NETL Life Cycle Inventory Data
Process Documentation File

Process Name:	NdFeB Permanent Magnet Manufacturing
Reference Flow:	1 kg of NdFeB Plated Magnet
Brief Description:	Manufacturing process for 1kg plated NdFeB permanent magnet

Section I: Meta Data

Geographical Coverage: United States **Region:** NA

Year Data Best Represents: 2014

Process Type: Manufacturing Process (MP)

Process Scope: Gate-to-Gate Process (GG)

Allocation Applied: No

Completeness: All Relevant Flows Captured

Flows Aggregated in Data Set:

☑ Process ☑ Energy Use ☐ Energy P&D ☐ Material P&D

Relevant Output Flows Included in Data Set:

Releases to Air:	☑ Greenhouse Gases	☑ Criteria Air	☑ Other
Releases to Water:	☑ Inorganic	☑ Organic Emissions	☐ Other
Water Usage:	☑ Water Consumption	☐ Water Demand (throughput)	
Releases to Soil:	☐ Inorganic Releases	☐ Organic Releases	☐ Other

Adjustable Process Parameters:

Delta_T_Water	*[ΔT] Increase in water temperature during cooling in strip casting process*
Heat_Sin_Factor	*[MJ/kg NdFeB, sintered block] Heat input required per 1 kg NdFeB sintered block*
G_S_Loss_Rate	*[%] Percent of NdFeB sintered block lost during grinding and slicing process*

G_S_Recy_Rate	*[%] Percent of scrap/lost material recycled/reclaimed*
G_S_Loss_Factor	*Factor to normalize flow requirements in grinding and slicing process to ultimately produce 1kg of NdFeB plated magnet*
Elec_Loss_Rate	*[%] Percent of NdFeB magnet lost during electroplating process*
Wat_Elec_Factor	*[kg/kg NdFeB, magnet] Water input required per 1kg input NdFeB magnet in electroplating process*
Elec_Elect_Fact	*[kg/kg NdFeB, magnet] Electricity input required per 1kg input NdFeB magnet in electroplating process*
Ni_Factor_2	*[kg/kg NdFeB, magnet] Nickel input required per 1kg input NdFeB magnet in electroplating process*
Ni_Wat_Factor	*[kg/kg NdFeB, magnet] Nickel sulfamate emissions to water per 1kg input NdFeB magnet in electroplating process*
Wat_D_Elec_Fac	*[kg/kg NdFeB, magnet] Waste water emissions per 1kg input NdFeB magnet in electroplating process*
Ni_Factor_3	*[kg/kg NdFeB, magnet] Nickel emissions to air per 1kg input NdFeB magnet in electroplating process*

Tracked Input Flows:

Iron [Intermediate]	*[Technosphere]*
Boron carbide [Intermediate]	*[Technosphere]*
Neodymium [Intermediate]	*[Technosphere]*
Hydrogen gas [Intermediate]	*[Technosphere]*
Sodium carbonate [Intermediate]	*[Technosphere]*
Trisodium phosphate [Intermediate]	*[Technosphere]*
Sodium gluconate [Intermediate]	*[Technosphere]*
Sodium hydroxide [Intermediate]	*[Technosphere]*
Sulphuric acid [Intermediate]	*[Technosphere]*
Nickel [Metals] [Intermediate]	*[Technosphere]*
Heat [Intermediate]	*[Technosphere]*

Electricity [Intermediate] *[Technosphere]*
Water [unspecified] *[Resource]*

Tracked Output Flows:

NdFeB plated magnet [Intermediate product] *Reference flow*

Section II: Process Description

Associated Documentation

This unit process is composed of this document and the data sheet (DS) DS_*Stage1_O_NdFeB_Magnet_Manufacturing.2014.01.xlsx*, which provides additional details regarding relevant calculations, data quality, and references.

