Modelling of the magnetic field and magnetohydrodynamic behaviour of a typical aluminium cell using COMSOL

Ievgen Necheporenko, Alexander Arkhipov

Emirates Global Aluminium, Dubai, UAE

Corresponding author: inecheporenko@ega.ae

Abstract

Aluminium production potlines operate under significant amperage in a range of 200 kA – 600 kA. High electrical DC currents induce strong magnetic fields. MHD-stability which is a result of electrical current and magnetic field interaction within aluminium reduction cell is one of highly important factors which has to be considered in the design.

Previous work on modelling magnetic field within aluminium production cell was based on scalar magnetic potential codes including Biot-Savart integration. Only recent studies included COMSOL simulations of magnetic field inside aluminium electrolysis cell using vector magnetic potential.

This article presents numerical modelling of the electromagnetic fields and their effect on molten electrolyte and aluminium flow within the cell using COMSOL software. Two uncoupled models were developed for evaluation of the magnetic field and prediction of magnetohydrodynamic behaviour of the operating fluids.

1. Introduction

Aluminium is reduced from alumina (aluminium oxide Al_2O_3) by electrolysis in aluminium reduction cells which are connected in a long electric series (up to 1.5 km long) with very high amperage (200-600 kA). Direct current from one cell to another is carried by aluminium busbar surrounding the cells (Figure 1).

Figure 1. Longest electrolysis potline with DX+ cells operating at 470 kA. EGA, Abu Dhabi

Strong magnetic field is generated around those busbars and interacts with electrical current within the melt of aluminium reduction cell, resulting in electromagnetic force called Lorentz force. Proper balancing of such forces inside the melt is a must to provide MHD-stability of a cell. MHD-stability is of paramount importance for aluminium reduction cell performance. Without good MHD-stability it is impossible to achieve high current efficiency (productivity) and low energy consumption since instabilities enhance the rate of back reaction and make pot control more difficult. MHD instabilities are defined as oscillations of metal-bath interface, driven by electromagnetic forces. Therefore, electromagnetic force spatial distribution is one of the most important factors to be considered during the design stage of an electrolysis cell. The electromagnetic force distribution mainly depends on the design of the current supply busbars surrounding electrolysis cell. Knowing the principles and being able to predict the consequences of particular busbar design, the selection of electrical current and magnetic field distribution is extremely important to create a well performing cell.

Building test cells is a very expensive project costing millions of USD and it is also very expensive and hazardous exercise to fix busbar design of live cell. This is why the cost of a mistake is very high. Therefore, numerical 3D simulation is the main tool for the selection of good busbar design.

COMSOL Multiphysics has capabilities which allow the simulation of crucial connections and dependencies between electrical, magnetic, thermal and hydrodynamic behaviour of the aluminium reduction cell. The modelling of these phenomena consists of studying different busbar designs and selecting the optimal one.

COMSOL Multiphysics has already been used for magnetic field calculation within an aluminium cell [1]. Present work will not only include a modelling study on the magnetic field, but it will also cover MHD (magnetohydrodynamics), which will take the magnetic field and electrical current distribution as input data.

2. Geometry

The complexity of aluminium electrolysis cell assembly adds difficulties in preparing a numerical model. The number of components is quite significant. Hence, certain geometrical simplifications are required before proceeding with mathematical setup.

Typical aluminium electrolysis cell transverse cross-section is shown in Figure 2.

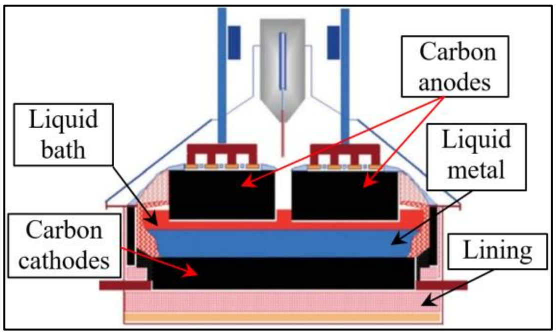

Figure 2. Typical aluminium production cell cross section

Figure 2 shows aluminium production cell components which are conducting electrical current entering from the top through anodes, flowing down through liquid electrolyte, liquid metal and exiting from cathode collector bars at the bottom. Liquid bath and metal, depicted in Figure 2, are the subjects of magnetohydrodynamic simulation.

