

Equilibrium Gasification of Spent Pot lining from the Aluminum Industry

Isam Janajreh¹, Khadije Elkadi¹, Olawale Makanjuola¹, Sherien El-Agroudy²

¹Khalifa University of Science and Technology, Mechanical Engineering Department, Abu Dhabi, UAE

¹AinShams University, Environment Engineering Department, Cairo, Egypt

²Sharjah University, Sustainable and Renewable Energy Department, Sharjah, UAE

Abstract: The notion of reuse, recycle and reduce is suited for almost all streams of solid waste; including municipal solid waste as well as many streams of industrial wastes. Spent potlining (SPL) is a poisonous and potentially explosive solid waste from aluminum industry that defies this general consensus, being hazardous to reuse, non-recyclable, and increasing with over 2Mt annually. In this work, the technical feasibility of gasification of SPL through equilibrium modeling following different levels of treatment (water washed-WWSPL, acid treated-ATSPL, fully treated-FTSPL) is pursued. The model considers 12 species (CO, H₂, CH₄, N₂, NH₃, H₂S, COS, H₂O and Ash) including the molar ratio of the moderator (H₂O) and the oxidizer (O₂) to that of the SPL. The process metrics are assessed via the produced syngas fraction (CO and H₂), gasification efficiency (GE) and in comparison/validation to the gasification of a baseline bituminous coal. The SPL results for each of the WWSPL, ATSPL, FTSPL, respectively, revealed GE of 40%, 65%, and 75% with corresponding syngas (CO & H₂) molar fractions at 0.804 & 0.178, 0.769 & 0.159, and 0.730 & 0.218 at temperatures of 1450 °C, 1100 °C, and 1150 °C. These results suggest the potential and feasibility of gasifying only the treated SPL.

Keywords: Spent potlining; Aluminum waste; Gasification; Syngas

1. Introduction:

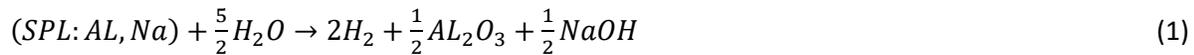
Aluminum industry produces a large amount of industrial solid waste such as the pre-baking anode electrolytic bath and its impermeable silicon carbide additional to electrolyzed slag of the used cathode carbon block and its insulation side to the refractory brick [1]. This waste stream is on the rise in front of the massively growing aluminum industry and either illegally landfilled or stockpiled. In China where 55% of the aluminum industry is located, an increase of SPL waste is reported to grow from 3.41 Mt to 18.06 Mt over ten years period [2]. In aluminum production, alumina is converted to a pure metallic aluminum via electrolytic reduction known as “Hall-Héroult” process. In this process, an electrical current is applied to the carbon anodes cell immersed in the electrolyte bath and passed down to the carbon cathodes at the bottom of the cell. The electrolyte (consists of alumina: Al₂O₃ and cryolite: Na₃AlF₆) is kept in liquid state owing to the high operational temperature near 960 °C [3]. Over an operational period of 3 to 8 years, the cathode becomes polluted with fluoride salts and other process additives that halt its function. This mandates the removal of the carbon cathode “potlining” or SPL and re-lining the shell. It is estimated that the generated amount of the SPL is between 18 and 35kg per ton of alumina; that mounts to nearly 2Mt annually [4,5] with large amounts stockpiled.

This SPL waste stream can be easily separated in two sub-stream known as 1st and 2nd cuts as per Fig.1. The 1st cut is a carbon rich fraction whereas the 2nd cut is non-carbonaceous and consists of the old refractories (SiO₂ and Al₂O₃), insulating bricks and ramming paste. The carbonaceous rich 1st cut has attracted interest as fuel substitute despite its inclusion of hazardous inorganic species (Na₃AlF₆, NaF, CaF₂, Al₂O₃ and NaAl₁₁O₁₇, cyanide compounds, and soluble fluorides). The SPL is listed as hazardous waste by United States Environmental Protection Agency (EPA – D088 [6]). The cyanide has the propensity to form highly toxic hydrogen cyanide and caustic dissolved cyanides solution that result in the production of H₂ and CH₄, and risk explosions.



