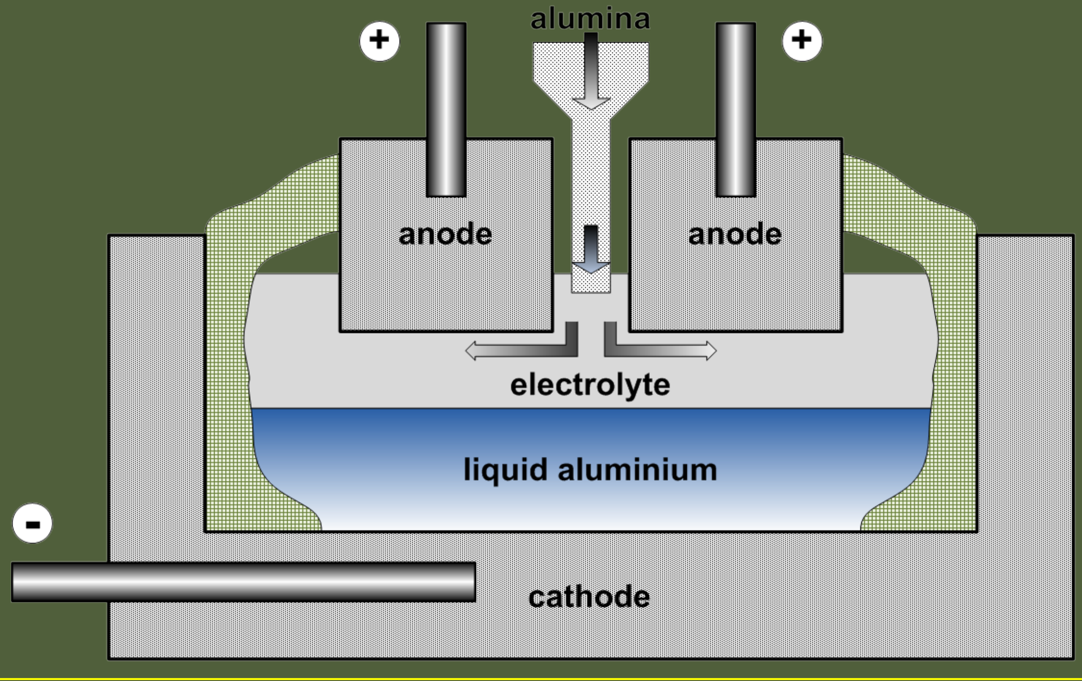
The process – containment I.

Finding appropriate refractory materials :

- temperatures up to 950-1000°C
- chemical aggression by Na^+, NaF, AlF_3 ions

Internal lining : carbon aggregates, graphite
- resists well to molten aluminum
- does not resist to molten bath

The process – containment II.