Another important component of each aluminium electrolysis cell is lining. The lining, shown in Figure 2 in pink colour at the bottom part of the sketch, plays an important role in the heat balance of the system, but does not conduct electrical current. Hence, in present work it was not included as part of the simulation. Nevertheless, the temperature of electrical current conducting parts of cathode assembly (carbon cathode block, cast iron, steel/copper collector bar, ramming paste) depends on lining layout and affects electrical conductivity of the materials used. Constant temperatures of the cathode assembly parts were assumed as a simplification. These temperatures can be obtained with thermo-electrical modelling of the cathode.

As mentioned previously, electrolysis cells are connected in series aluminium busbars.

A real reduction cell design is a commercial secret, therefore, the cell geometry taken for the present study is a typical design used to establish the modelling approach.

The magnetic field model prepared in present work consists of parts shown in Figure 3.

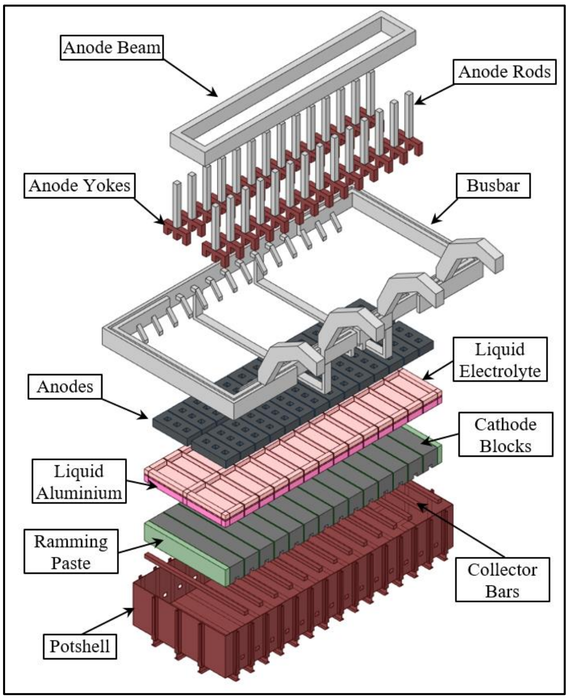

Figure 3. Magnetic field model geometry parts

The magnetohydrodynamic model, developed with COMSOL Multiphysics includes liquid aluminium and electrolyte, which floats on the top of liquid aluminium.

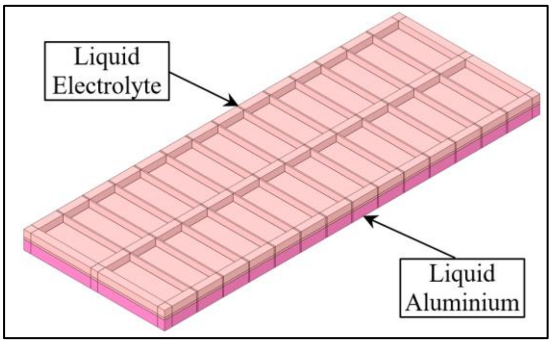

Figure 4. Magnetohydrodynamic model geometry parts

Certain simplifications were made in the electrolyte subdomain of the MHD model. Gaps between anodes were eliminated. Hence, the model became computationally less demanding. Figure 5 shows the simplified geometry of the MHD model.

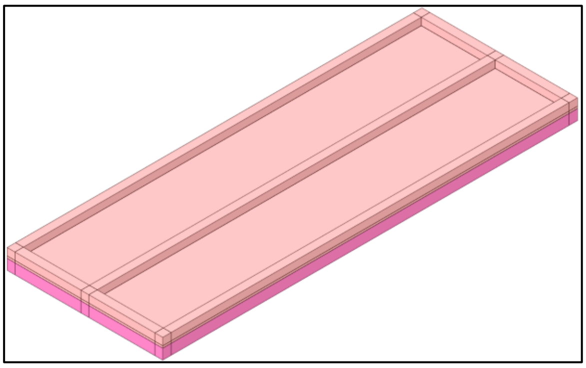

Figure 5. Simplified geometry of the MHD model

3. Materials

A wide range of materials is used in the aluminium reduction cell. Material properties used for electrical current simulation and magnetic field modelling described in current paper were considered as temperature dependent.

Materials and corresponding model parts are listed in Table 1. Corresponding material properties in the model are given in Appendix 1.

