INSULATING REFRACTORIES AS AN ENABLER TO CARBON SUSTAINABILITY DEMONSTRATED THROUGH LIFE CYCLE ASSESSMENT

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ABSTRACT

Legislation and market forces are necessitating an increasing range of products to declare their environmental impact, reverberating down the supply chain. This paper discusses the cradle-to-gate Life Cycle Assessment (LCA) for insulating refractories, including the challenges of obtaining accurate raw material data and attributing Scope 1 and Scope 2 emissions to individual products. Insulating refractory products reduce the amount of carbon emissions from thermal processes, a methodology of differentiating between best-in-class and consumer grades is presented. This utilises heat flow models, and fuel carbon intensity calculations over the full expected lifetime of a refractory lining.

DRIVING FORCES FOR MEASURING CARBON FOOTPRINT THROUGH LIFE CYCLE ASSESSMENT

According to the United Nations Intergovernmental Panel on Climate Change (UN IPCC), climate change is causing global temperatures to increase[1], resulting in rising sea levels, and more frequent extreme weather events. The principal cause of global warming is the rise in man-made greenhouse gas (GHG) emissions.

Legislation is pushing the need to measure and declare an increasingly detailed amount of environmental impact data. Over the past several years and in many jurisdictions, there has been the requirement that the company's annual directors report must contain energy use and greenhouse gas emissions[2,3]. Recently, the EU introduced the Carbon Border Adjustment Mechanism (CBAM)[4] , which is a tool to put a fair price on the carbon emitted during the production of carbon-intensive goods that are entering the EU, and to encourage cleaner industrial production in non-EU countries. The CBAM will initially apply to imports of certain goods and selected precursors whose production is carbon intensive and at the most significant risk of carbon leakage: cement, iron and steel, aluminium, fertilisers, electricity, and hydrogen. These and other legislations are requiring companies to track, in detail, their Scope 1 (direct), Scope 2 (indirect energy emissions) and, increasingly Scope 3 (other indirect) environmental emissions. Knowledge of the environmental impact of raw materials and components is required for the accurate calculation of Scope 3.

As stakeholders' opinions shift towards a more vital environmental consciousness, it becomes critical for companies to prioritise sustainability against the three pillars of: environmental, social and governance (ESG). Therefore, a company cannot solely focus on one pillar (e.g., focusing on governance goals solely while disregarding environmental impact). Doing so may be profitable in the short term but detrimental to the company's long-term viability as regulatory penalties, investor or other stakeholder interests and public opinion can negatively impact the company. By contrast, every company will have an environmental footprint, and there is a limit to reducing the impact of that footprint before the price becomes so large that it impacts the governance pillar. As public concern grows, more customers ask about industries GHG emissions as part of the manufacturing process and request information on products' environmental impacts.

The above factors are driving the need for the measurement and declaration of the environmental impact of their products. Refractories are no exception to this. In fact, their influential role in the production of carbon-intense goods mentioned in CBAM, put them in a group of high-interest materials. The process for measuring the environmental impact of a product is called Life Cycle Assessment.

LIFE CYCLE ASSESSMENT PROCESS

Life Cycle Assessment (LCA) is a systematically analyses the environmental impacts across a product's life[5]. The beginning of a refractory materials life is mineral extraction at many separate mines, followed by transportation and a first round of manufacturing steps. These intermediate products then undergo more transportation and get used by the refractory producer as raw materials in further manufacturing steps. When the product reaches the end user, it may have gone through numerous manufacturing and transportation stages. The product is then used, maintained, and eventually recycled or disposed of. The summation of the environmental impact, in numerous categories, across all these steps comprises the LCA.

A complete assessment of manufacturing a product, its use and recycling are referred to as "cradle-to-cradle" see Figure 1. An assessment including manufacturing and use, but not recycling is called "cradle-to-grave". An assessment of only the manufacturing level is called a "cradle-to-gate" assessment. Cradle-to-gate refers to all environmental impacts associated with a product until it leaves the refractory manufacturer's site; it includes the impact of:

- Raw materials
- Transportation of raw materials from the last manufacturing / processing site
- Manufacturing impacts

Environmental impact encompasses many categories, including, but not limited to: climate change (CO_2e) -often referred to as carbon footprint, ozone depletion, acidification, and resource use, to name a few out of more than 20 categories usually tracked.