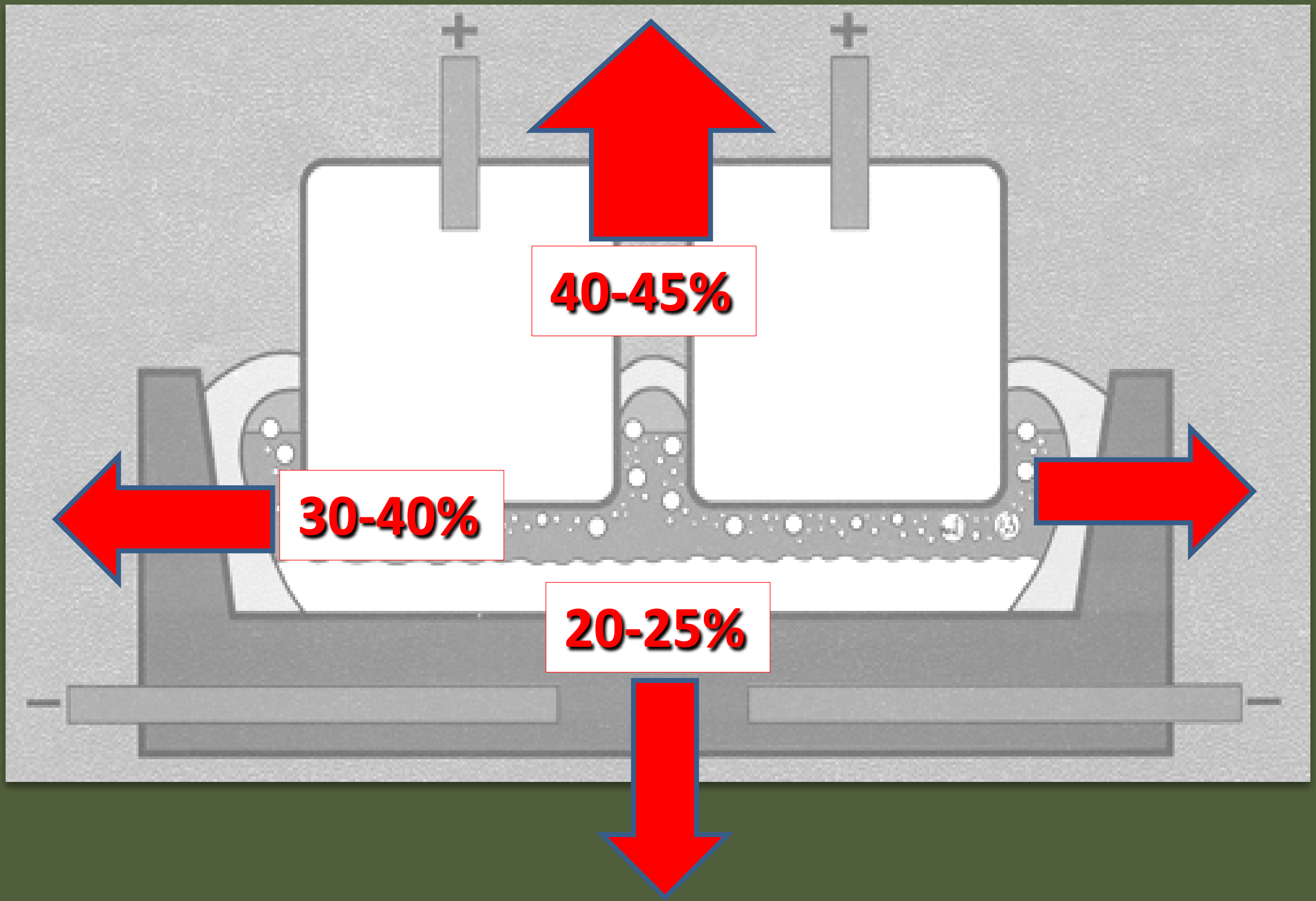


The molten bath is contained

- by the liquid metal at the *bottom*
- by itself, by solidified bath *laterally*
- by the carbon anode that is consumed, at the *top*