Table 1. Materials used in simulations

	Model Part	Material
1	Potshell	Steel 1
2	Busbar	Aluminium
3	Anode Rods	Aluminium
4	Anode Yokes	Steel 2
6	Anodes	Carbon 1
7	Liquid Electrolyte	-
8	Liquid Aluminium	-
9	Cathode Blocks	Graphite
10	Ramming Paste	-
11	Collector Bars	Steel 3

In the magnetic field model, the potshell stell (Steel 1) is taken as ferromagnetic material whose B-H curve is given in Appendix 1. Anode yokes and collector bars are also made of steel (Steel 2 and Steel 3), but they are treated as non-ferromagnetic in the model. In the MHD model of the liquids, the electrolyte density = 2070 kg/m^3 and the metal density = 2270 kg/m^3. The liquids are turbulent with constant turbulent dynamic viscosity of electrolyte = 0.4 Pa*s and metal = 0.6 Pa*s.

4. COMSOL Multiphysics Setup

Two separate models were developed using COMSOL Multiphysics to solve the MHD problem. Magnetic field model was built using a coupled simulation of thermal, electrical and magnetic problems. MHD solution was obtained calculating fluid flow parameters affected by body forces calculated from electrical current density distribution and magnetic field, obtained from the previous step of the model.

4.1 Interfaces

Electric currents, Heat Transfer in Solids and Magnetic Fields interfaces were used for magnetic field model. Electromagnetic Heating coupling interface is used in order to take into account temperature dependence of the material properties.

MHD model includes Turbulent Flow and Electric Currents interfaces.

4.2 Boundary Conditions

The accuracy of magnetic field magnitude prediction depends on the number of aluminium reduction cells included in the simulation. In the present, work there are 2 full cells and 3 full busbars included in the simulation domain.

As long as the magnetic field model includes several interfaces (electric currents, heat transfer and magnetic fields), it is required to prescribe boundary conditions for each corresponding physics.

Table 2 summarizes boundary conditions applied in the magnetic field model. Electric current interface requires terminal (total electrical current supplied to potline) and electrical potential boundary conditions. The temperature prediction of the assembly parts requires heat flux, radiation and constant temperature boundary conditions. Radiation and convection boundary conditions are applied on busbar and anode beam surfaces, which affect temperature and electrical current distribution in the busbar. Constant temperature is applied to operating liquids, anodes, cathode blocks and collector bars. This is done in order to be able to eliminate lining parts from simulation (decrease computational effort) and in any case, the previous experience shows that this simplification does not have significant impact on simulation results.

Table 2. Boundary conditions within interfaces

BC Used	Electric Currents	Heat Transfer in Solids	Magnetic Fields
Terminal	✓		
Electrical Potential	✓		
Natural Convection		✓	
Radiation to Ambient		✓	
Constant Temperature		✓	
External Current Density			✓
Magnetic Insulation			✓
Gauge Fixing for A-field[1]			✓

Magnetic field model study steps are arranged so that Joule heating problem is solved first (Electrical Currents and Heat Transfer in Solids coupled interfaces).

---

[1] This is often necessary in order to get a unique and numerically stable solution of the equation for the magnetic vector potential **A**

Electrical current densities obtained from this step become input data for Magnetic Field interface. The second step includes calculation of magnetic vector potential with external current density (applied to current carrying parts) and magnetic insulation (external surfaces of the air domain) boundary conditions.

MHD model is prescribed with electrical current density at the bottom of liquid aluminium (electrical current density imported from electromagnetic field model) and zero electric potential at the interface between anodes and liquid electrolyte.

Fluid flow interface of MHD model requires gravity and volume force boundary conditions. Volume force represents electromagnetic force caused by an interaction of the magnetic field, which is imported from the magnetic field model, and electrical current passing through electrolyte and aluminium (calculated in electric currents interface).

It is important to mention that two-phase flow with a moving mesh approach was used for MHD calculations. This requires another boundary condition which is prescribed on the liquid-liquid interface. The importance of this boundary condition is the result of the simplification introduced, which is related to anodes consumption. The anode carbon material is consumed proportionally to electrical current density. Theoretically this means, that the distance between liquid electrolyte-liquid aluminium interface and anode bottom surface should be maintained constant during the pot operation. This distance is called ACD (anode-cathode distance).