Goal and Scope

This unit process provides a summary of relevant input and output flows associated with the manufacturing of 1kg of plated NdFeB permanent magnet. The unit process includes widely used industrial processes for making NdFeB permanent magnets, which include alloying and strip casting, hydrogen decrepitation, jet milling, aligning and pressing, vacuum sintering, grinding and slicing, and electroplating. Input and output flows are aggregated and represent all of these sub-processes rolled into one unit process, "NdFeB Permanent Magnet Manufacturing". The reference flow of this unit process is: 1 kg of NdFeB Plated Magnet

Boundary and Description

The initial step for manufacturing NdFeB plated permanent magnets in this unit process is NdFeB alloying and strip casting. NdFeB alloy is composed of 72% iron, 27% neodymium, and 1% boron from boron carbide (Sprecher et al., 2014). In order to stop free iron from forming, a small amount of iron formed between NdFeB crystals, the alloy is cooled very rapidly from a molten to a solid state via strip casting. A mixture of Nd, Fe, and B is melted in an induction furnace and then poured over a spinning copper wheel that is water cooled. It is estimated that approximately 1.32E-01 MJ is absorbed by the cooling water and it is assumed that the change in water temperature ranges between 5 and 10 degrees C. The alloy on contact with the wheel solidifies instantly and flies off into flakes ranging from 2mm to 7cm in length (Sprecher et al., 2014). Next, NdFeB flakes are exposed to hydrogen in hydrogen decrepitation, which form a hydride and expands in volume, causing the alloy to crack and form finer particles.

Subsequent to this process, jet milling is used. The NdFeB particles are fed into a cylindrical grinding chamber using compressed gas that forms a vortex and grinds the particles even further (Sprecher et al., 2014). The NdFeB powder is collected and poured into a mold and aligned using a short 4-8 magnetic pulse (Sprecher et al., 2014). Die pressing is assumed to be utilized at this stage, where the powder is put in a mold and pressed from the sides mechanically. The aligned and pressed NdFeB blocks are vacuum-sintered at pressures of 2-10 mbar and at a temperature of 1000 degrees C, where 1kg of NdFeB alloy requires 2.4 kWh of electricity (Sprecher et al., 2014). Any remaining hydrogen is removed at this stage. All other flows for vacuum sintering are taken from ecoinvent process, "sinter, iron, at plant" (Sprecher et al., 2014; Classen et al., 2009). The sintered block of NdFeB alloy is then sliced, ground, and polished. Depending on the shape of the magnet, grinding losses will vary. If a reference flow of 1kg NdFeB magnet is a solid block, there are no losses. Permanent magnets similar in shape to a hard disk drive (HDDs) can have losses up to 40% (Sprecher et al., 2014). The lost material during grinding can be recycled, ranging from 0 to 100% of lost material recovered for reuse. For the final step in the process, the NdFeB magnets are assumed to have a nickel coating applied via electroplating. Approximately 0.068 m^2 of nickel coating is required per 1 kg of magnet. All flows for electroplating were taken from Moing et al. (2009). The unit process for NdFeB permanent magnet manufacturing that is describes prior is illustrated as a flow diagram in **Figure 1**.