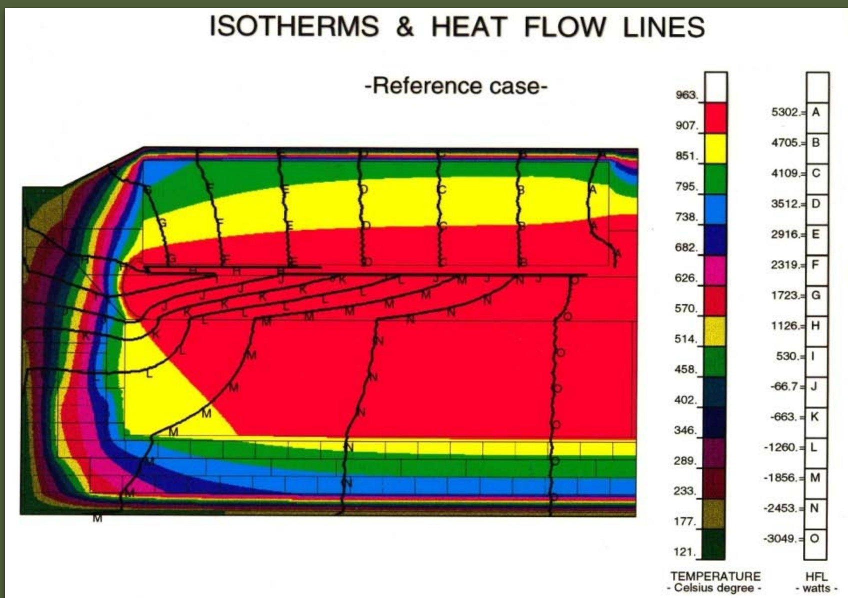
Heat losses of the cell

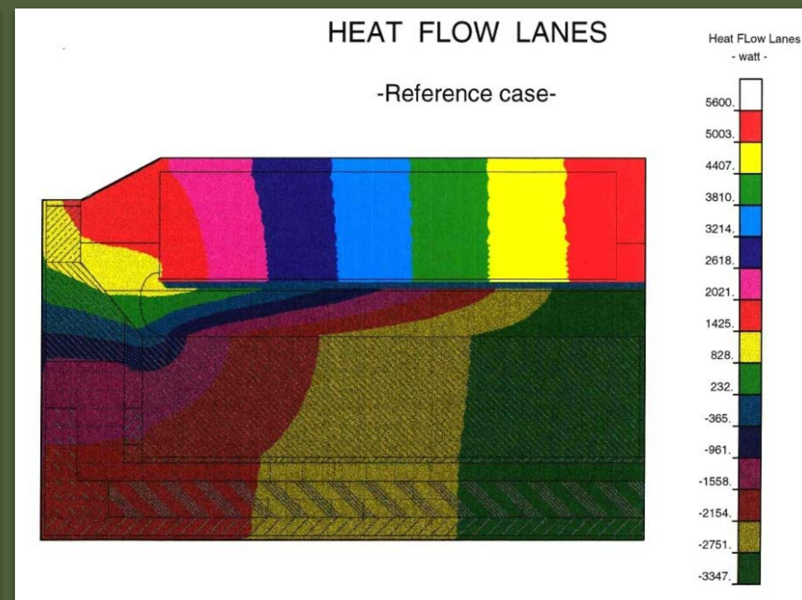
Ratio of bottom&top surfaces to sidewall (lateral) surface...



Heat balance of the reduction pots

Heat flow driven by → bath temperature or heat source → role of the heat transfer coefficient





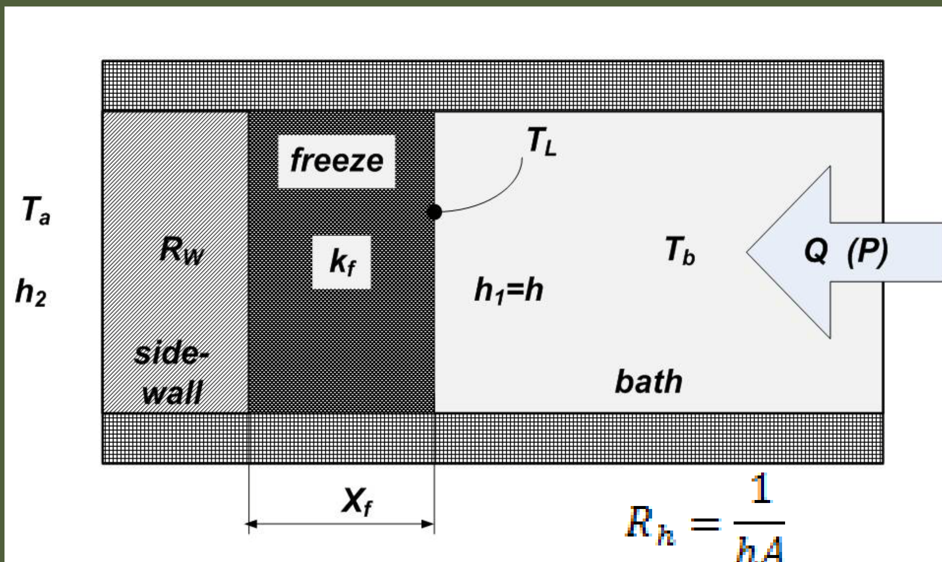
The sidewall freeze (“ledge”) plays a critical role in the protection of the cell lining

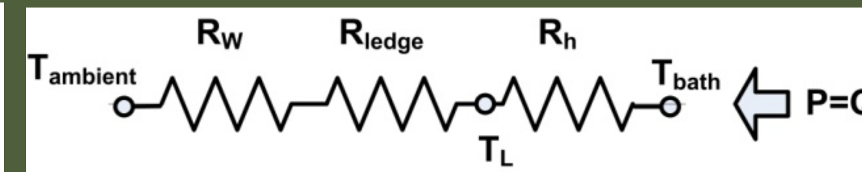
As the freeze is formed thermally, it plays a critical role in the energy balance of the cell

As the metal production per cell is increasing, one must reduce the insulating capacity of the sidewall

Estimation of the freeze thickness

"single-channel model" - lumped parameters





$$R_{ledge} = \frac{X_f}{k_f A_f} = R_h \frac{\Delta T_L}{\Delta T_S} - R_W$$

Primary input parameter:

the bath superheat ΔT_S

$$\Delta T = T_b - T_a$$

$$\Delta T_L = T_L - T_a$$

$$\Delta T_S = T_b - T_L$$

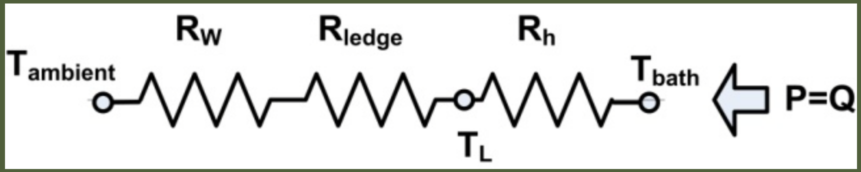
$$\frac{\Delta T_L}{\Delta T_S} \approx 40 - 80$$

lumped parameters – global resistances (conductances), heat capacities etc.