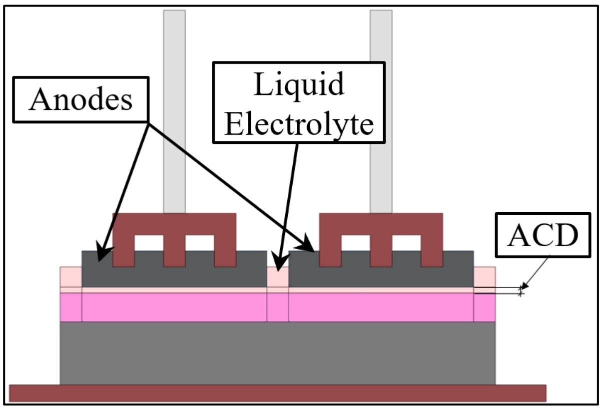

Figure 6. Anode-cathode distance

Practically, we should somehow maintain ACD constant in the model. A straightforward approach would be to model electrochemical behaviour which could estimate the consumption of anode carbon and adjust anode bottom surface. But in the present work, for the sake of simplification, anode consumption is represented by simple mimicking of liquid-liquid interface with constant offset (ACD). This approach is implemented using non-local couplings available within COMSOL Multiphysics component definitions.

4.3 Mesh

Magnetic field model was developed using full tetrahedral mesh with local refinements

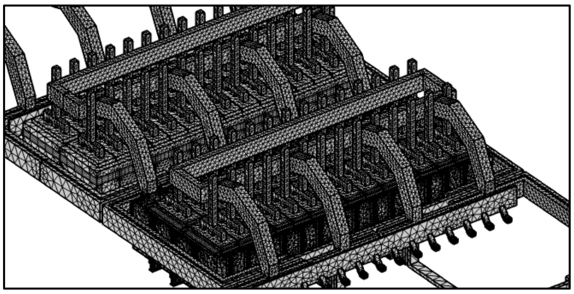

Figure 7. Magnetic field model mesh

Several mesh iterations were conducted to achieve grid independence. Operating liquids were built with hexahedral mesh and several local refinements were applied to busbar locations.

Electromagnetic field modelling using vector potential method requires an air domain. In the present study air domain was added to cover the central cell and half of each neighbour cell (Figure 8).

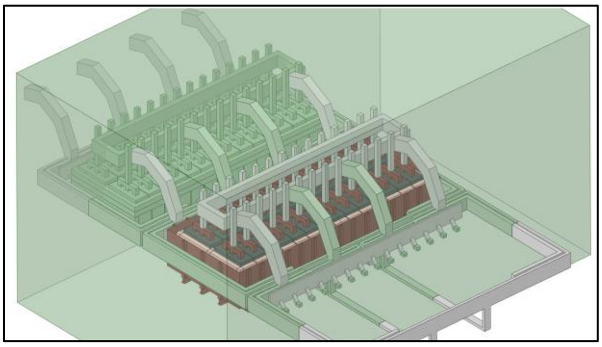

Figure 8. Air domain around electrolysis cells

MHD model mesh was constructed with hexahedral elements using swept method (Figure 9).

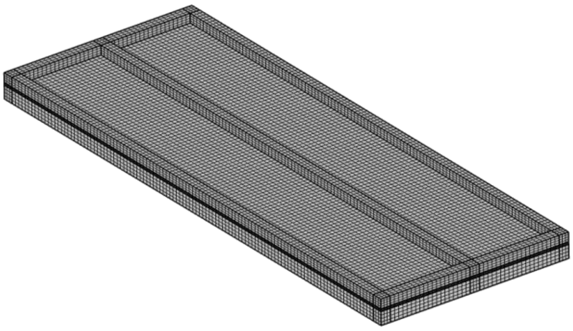

Figure 9. MHD model mesh

4.4 Results

Magnetic field model gives the following distributions: Temperature, electrical potential, electrical current density and magnetic flux density in the computational domain, which includes several aluminium reduction pots and neighbouring air domain (magnetic flux only).

Some of the results are shown in Figures 10 – 15.