Figure 1: Unit Process Scope and Boundary

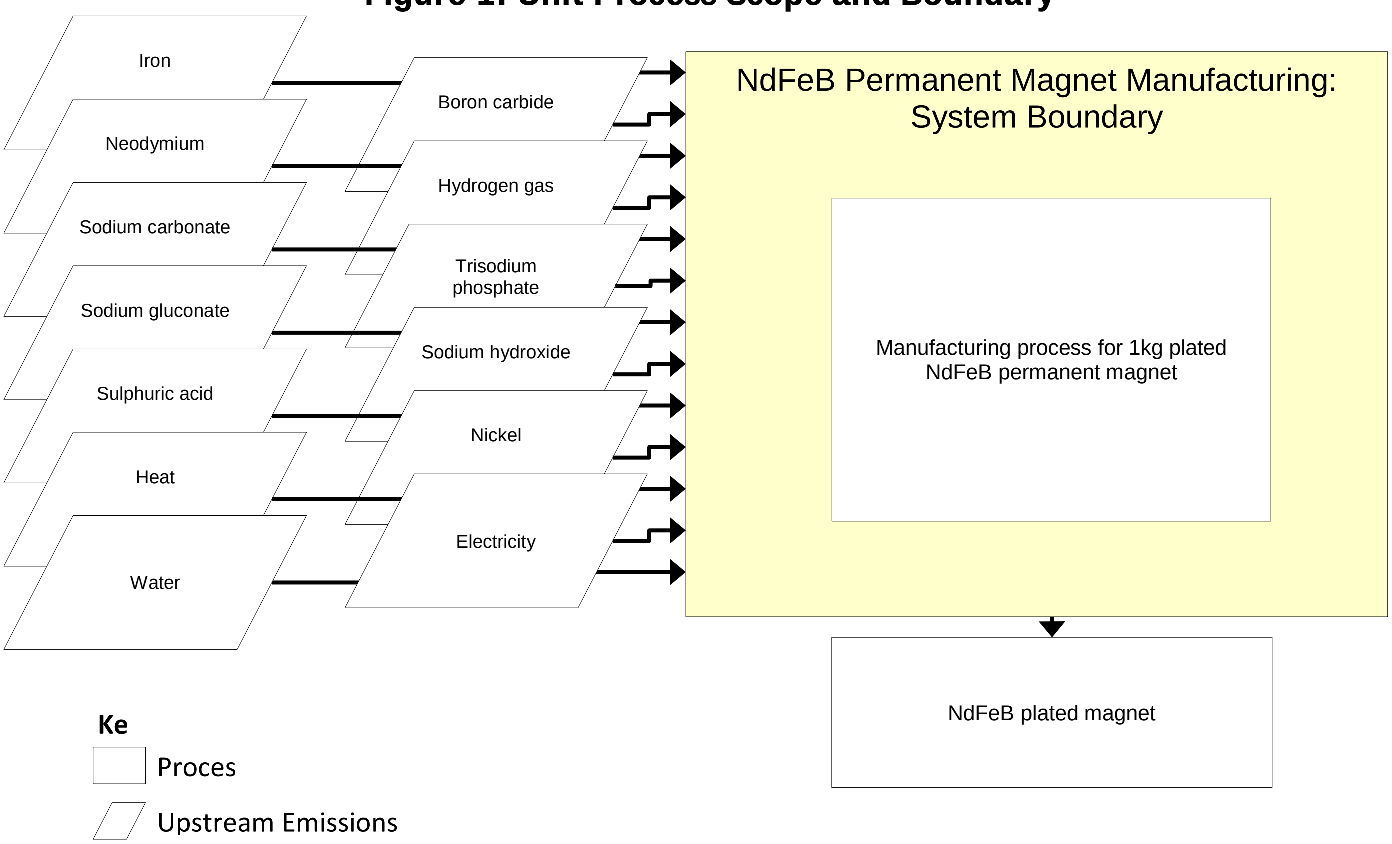

Table 2: Unit Process Input and Output Flows, 30% Electroplating Loss Rate, 30% Grinding and Slicing Loss Rate, and 50% Grinding and Slicing Recycling Rate