To ensure uniformity in approach and comparison between manufacturers and industries, numerous standards cover the process such as ISO 140406, ISO 140447, EN 15804+A28.

Fig. 1: the LCA process

LIFE CYCLE ASSESSMENT FOR REFRACTORIES

Below, a Cradle-to-Gate Life Cycle Assessment is discussed on materials from Morgan Advanced Materials. The Cradle-to-Gate method is selected because it is currently problematic for a manufacturer to predict use and disposal / recycling due to the myriad uses of each refractory, the high impact of various applications in different use environments (eg. Glass, Iron & Steel, Energy production, Petrochemicals, Ceramics.) on lifetime and variability in end of life due to contamination. As more industries adopt LCA, this will resolve by the integration of multiple assessments. The order and detail of the steps below are not intended to be instructional or comprehensive. Instead, they are intended to highlight some of the important considerations and challenges experienced with specific reference to refractories.

Software to calculate, analyse and present LCA

Multiple companies offer software and support for calculating Life Cycle Assessment. Most of these integrate databases of the environmental impact of standard raw materials, packaging, transportation, water usage, waste disposal and Scope 1 and Scope 2 emissions. The user interface guides the entry of data in the categories mentioned below and automatically generates a Life Cycle Assessment. Often the software has tools to help the user understand which materials or process steps have the largest impact. In the below assessment, Ecochain Helix[6] cloud-based LCA software tool was used, with integrated Ecoinvent v6.3 database. The quality and accuracy of the software output is highly dependent on the input's quality and accuracy; careful verification is required to avoid inappropriate selection of raw materials or order of magnitude errors in mass or energy allocations. To ensure sufficient LCA quality, adherence to the previously mentioned standards[6,7,8] is imperative.

Raw Material Environmental Impact.

In the best-case scenario, the raw material suppliers can provide a Cradle-to-Gate LCA on each raw material. Currently for the specialist minerals grades used in refractory production, such information is quite rare. An alternative is using a standard materials database, such as Ecoinvent V6.3. Whilst these are very large and powerful, it is not always easy to identify the most appropriate entry. Common materials, such as Alumina, have many entries, some with similar descriptions and maybe none exactly matching to a specialist grade used in refractories. Where no close match can be found, read across from analogous product, or the combination of a base material with a process step can be used, e.g. a calcination step could be combined with a standard Alumina to yield the environmental impact data for calcined alumina. More complexity can result where the raw material is from a recycled source or is a by-product of another process. Detailed rules for considering these are available in relevant standards and texts[5,8]. For some refractories such as castables (see below), the raw materials constitute the majority of the finished product's environmental impact; therefore, errors in the supplier data can be very significant in the accuracy of Cradle-to-Gate LCA.

Environmental impact of transportation.

In a cradle-to-gate LCA, the manufacturer must include the impact of all materials being transported to their site and waste removed. This will vary by distance and type / efficiency of vehicle used, e.g. truck type, size, Euro emissions rating and loading factor. The most accurate data for this would come from an LCA that had been carried out on that type of Vehicle (giving climate change potential per km per kg of material transported). Where this is not available, standard databases can provide relevant data. Generally, transportation is only a small component of refractory production, this is due to the high packing density of raw materials and the relatively high energy intensity of extraction and manufacturing steps.

Emissions from energy used in manufacturing

It is required to consider both direct emissions, Scope 1, e.g. from burning natural gas, fuel oil, diesel etc. and Scope 2, where the energy is used on-site, but the emissions are made elsewhere, e.g. electricity. For Scope 1, it should be noted that in the calculation of the LCA, the environmental impact will be higher than that for just fuel combustion. This is because it is also necessary to include the fuel's life cycle, including its extraction, refining and transportation. This data can be taken from a supplier who has performed an LCA, or from a standard database. For Scope 2, many electricity suppliers do provide the carbon intensity of the supplied power (calculated through LCA). Although databases do have standard entries by geographic region, these are of limited use as each energy supplier will have its own, ever-changing mix of electricity sources, some with higher or lower environmental impact. Even where a manufactures electricity comes from a 100% renewable source, the LCA will need to considered contributions from the manufacture of the production unit, its operation and electricity transmission etc.

Emissions from process releases

Many processes in refractory manufacturing may lead to direct process emissions, such as CO_2 from calcination of carbonates. These need to be accurately calculated and included in the LCA. Other factory and office releases such as refrigerants, have a very high environmental impact by mass, so the amount used on a site needs careful monitoring and allocation. Waste and water leaving the site are also environmental emissions and need to be accounted.

