NETL Life Cycle Inventory Data
Process Documentation File

Process Name: Chromium products

Reference Flow: 1 kg of chromium product

Brief Description: Production of chromite, high-carbon ferrochromium, or chromium metal

Section I: Meta Data

Geographical Coverage: Various **Region:** Various

Year Data Best Represents: 2005

Process Type: Manufacturing Process (MP)

Process Scope: Cradle-to-Gate Process (CG)

Allocation Applied: No

Completeness: Individual Relevant Flows Recorded

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:

None

Tracked Input Flows:

Electricity	*[Technosphere] Electricity*
Water (municipal)	*[Technosphere] Treated water*
Water (ground water)	
Explosives	*[Technosphere] Explosives for mining*
Diesel, combusted	*[Technosphere] Fuel for operations*

Heavy fuel oil, combusted	*[Technosphere] Fuel for operations*
Natural gas, combusted	*[Technosphere] Fuel for operations*
Liquid petroleum gas, combusted	*[Technosphere] Fuel for operations*
Light fuel oil, combusted	*[Technosphere] Fuel for operations*
Flocculant	*[Technosphere] Unspecified flocculant*
Coal	*[Technosphere] Unspecified coal*
Coke, imported	*[Technosphere] Imported coal-coke*
Coke, local	*[Technosphere] Locally sourced coal-coke*
Char	*[Technosphere] Char biomass fuel*
Anthracite	*[Technosphere] Unspecified anthracite*
Silica sand	*[Technosphere] Unspecified sand*
Electrode paste	*[Technosphere] Unspecified electrode paste*
Thermal energy (MJ)	*[Technosphere] Thermal energy from any fuel source for rotary kiln*
Soda ash	*[Technosphere] Soda ash*
Sulfuric acid	*[Technosphere] Sulfuric acid – 100%*
Sulfur	*[Technosphere] Elemental sulfur*
Aluminum	*[Technosphere] Un-alloyed aluminum*

Tracked Output Flows:

Chromite concentrate	*Reference flow – mineral concentrate (95% chromite, 44% Cr)*
Ferrochromium	*Reference flow – High-carbon ferrochromium (56.7% Cr)*
Chromium	*Reference flow – Refined chromium metal (99% Cr)*
Tailings, from chromite beneficiation	*Mixed water/solids waste*
FeCr slime	*Mixed water/solids waste*
Slag	*Solid waste*
Iron (III) oxide	*Potential co-product*
Sodium sulfate	*Potential co-product*
Aluminum oxide	*Potential co-product*

Section II: Process Description

Associated Documentation

This unit process is composed of this document and the data sheet (DS) *DS_Stage12345_M_chromium_products_2016.01.xlsx*, which provides additional details regarding relevant calculations, data quality, and references.