Estimation of the freeze thickness

"single-channel model" - superheat driven

How does the freeze react to the variation of certain parameters ?



$$R_{ledge} = \frac{X_f}{k_f A_f} = R_h \frac{\Delta T_L}{\Delta T_S} - R_W$$

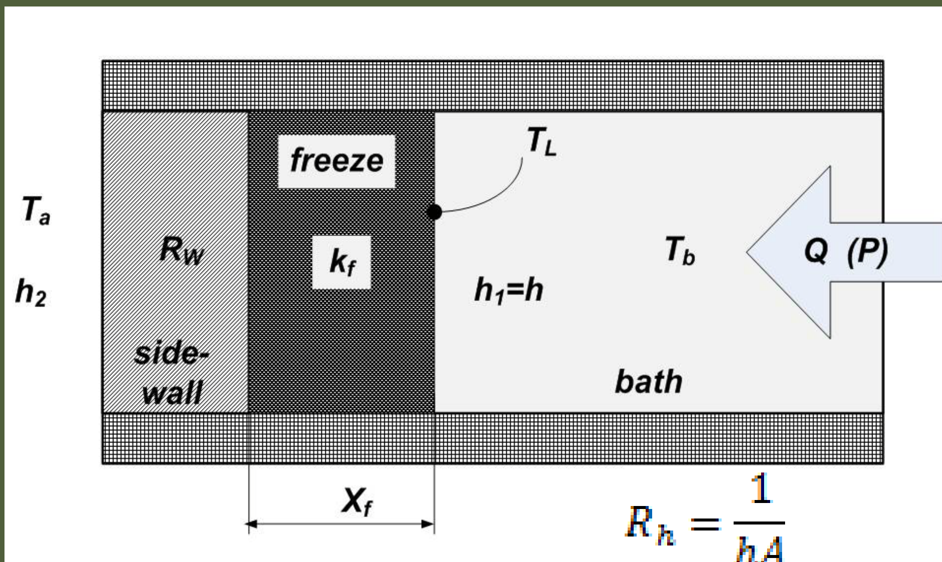
The sensitivity of freeze thickness (thermal resistance):

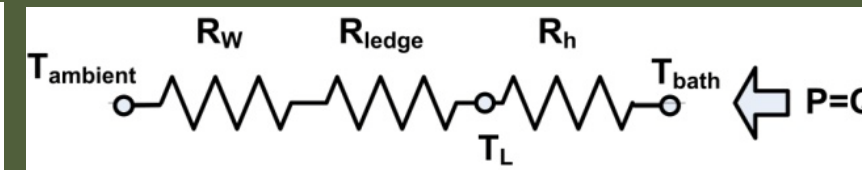
$$\frac{\partial R_{ledge}}{\partial R_W} = -1 \quad ; \quad \frac{\partial R_{ledge}}{\partial R_h} = \frac{\Delta T_L}{\Delta T_S}$$

$$\frac{\partial R_{ledge}}{\partial \Delta T_S} = -\frac{R_h \Delta T_L}{\Delta T_S{}^2} = -\frac{R_h}{\Delta T_S} \frac{\partial R_{ledge}}{\partial R_h} \qquad \frac{\Delta T_L}{\Delta T_S} \approx 40 - 80$$

Estimation of the freeze thickness

"single-channel model" - lumped parameters





$$R_{ledge} = \frac{X_f}{k_f A_f} = \frac{\Delta T_L}{P} - R_W$$

Primary input parameter:

the rate of injected heat *P*

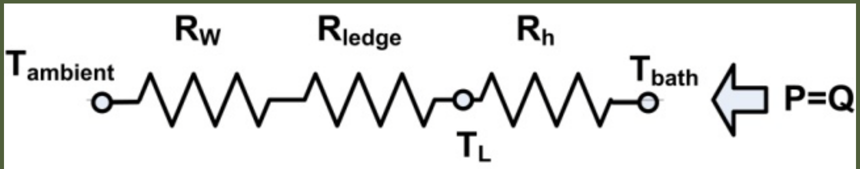
$$\Delta T = T_b - T_a$$

$$\Delta T_L = T_L - T_a$$

$$\Delta T_S = T_b - T_L$$

Estimation of the freeze thickness

"single-channel model" - heat input driven



$$R_{ledge} = \frac{x_f}{k_f A_f} = R_h \frac{\Delta T_L}{\Delta T_S} - R_W$$

How does the freeze react to the variation of certain parameters ?