Allocation of resources to products

Presuming a manufacturing facility has multiple production lines and products, it is necessary to map all raw material and energy use onto those lines and products. Where there is metering and logging on each process, this can be a relatively simple task of data enquiry. A system for fair allocation will be required where metering covers multiple processes or lines.

Calculation and reporting of LCA.

Once the raw materials have been identified, the transportation distances and methods measured, the energy sources identified, and each allocated to a process and product, then the LCA can be calculated. This is a mathematical process of ratioing the environmental impact of each input by the amount used to manufacture the product. Often it is easiest to calculate the LCA of a product in environmental impact per kg manufactured. However, end users may often work in terms of per unit area or unit volume of insulation or per box or bag of product purchased. When interpreting a LCA, paying attention to the reporting unit is important.

COMPARISON OF THE OUTPUT OF A LCA ON FIBRE BLANKET, INSULATING FIRE BRICK (IFB) AND LIGHTWEIGHT CASTABLE

An LCA will report on many environmental impact categories. The most reported and compared is climate change (CO_2e) [EN15804+A2], often called carbon footprint. Figure 2 shows the relative climate change CO_2e for 3 typical refractory products as calculated by Ecochain Helix software[9] (the actual values are not revealed as they are not yet verified for publication). The breakdown shows the contribution of raw materials, transportation, and manufacturing. This breakdown and their subcomponents are useful information for targeting improvements in environmental impact of products. It should be noted that this is at the manufacturer's level; at the supplier level, the raw materials themselves could be again subdivided into these 3 categories; this data is not carried through to the final assessment.

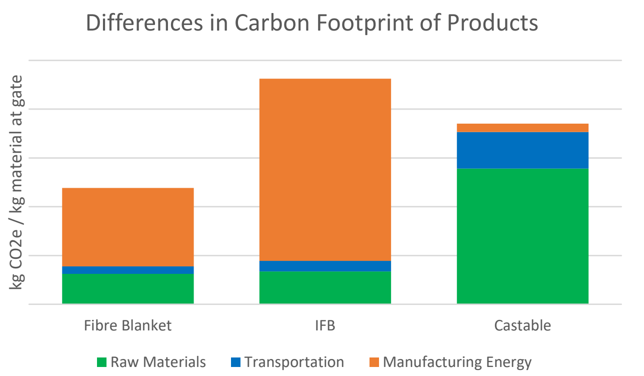

Fig. 2: relative climate change impact of various refractories as calculated by LCA (Cradle-to-Gate).

Figure 2 shows that per kg of product, Fibre blankets are accountable for about half the CO_2e emissions compared to an Insulating Firebrick (IFB), the major difference being the large Scope 1 emissions in firing the IFB compared to the Scope 2 electricity used in melting raw materials for fibres. The Castable has little energy input in manufacturing with the major contributor being the raw materials (although at the supplier level, manufacturing, transport, and process emissions would have contributed most of their cradle-to-gate LCA).

When considering the effect of manufacturing location on LCA, typically the contribution from Scope 1 emissions will typically be very stable around the world, barring any variations in process efficiency. Hence the carbon footprint for an IFB from Europe will be largely similar to one from America. This is not necessarily the case for Scope 2 emissions; a fibre blanket from a country with predominantly green electricity may have a significantly lower carbon footprint than one from a country generating electricity from mostly fossil fuels.

IMPACT OF REFRACTORY SELECTION ON PROCESS EFFICIENCY AND CARBON EMISSIONS

The selection of grade, quality, and thickness of an insulating refractory lining will greatly influence the efficiency of any high-temperature process and hence the environmental impact of any product manufactured by that process. Heat flow calculation, combined with the fuel cost and carbon footprint can demonstrate the payback of a lining selection, both financially and environmentally. Figure 3 compares three options for insulation on the walls of an ethylene cracker operating at 1250ºC. Originally "Consumer grade" fibre refractories were installed; the customer was not happy with the heat loss; this is shown in the "Existing Lining" scenario. Two alternative systems were proposed, to prove performance, the customer chose to have both installed in different regions of the walls. System 1 comprises best-in-class Pyro-Bloc®[10] fibre modules and Superwool® Plus fibre blankets[11]. System 2 comprises the Pyro-Bloc with ultra-low thermal conductivity WDS® microporous board[12] replacing the fibre blanket. Figure 3 shows for each scenario a thermal image scan of the outside casing, and a thermal calculation using Morgan Heat Flow[13] calculator.