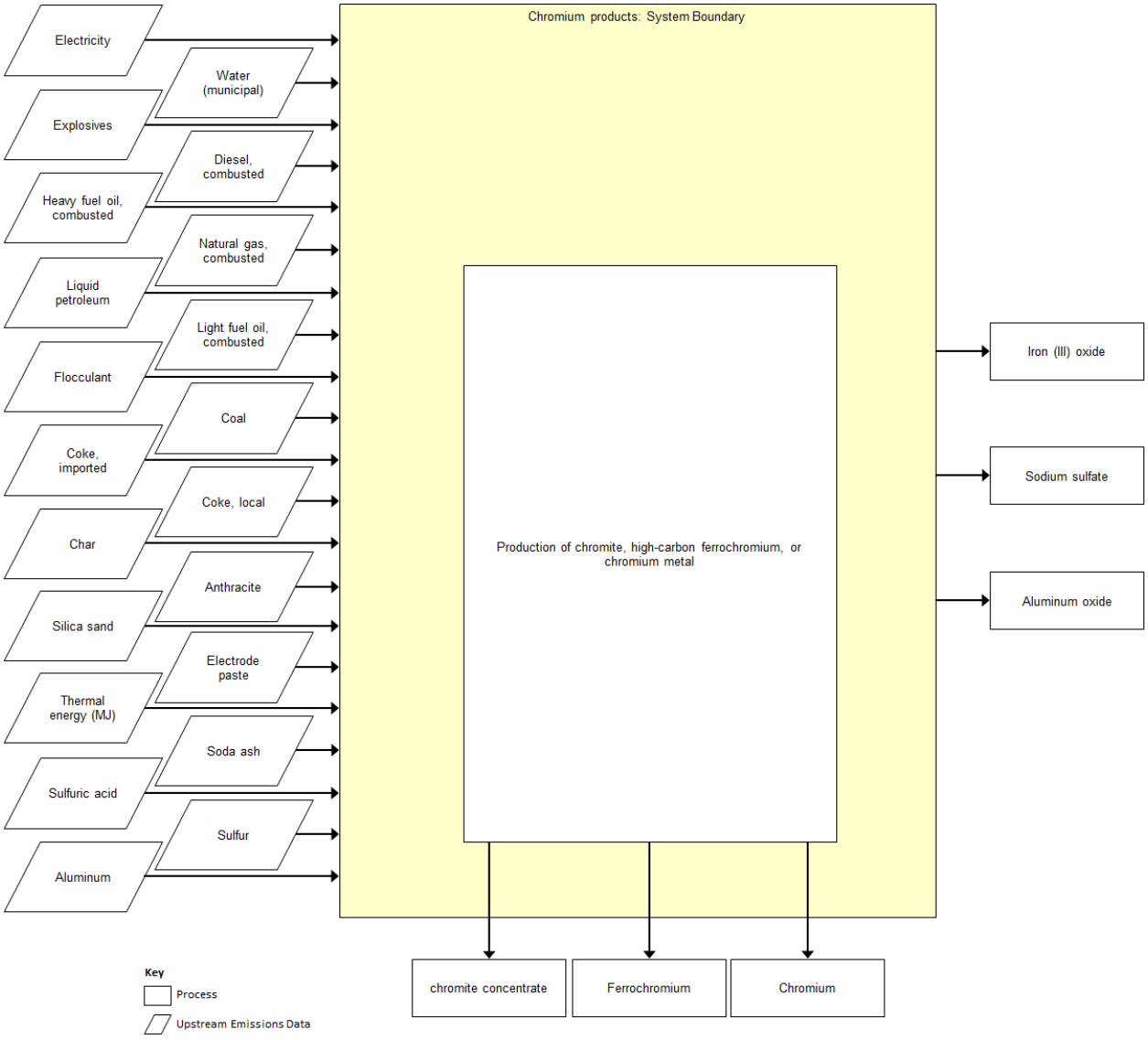
Goal and Scope

This unit process provides a summary of relevant input and output flows associated with the production of chromite, high-carbon ferrochromium, or chromium metal. Aggregated processes include underground mining, surface mining, and beneficiation of chromite; open-furnace and closed-furnace smelting for high-carbon ferrochromium production; and aluminothermic process for chromium metal production.

Boundary and Description

Figure 1 provides an overview of the boundary of this unit process. Rectangular boxes represent relevant sub-processes, while trapezoidal boxes indicate upstream data that are outside of the boundary of this unit process. As shown, the upstream emissions from the electricity, sulfuric acid, and other trapezoidal boxes are calculated in another unit process. The methods for calculating these operating activities are described below.

Figure 1: Unit Process Scope and Boundary



This unit process can provide three different products: chromite concentrate, high-carbon ferrochromium, and chromium metal. Chromite is a mineral and the main source of chromium. High-carbon ferrochromium is the primary chromium product globally and is primarily used as an alloying agent in stainless steel. Chromium metal is used in other alloying applications.

This cradle-to-gate unit process aggregates the processes and thus materials and energy necessary to create each of the chromium products. For example chromium metal will include the mining and beneficiation in addition to the processes required to refine chromite into chromium metal.

The data for mining, beneficiation, and smelting came from data compiled for a report sponsored by the International Chromium Development Association (PE International,

2007). Within the report, they detail gate-to-gate inputs, products, and emissions for underground mining, surface mining, beneficiation, and three variations of smelting. All 5 of these gate-to-gate profiles are individually represented in the spreadsheet. When processes need to be connected (e.g., underground mining to beneficiation to open-furnace smelting), they are connected through the parameter scenarios (PS) tab. The philosophy behind this process is that this UP can be used to generate a profile for the different pathways for chromium. The complete system can be modeled externally, and the complete life cycle inventory can be multiplied by the percentages in **Table 1** to provide an average profile. As shown in **Table 1**, the majority of chromite mining is underground, so all of the smelter scenarios (and the chromium metal) are only connected to underground mining.