The sensitivity of freeze thickness (thermal resistance):

$$\frac{\partial R_{ledge}}{\partial R_W} = -1 \qquad \frac{\partial R_{ledge}}{\partial P} = -\frac{\Delta T_L}{P^2} \qquad \frac{\partial R_{ledge}}{\partial R_h} = 0$$

$\Delta T = T_b - T_a$

$\Delta T_L = T_L - T_a$

$\Delta T_S = T_b - T_L$

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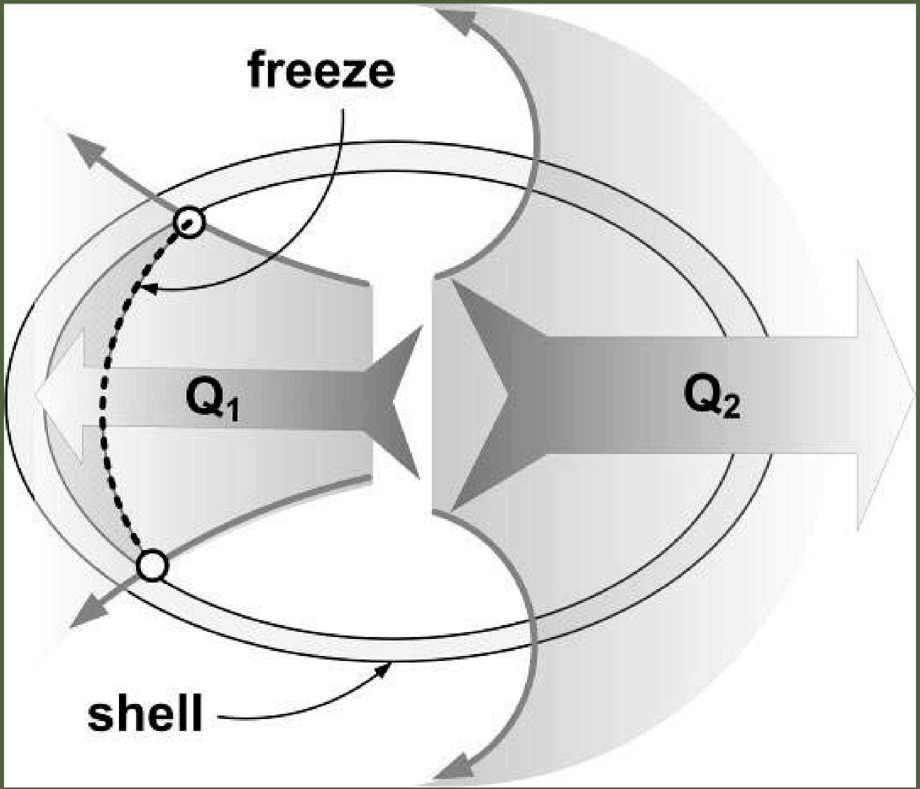
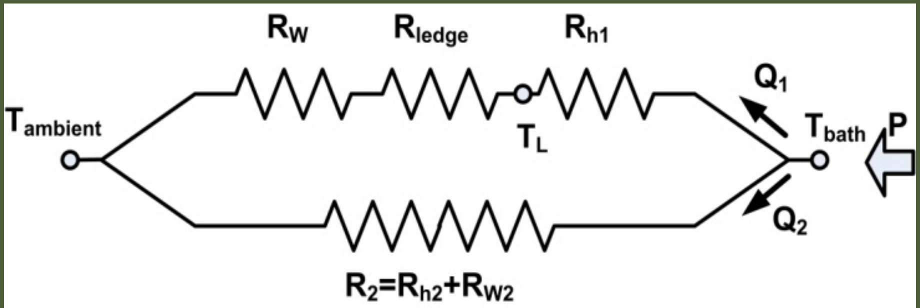
Estimation of the freeze thickness

"two-channel model"





$$P = Q = Q_1 + Q_2$$

$$R_{ledge} = \frac{X_f}{k_f A_f} = \frac{R_2 + R_{h1}}{\frac{PR_2}{\Delta T_L}} - R_W$$

The global resistances R_2, R_W, $R_{h1}=R_h$, R_{h2} can be determined from the results of the numerical simulations

Estimation of the freeze thickness

"two-channel model"