Using the supplier data for the "Consumer grade" refractory, the outside casing was calculated to have a temperature of 123ºC and a heat loss of 1400W/m^2. In actuality, the thermal imaging showed the temperature, and hence heat loss to be even higher. With System 1, the casing was calculated to have a temperature of 104ºC and a heat loss of 1041W/m^2, this was found to be accurate within measurement error. For system 2, the casing was calculated to have a temperature of 82ºC and a heat loss of 663W/m^2, again the thermal imaging demonstrated the accuracy of the calculation.

Figure 4 shows a lifetime performance comparison of the three linings using, Morgan's Thermal Efficiency and CO_2 Emissions (TECE) calculator software[14]. This calculates financial and environmental impacts over a 16-year life and gives a payback period in comparison to the existing lining. Typical market prices for the refractory, natural gas and carbon credits are used, as shown in the figure.

The TECE predicts that over the lifetime of the ethylene cracker wall lining (700m^2), the use of Pyro-Bloc and WDS instead of "Consumer grade" refractories would save 13,000 tons of CO_2 emissions and €3.9 Million in natural gas and carbon credits (based on 0.04€/kWh for natural gas and €85/ ton of CO_2). The upgrade in lining would have a payback period of 6 months. A future revision to the TECE, will take the carbon footprint from LCA (once available) and calculate a carbon payback time.

CONCLUSIONS

Legislation and customer demand increasingly require all products, including refractories, to declare their environmental impact. The method for calculating this is through Life Cycle Assessment (LCA), for which there are defined standards. For refractories, there are complexities in calculation resulting from the use of specialist raw materials, which may not have had LCA performed upon them and for which it is not easy to identify analogous materials in standard databases. Where uncertainty exists in material flow and facility metering, emissions from manufacturing may be hard to map. The scope 2 emissions of electricity used in production can be location dependent; hence the LCA for refractory products consuming a large proportion of electricity in manufacture may vary by geography. An LCA informs consumers about the environmental impact of a product and the manufacturer about which components have the largest influence on emissions. Thermal heat flow calculations combined with the cost and environmental impact of fuels can be used to demonstrate the payback time of additional high-quality insulation. Once LCAs are available on refractory materials, the environmental payback times can also be calculated

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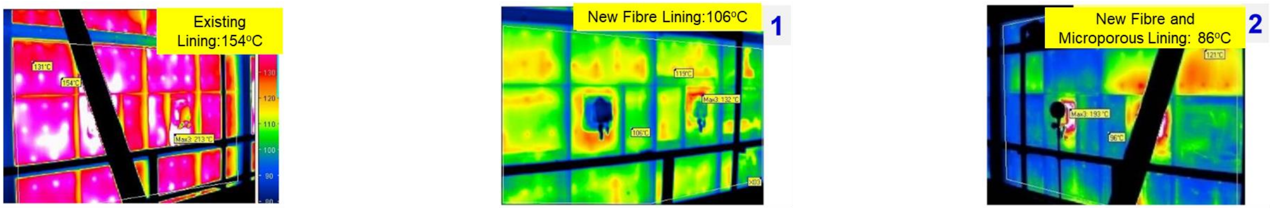

Existing scenario	**New lining – System 1**	**New lining – System 2**
200mm Lining:	200mm Lining:	200mm Lining:
• 175mm 160 kg/m³ conventional fibre modules 1430° C	• 175mm **240 kg/m³ Pyro-Bloc** fibre modules 1430° C	• 175mm **240 kg/m³ Pyro-Bloc** fibre modules 1430° C
• 25mm 96 kg/m³ fibre blanket	• 25mm 128 kg/m³ SW fibre blanket	• 25mm **WDS Microporous board**
*(Average casing temperature **154° C**)*	*(Average casing temperature **106° C**)*	*(Average casing temperature **86° C**)*