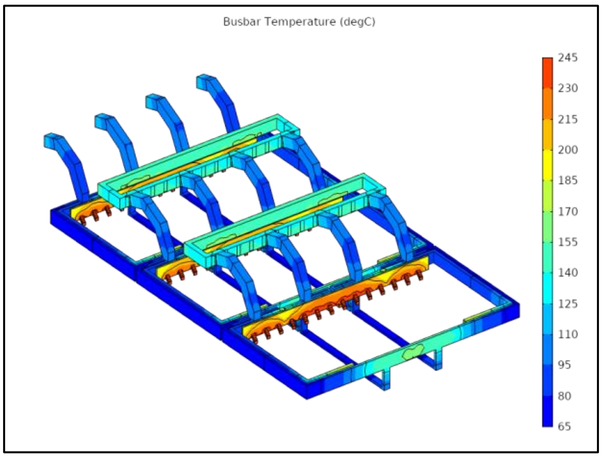

Figure 10. Temperature contours of the potline busbar

High temperature spots on the potline busbars have to be inspected carefully since those locations might be indicators of poor busbar design which has to be corrected to avoid overheating.

Another outcome of the model is the distribution of electrical potential. Optimizing different assembly parts of the reduction pot may result in voltage drop decrease. Such optimization can lead to more energy-efficient aluminium electrolysis cell design.

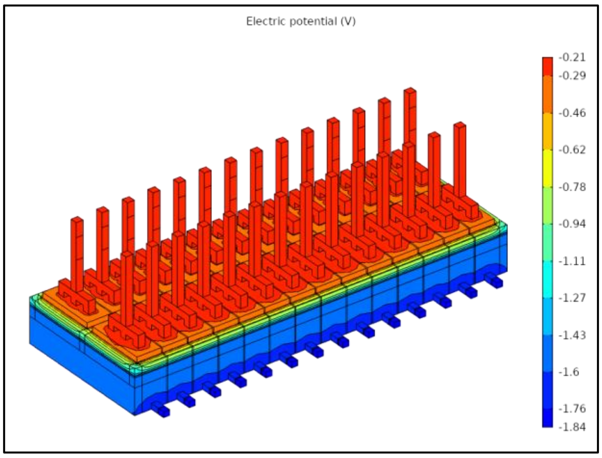

Figure 11. Electrical potential contours

Magnetic flux density is another important output result which is crucial as an input for further MHD simulation. These results are exported from magnetic field model and imported into MHD model (particularly for liquid domain).

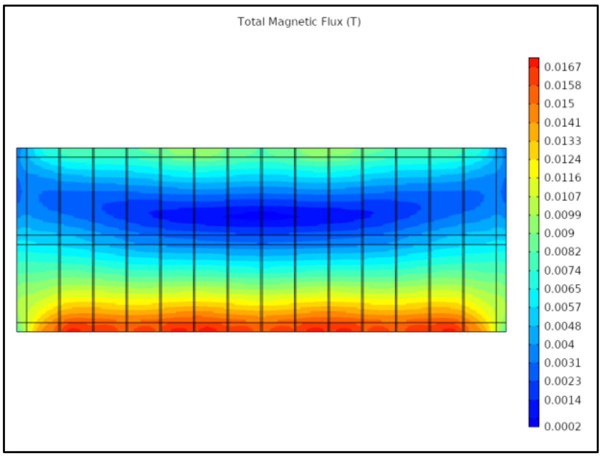

Figure 12. Total magnetic flux contours in the middle of the metal

MHD model gives flow patterns in the liquid metal and electrolyte. Based on velocity distribution we can conclude that electrolyte flow is sufficiently high to transport and dissolve alumina uniformly in the electrolyte volume, which is a very important aspect of the aluminium electrolysis. On the other hand, high liquid aluminium velocities can cause MHD instabilities and self-propagating waves as well as melting of a frozen layer of electrolyte on inner walls of the cell cavity; this causes side lining erosion and possible metal and bath tap-out and pot shutdown.

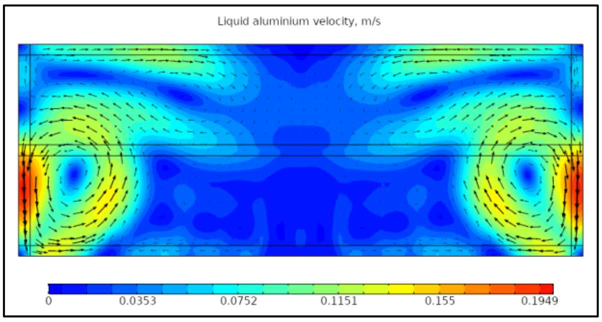

Figure 13. Velocity pattern in the middle of the metal

ACD is a particular region where mixing and transport of the alumina happens. Figure 14 shows velocity flow pattern in this region.