The sensitivities :

$$\frac{\partial R_{ledge}}{\partial R_W} = -1 \quad ; \quad \frac{\partial R_{ledge}}{\partial R_{h1}} = \frac{1}{X-1}$$

$$\frac{\partial R_{ledge}}{\partial R_2} = -\frac{1}{(X-1)^2}\left[1 + X\left(\frac{R_{h1}}{R_2}\right)\right]$$

where $X = \frac{PR_2}{\Delta T_L}$

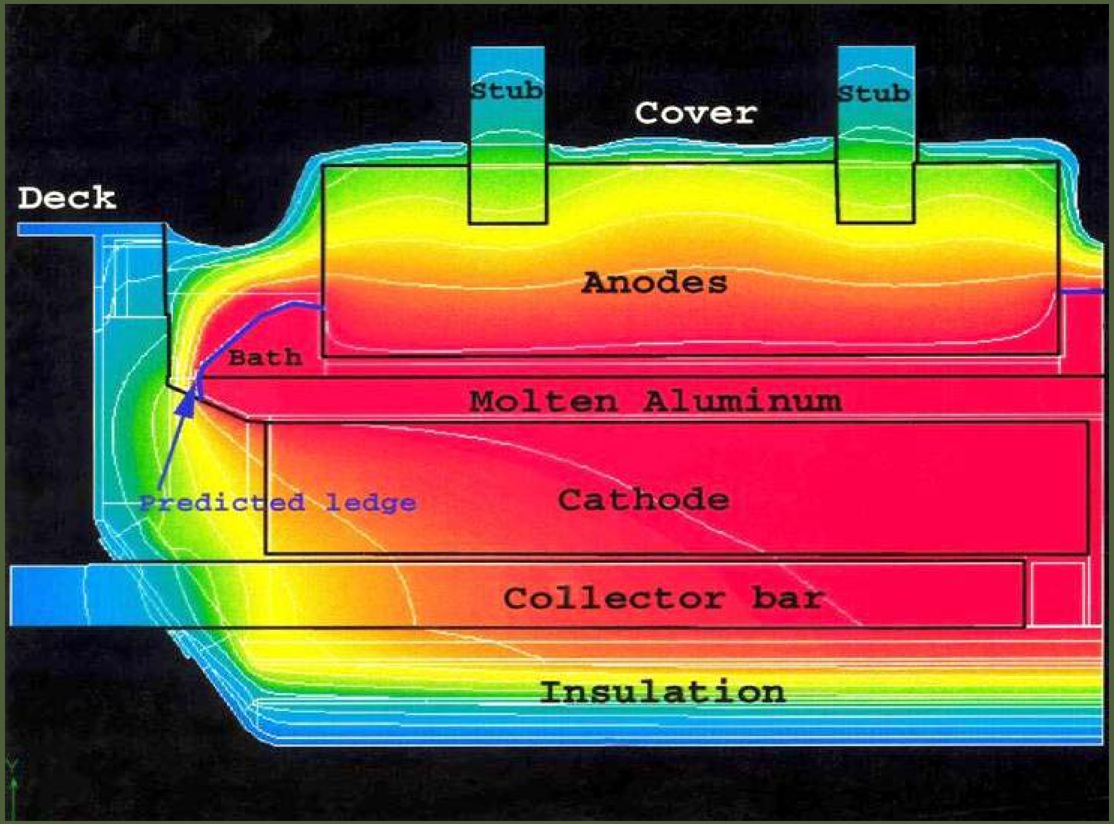
$X \approx 1.44$

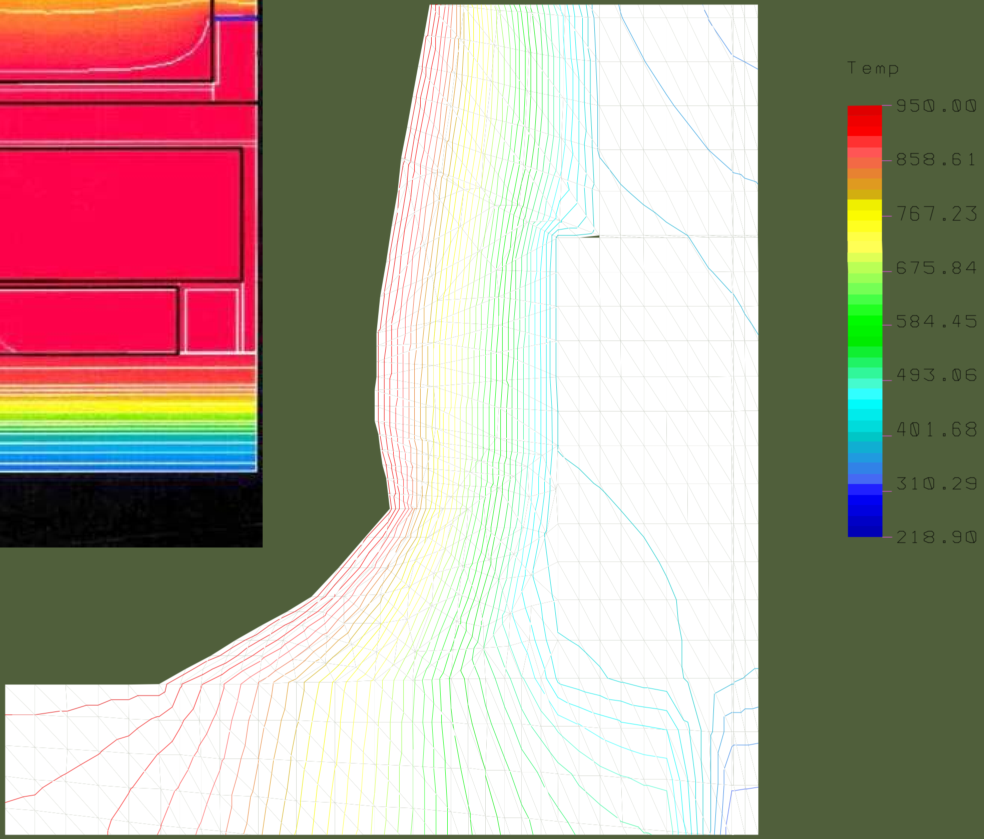
$$\frac{\partial R_{ledge}}{\partial R_W} = -1$$