Flow Name	Value	Units (Per Reference Flow)
Inputs		
Iron [Intermediate]	1.47E+00	kg
Boron carbide [Intermediate]	2.61E-02	kg
Neodymium [Intermediate]	5.51E-01	kg
Hydrogen gas [Intermediate]	8.78E-01	kg
Sodium carbonate [Intermediate]	9.71E-05	kg
Trisodium phosphate [Intermediate]	1.94E-04	kg
Sodium gluconate [Intermediate]	2.33E-04	kg
Sodium hydroxide [Intermediate]	4.86E-04	kg
Sulphuric acid [Intermediate]	1.79E-03	kg
Nickel [Metals] [Intermediate]	1.36E-01	kg
Heat [Intermediate]	1.13E+01	MJ
Electricity [Intermediate]	8.22E+00	kWh
Water [unspecified]	8.83E+00	kg
Outputs		
NdFeB plated magnet [Intermediate product]	1.00E+00	kg
Waste heat [Other]	3.14E+00	MJ
Dust (PM2.5) [Particles to air]	4.20E-04	kg
Cadmium (+II) [Heavy metals to air]	3.94E-08	kg
Copper (+II) [Heavy metals to air]	1.56E-07	kg
Mercury (+II) [Heavy metals to air]	1.54E-07	kg
Manganese (+II) [Heavy metals to air]	3.94E-07	kg
Nickel (+II) [Heavy metals to air]	5.48E-06	kg
Lead (+II) [Heavy metals to air]	6.59E-06	kg
Titanium [Heavy metals to air]	3.27E-08	kg
Vanadium (+III) [Heavy metals to air]	2.35E-08	kg
Zinc (+II) [Heavy metals to air]	1.69E-06	kg
Hydrochloric acid [Inorganic emission to air]	7.67E-05	kg
Hydrogen fluoride [Inorganic emissions to air]	4.59E-06	kg
Nitrogen oxides [Inorganic emissions to air]	1.08E-03	kg
Sulphur dioxide [Inorganic emissions to air]	2.57E-03	kg
Carbon monoxide [Inorganic emissions to air]	5.24E-02	kg
Carbon dioxide [Inorganic emissions to air]	4.16E-01	kg
NMVOC (unspecified) [Group NMVOC to air]	2.82E-04	kg
Polycyclic aromatic hydrocarbons (carcinogenic) [Group PAH to air]	9.63E-10	kg
Polychlorinated biphenyls (PCB unspecified) [Halogenated organic emissions to air]	1.31E-11	kg

Dioxins, measured as 2,3,7,8-tetrachlorodibenzo-p-dioxin [unspecified]	1.43E-11	kg
NdFeB scrap [Solid waste]	3.06E-01	kg
Nickel (+II) [Heavy metals to fresh water]	1.55E-06	kg
Nickel chloride [Inorganic emissions to fresh water	9.71E-05	kg
Boric acid [Inorganic emissions to fresh water]	2.91E-04	kg
Sodium saccharinate [Organic emissions to fresh water]	4.86E-05	kg
Waste water - untreated [Production residues in life cycle]	7.03E+00	kg

* **Bold face** clarifies that the value shown *does not* include upstream environmental flows.

Embedded Unit Processes

None.

References

Classen et al. (2009) — Classen M., Althaus H.-J., Blaser S., Tuchschmid M., Jungbluth N., Doka G., Faist Emmenegger M., and Scharnhorst W. (2009). Life cycle inventories of metals. Final report ecoinvest data v2.1, No 10. EMPA Dubendorf, Swiss Centre for Life Cycle Inventories, Dubendorf, CH, www.ecoinvent.ch

Moing et al. (2009) — Moing A., Vardelle A., Legoux J., Themelis N.J. (2009). LCA comparison of electroplating and other thermal spray processes. National Research Council Canada. http://nparc.cisti-icist.nrc-cnrc.gc.ca/npsi/ctrl?action=rtdoc&an=17118277&lang=fr. Last Accessed: July 9, 2014.

Sprecher et al. (2014) — Sprecher B., Xiao Y., Walton A., Speight J., Harris R., Klein R., Visser G., and Kramer G.J. (2014). Life cycle inventory of the production of rare earths and the subsequent production of NdFeB rare earth permanent magnets. ACS Publications. dx.doi.org/10.1021/es404596q. Environ. Sci. Technol.

Section III: Document Control Information

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Section IV: Disclaimer