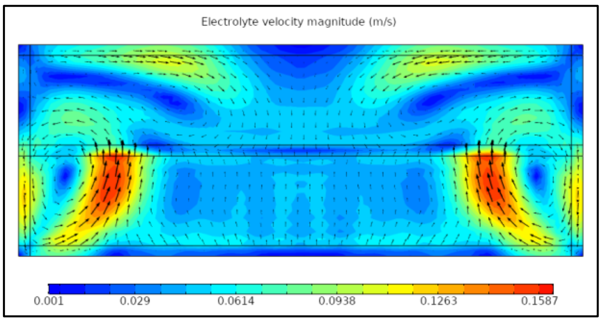

Figure 14. Velocity pattern in the middle of the electrolyte

The interface between the electrolyte and the metal is deformed (metal heave) while the pot is in operation.

This happens because the electromagnetic forces in the metal are different than in the electrolyte. Metal heave is also a valuable modelling output which is also calculated in COMSOL Multiphysics (Figure 15).

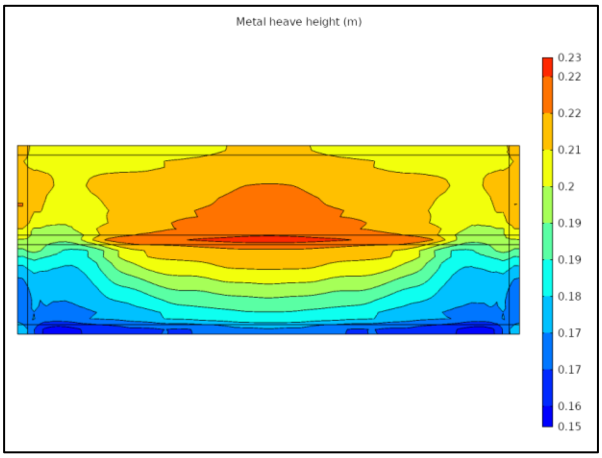

Figure 15. Metal-electrolyte interface height

5. Conclusions and Way Forward

Magnetic field and magnetohydrodynamic models developed and presented in this paper allow to calculate liquid electrolyte and liquid aluminium flow () in an aluminium electrolysis pot. The results may be used for modern aluminium reduction cell design optimization in order to achieve better performance and stable operation.

Electromagnetic model results also give us with crucial insight into the electrical current distribution and thermal conditions of the pot.

We have built a steady state thermal and electrical model of the electrically conductive parts of the pot as well as a steady state MHD model of the pot. In the future, the modelling should be taken further by including MHD instability (oscillations of the metal-electrolyte interface), impact of the carbon anode change (every 32 hours) on liquids flow, complex physics behaviour such as alumina feeding and dissolution, formation of the frozen electrolyte layer on cell interior walls and finally coupling of the two separate models described in the present paper.

References

1. Vandelei Gusberti, Dagoberto S. Severo, Electromagnetic Modelling of Aluminium Electrolysis Cells Using Magnetic Vector Potential, *TRAVAUX 48, Proceedings of the 37th International ICSOBA Conference and XXV Conference «Aluminium of Siberia»*, Krasnoyarsk, Russia, 16 – 20 September 2019, pages 967 – 980.
2. Alexander Arkhipov, Abdalla Alzarooni et al., Improving the Understanding of Busbar Design and Cell MHD Performance, *Light Metals*, 2017, pages 671 – 677.
3. COMSOL 5.5, *Reference Manual*.

Appendix 1. Material Properties

Table 1. Electrical and thermal material properties. T = absolute temperature

	Electrical Resistivity, Ω*m	Thermal Conductivity, W/(mK)
Steel 1	7.69e-7	N/A
Aluminium	(T*1.1447e-10-5.29248e-9)	155
Carbon 1	4.3e-5	150
Steel 2	4.6e-7	44.5
Liquid Electrolyte	4.35e-3	N/A
Liquid Aluminium	2.44e-7	N/A
Graphite	1.1e-5	N/A
Ramming Paste	4.5e-5	N/A
Steel 3	1.134e-6	N/A
Air	N/A	N/A