The production of refining chromium metal was modeled using descriptions of the process and the chemical reactions. The aluminothermic reaction is the modeled process as it represents 95% of the global chromium metal production with electrolytic making up the remainder (USGS, 2011). In preparation for the actual aluminothermic process, chromium (III) oxide is created by first separating the chromium from the iron by roasting the chromite with soda ash in a rotary kiln, creating sodium chromate. This sodium chromate is converted to sodium dichromate by mixing with sulfuric acid, and then the sodium dichromate is calcined with sulfur to yield chromium (III) oxide. The roasting and calcination processes both require heat. It is assumed that the amount of heat required is equal to the activation energy for the specific chemical reactions. While a source for the roasting activation energy could be found, the activation energy for calcining could not be found, so it is assumed to the same as the roasting reaction. Further there will be some efficiency associated with transferring that heat to facilitate the reaction. The efficiency for a rotary kiln was calculated using the activation energy for converting limestone to quicklime (3.16 GJ/Mg) and the average heat input to long dry kilns (5.23 GJ/Mg) giving an efficiency of 60.4%.

Judging from the available material, there is no heat input required for the aluminothermic reaction, as the heat for the reaction initially comes from igniting a mixture of aluminum and barium peroxide which provides the heat necessary to trigger the exothermic reaction reducing Cr_2O_3 to Cr and also Al to Al_2O_3.

Table 1: Production splits for high-carbon ferrochromium pathway

Processes	Share of production
Mining	
Underground	82.8%
Surface	17.2%
Smelting	
Open furnace	44.4%
Closed furnace, no preheat	18.6%
Closed furnace, preheat	36.9%

Table 2: Unit Process Input and Output Flows

Flow Name	Chromite concentrate from underground	Chromite concentrate from surface mining	Open furnace ferrochromium	Closed furnace, no preheat ferrochromium	Closed furnace, w/ preheat ferrochromium	Chromium metal	Units (Per Reference Flow)
Inputs							
Electricity [Electric power]	**7.50E-02**	**8.30E-02**	**4.45E+00**	**4.42E+00**	**3.53E+00**	**1.61E-01**	**kWh**
Water (municipal) [Water]	**1.75E+00**	**1.20E+00**	**5.99E+00**	**3.42E+00**	**3.94E+00**	**3.78E+00**	**kg**
Water (ground water) [Water]	1.22E+00	3.06E+00	5.29E+00	5.27E+00	5.84E+00	3.91E+00	kg
Water (surface water) [Water]	1.22E+00	3.06E+00	5.29E+00	5.27E+00	5.84E+00	3.91E+00	kg
Explosives [Operating materials]	**5.00E-04**	**2.00E-03**	**1.10E-03**	**9.75E-04**	**1.02E-03**	**1.08E-03**	**kg**
Diesel, combusted	**2.70E-04**	**2.70E-04**	**7.06E-02**	**9.27E-04**	**3.05E-03**	**5.81E-04**	**kg**
Heavy fuel oil, combusted	**1.90E-04**	**1.90E-04**	**4.16E-04**	**3.71E-04**	**3.86E-04**	**4.09E-04**	**kg**
Natural gas, combusted	**2.10E-04**	**2.10E-04**	**4.60E-04**	**4.10E-04**	**4.26E-04**	**4.52E-04**	**kg**
Liquid petroleum gas, combusted	**1.20E-04**	**1.20E-04**	**2.63E-04**	**2.34E-04**	**2.44E-04**	**2.58E-04**	**kg**
Light fuel oil, combusted	**1.12E-03**	**1.11E-02**	**2.45E-03**	**2.18E-03**	**2.27E-03**	**2.41E-03**	**kg**
Flocculant	**1.30E-05**	**1.30E-05**	**2.85E-05**	**2.54E-05**	**2.64E-05**	**2.80E-05**	**kg**
Coal	**0.00E+00**	**0.00E+00**	**1.58E-01**	**2.10E-01**	**2.60E-02**	**0.00E+00**	**kg**
Coke, imported	**0.00E+00**	**0.00E+00**	**1.34E-01**	**1.91E-01**	**1.27E-01**	**0.00E+00**	**kg**
Coke, local	**0.00E+00**	**0.00E+00**	**1.30E-01**	**7.90E-02**	**1.72E-01**	**0.00E+00**	**kg**
Char	**0.00E+00**	**0.00E+00**	**1.10E-01**	**1.23E-01**	**2.45E-01**	**0.00E+00**	**kg**
Anthracite	**0.00E+00**	**0.00E+00**	**4.00E-02**	**9.10E-02**	**4.10E-02**	**0.00E+00**	**kg**
Silica sand	**0.00E+00**	**0.00E+00**	**2.20E-01**	**2.20E-01**	**2.20E-01**	**0.00E+00**	**kg**
Electrode paste	**0.00E+00**	**0.00E+00**	**1.50E-02**	**2.00E-02**	**1.00E-02**	**0.00E+00**	**kg**
Thermal energy	**0.00E+00**	**0.00E+00**	**0.00E+00**	**0.00E+00**	**0.00E+00**	**5.41E+03**	**kJ**
Soda ash	**0.00E+00**	**0.00E+00**	**0.00E+00**	**0.00E+00**	**0.00E+00**	**2.04E+00**	**kg**
Sulfuric acid	**0.00E+00**	**0.00E+00**	**0.00E+00**	**0.00E+00**	**0.00E+00**	**9.43E-01**	**kg**
Sulfur	**0.00E+00**	**0.00E+00**	**0.00E+00**	**0.00E+00**	**0.00E+00**	**3.08E-01**	**kg**
Aluminum	**0.00E+00**	**0.00E+00**	**0.00E+00**	**0.00E+00**	**0.00E+00**	**5.19E-01**	**kg**