$$\frac{\partial R_{ledge}}{\partial R_{h1}} \approx 2.3$$

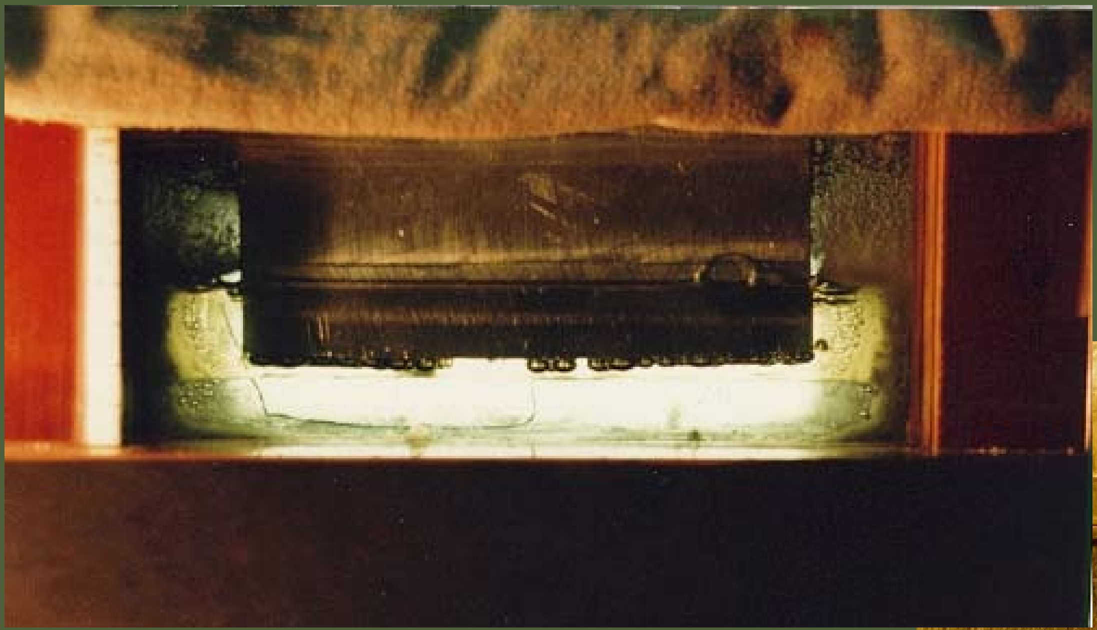
$$\frac{\partial R_{ledge}}{\partial R_2} \approx -5.5$$