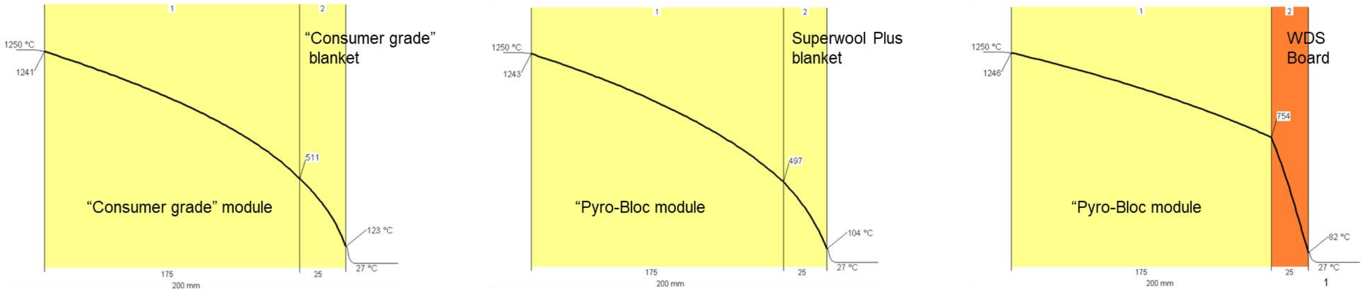

Fig 3 Heat flow calculation of 3 alternative refractory linings for a 1250°C Ethylene cracker wall

Morgan Advanced Materials — Thermal Effficency and CO_2 Emissions (TECE) Calculator, Version 1.6

Settings					
Project Name:	Ethylene Cracker revamp				
Cost of Energy	0.04	EUR €/kWh	Currency	EUR €	
Cost of CO_2	85.00	EUR €/MT	No. of Heat Up	1.0	per Year
Type of Fuel	Natural Gas		Service Life	16.0	Year(s)
CO_2 Coefficient	0.181	kg/kWh	Surface Area	700.0	m²

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Existing Lining			
Hot Face		1250	°C
Cold Face		123	°C
Heat Loss		1400.0	W/m²
Heat Storage		22.0	MJ/m²
Ref.	**Materials**	**Thickness (mm)**	**EUR €/m²**
1	Fibre module 160 kg/m3	175	
2	Blanket 96	25	
3			
4			
5			
6			300
Totals		200	300

System 1			
Hot Face		1250	°C
Cold Face		104	°C
Heat Loss		1041.0	W/m²
Heat Storage		36.2	MJ/m²
Ref.	**Materials**	**Thickness (mm)**	**EUR €/m²**
1	Pyro-Bloc fib. mod. 240k	175	
2	SW blanket 128	25	
3			
4			
5			
6			345
Totals		200	345

System 2			
Hot Face		1250	°C
Cold Face		82	°C
Heat Loss		663.2	W/m²
Heat Storage		50.6	MJ/m²
Ref.	**Materials**	**Thickness (mm)**	**EUR €/m²**
1	Pyro-Bloc fib. mod. 240k	175	
2	WDS Nextra Board	25	
3			
4			
5			
6			470
Totals		200	470

System 3			
Hot Face			°C
Cold Face			°C
Heat Loss			W/m²
Heat Storage			MJ/m²
Ref.	**Materials**	**Thickness (mm)**	**EUR €/m²**
1			
2			
3			
4			
5			
6			
Totals		0	0

Lining	Hot Face	Cold Face	Heat Loss	Heat Storage	Total Mat. Price	Total Thermal Resistance	Energy Loss From Insulation After 16 Years Service			Energy Loss From Heat Storage After 16 Years Service			CO_2 Emissions After 16 Years Service		Total True Cost After 16 Years Service	Payback Period
	°C	°C	W/m²	MJ/m²	EUR €	m² K/W	MJ	kWh	EUR €	MJ	kWh	EUR €	MT	EUR €	EUR €	Years
Existing Lining	1250	123	1400.0	22.0	210,000	0.81	494,484,480	137,356,800	5,494,272	246,400	68,444	2,738	24,874	2,114,287	7,821,297	
System 1	1250	104	1041.0	36.2	241,500	1.10	367,684,531	102,134,592	4,085,384	405,440	112,622	4,505	18,507	1,573,073	5,904,462	0.3
System 2	1250	82	663.2	50.6	329,000	1.76	234,244,362	65,067,878	2,602,715	566,720	157,422	6,297	11,806	1,003,491	3,941,503	0.5
System 3	0	0	0.0	0.0	0	0.00	0	0	0	0	0	0	0	0	0	

Fig 4 Thermal Efficiency and CO_2 Emissions (TECE) calculations for 3 alternative refractory linings for a 1250°C ethylene cracker walls