Flow Name	Chromite concentrate from underground	Chromite concentrate from surface mining	Open furnace ferrochromium	Closed furnace, no preheat ferrochromium	Closed furnace, w/ preheat ferrochromium	Chromium metal	Units (Per Reference Flow)
Outputs							
chromite concentrate	**1.00E+00**	**1.00E+00**	**0.00E+00**	**0.00E+00**	**0.00E+00**	**0.00E+00**	**kg**
Ferrochromium	**0.00E+00**	**0.00E+00**	**1.00E+00**	**1.00E+00**	**1.00E+00**	**0.00E+00**	**kg**
Chromium	**0.00E+00**	**0.00E+00**	**0.00E+00**	**0.00E+00**	**0.00E+00**	**1.00E+00**	**kg**
Tailings, from chromite beneficiation	6.80E-01	6.80E-01	1.49E+00	1.33E+00	1.38E+00	1.46E+00	kg
FeCr slime	0.00E+00	0.00E+00	1.20E-01	1.10E-01	1.10E-01	0.00E+00	kg
Slag	0.00E+00	0.00E+00	1.45E+00	1.58E+00	1.62E+00	0.00E+00	kg
Iron (III) oxide	**0.00E+00**	**0.00E+00**	**0.00E+00**	**0.00E+00**	**0.00E+00**	**7.68E-01**	**kg**
Sodium sulfate	**0.00E+00**	**0.00E+00**	**0.00E+00**	**0.00E+00**	**0.00E+00**	**2.73E+00**	**kg**
Aluminum oxide	**0.00E+00**	**0.00E+00**	**0.00E+00**	**0.00E+00**	**0.00E+00**	**9.80E-01**	**kg**
Wastewater	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.73E-01	kg
Carbon dioxide [Inorganic emissions to air]	0.00E+00	0.00E+00	1.53E+00	1.68E+00	1.51E+00	8.46E-01	kg
Chromium (unspecified) [Heavy metals to fresh water]	1.10E-08	1.10E-08	2.41E-08	2.15E-08	2.23E-08	2.37E-08	kg
Chromium (+III) [Heavy metals to air]	0.00E+00	0.00E+00	3.50E-04	0.00E+00	0.00E+00	0.00E+00	kg
Chromium (+VI) [Heavy metals to air]	0.00E+00	0.00E+00	3.00E-07	0.00E+00	0.00E+00	0.00E+00	kg
Lead [Heavy metals to air]	0.00E+00	0.00E+00	1.10E-06	1.10E-06	1.10E-06	0.00E+00	kg
Manganese [Heavy metals to air]	0.00E+00	0.00E+00	1.50E-06	1.50E-06	1.50E-06	0.00E+00	kg
Cadmium [Heavy metals to air]	0.00E+00	0.00E+00	1.40E-08	1.40E-08	1.40E-08	0.00E+00	kg
Vanadium [Heavy metals to air]	0.00E+00	0.00E+00	7.60E-10	7.60E-10	7.60E-10	0.00E+00	kg
Dust (unspecified) [Particles to air]	0.00E+00	0.00E+00	3.80E-03	4.80E-03	4.80E-03	0.00E+00	kg
Zinc [Heavy metals to air]	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.10E-03	0.00E+00	kg

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

Embedded Unit Processes

None.

References

PE International. (2007). Life Cycle Inventory (LCI) update of primary Ferrochrome production. Leinfelden-Echterdingen, DE. http://www.icdacr.com/publication/hse/LCI/ICDAFinalReportLCI2005.pdf

USGS. (2011). *2009 Minerals Yearbook: Chromium*. United States Geological Service. Retrieved from http://minerals.usgs.gov/minerals/pubs/commodity/chromium/myb1-2009-chrom.pdf.

Section III: Document Control Information

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