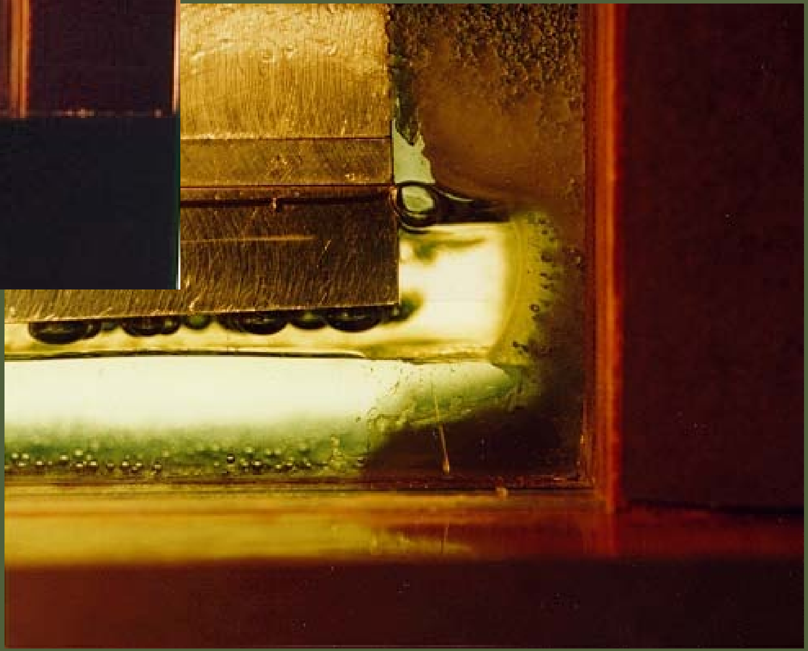
Results of mathematical modeling of the freeze profile





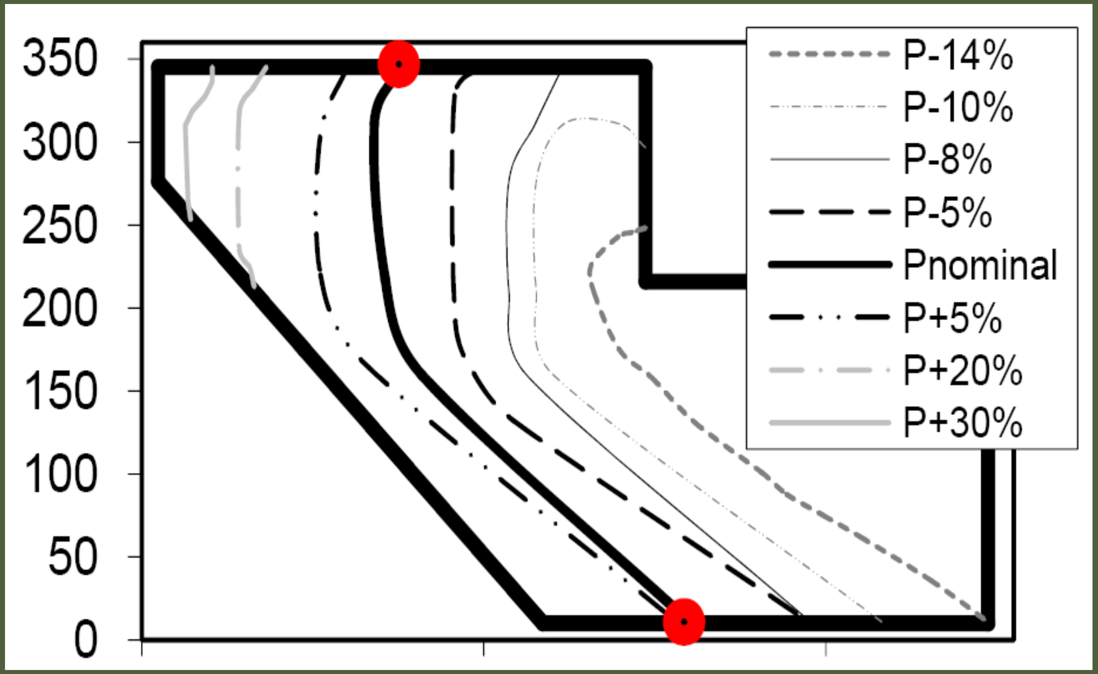
Freeze formation–
- validation of the thermal model





Small size
thermo – hydraulic model

Freeze profile - increasing amperage



New technologies:

- 500-600 kiloamperes line current
- 5-10 meters horizontal dimensions, 2-4 cm bath depth
- need for active cooling
- potential for recuperation of energy
- about 10kW/m^2 heat flux density, 300-500°C temperature level

Conclusions

ways to improve the energy efficiency of the aluminum reduction

A. Reducing internal, parasite heat generation

1) in the liquid phase (anode-cathode distance, bubble layer)

– realistic, but limited potentials

2) in the electrodes, including the contact resistances

- new materials, new joining methods

Conclusions

ways to improve the energy efficiency of the aluminum reduction

B. Recuperation of the heat losses

- from the exhaust gases – already done partially
- from the sidewall – need to find use of the heat
    - space/process heat
    - electricity generation, conversion

Conclusions

ways to improve the energy efficiency of the aluminum reduction

C. Removing the need to form a protective layer by freezing bath on the sidewall

– need to find new refractory materials

D. Identifying a completely new aluminum reduction technology

- Low temperature electrolysis
- New electrolyte to dissolve alumina
- Non-electrolytic methods
- ...