Fig. 1. 1st SPL cut of carbonaceous grade (left) and 2nd SPL cut made of refractory, insulation bricks, and ramming paste (right).

On 19th March 1990, a ship carrying SPL resulted in onboard explosion in Port Alfred, Canada claiming the lives of two people and causing \$30M property damages [7]. Other SPL environmental concerns are the long-term leaching of fluoride and contamination of rainwater runoff. SPL reacts exothermally with water producing huge amounts of gases including NH₃, H₂, and CH₄. A summary of the reaction chains are as follows:



Still and unfortunately, landfilling is the common practice for SPL management, claiming nearly 50% of the generated and untreated waste [7]. However, there are strong concerns of fluorides leaching (nearly 15%) and emission of unoxidized cyanides that have brought legislative interest in SPL detoxification and usage in other industries. Successful usage of the SPL in the cement industry have been reported [8,9,10], yet details on its potential as fuel substitute are still lacking. Additionally, Cement industry put an upper limit to SPL usage amount of 0.2% by mass and restricts the inclusion of metal particles such as Al which are damaging in the finished cement. Another concern is the long term effect that has not been investigated by researcher. The steel industry is another gateway that can accommodate SPL as fuel and CaF₂ substitutes where the latter helps in better formation of slags. Nevertheless, the amount of SPL that has been used in the steel industry is rather very small. In Australia, Regain Inc. detoxify SPL at the generation source after classification and crushing into inert and reactive streams [11]. The latter is hydrated per the above reactions and the generated H₂ and CH₄ are partially used to destroy the cyanides leading to non-hazardous grade that can be accommodated by various industries, i.e. cement, steel, and brick or wall rock.

Two industries (Reynolds and Alcoa) claimed that stabilizing the leachable fluorides and destroying the cyanides is the winning approach to detoxification of 1st cut SPL. They used a mixture of SPL with CaO and antiagglomeration agent to shift NaF and AlF₃ into less soluble CaF₂, destroying the cyanide in the process. The process, however, is energy intensive and further leachability tests showed the inability of the Reynolds process to adhere to stipulated EPA limits without basic buffering.

The 1st cut SPL was used as an auxiliary reducing agent by VonKrüger [12], tapping on its additional fluxing characteristics in ferro-silicon manganese smelting. More recently, 1st cut SPL was considered for gasification in a pilot scale plant where the destruction of cyanide and nearly 21% conversion was reported [13]. Plasm detoxification and production of energy and vitrified inert slag that safely landfilled was also claimed through Tectonics group [14]. Claim of recycling 1st cut SPL was reported also by ELkem who developed a process to crush and sieve SPL and introduced with Quartz and Iron ore inside electric smelting

furnace to produce reactive slag [7]. The reaction of the produced slag with the steam results in AlF_3 which is a necessary electrolytic additive for the Hall-Héroult aluminum making process. The process energy cost, however, limited their deployment to full scale.

By and large and despite the progress made, industrial utilization for SPL is not deployed at a rate that manages this growing waste stream properly in view of the massively growing aluminum industry. This is due to lack of the technical feasibilities for alternatives such as thermochemical pathways. There is a clear need to manage this stream effectively. This work attempts to narrow this literature gap by assessing the gasification of SPL and benchmarking its conversion against the common gasification of the coal.

2. Methodology:

2.1 Material characterization: Gasification is suited for coal, biomass, and other streams of solid waste based on consideration of the fixed carbon as well as the volatile contents of the candidate feedstock. This is revealed through well-established material characterization which would infer the proximate and ultimate composition of the feedstock. Proximate analysis reveals the main four fractions of the materials, i.e. moisture, volatile, fixed carbon or char, and minerals or ash. Ultimate analysis, on the other hand, provides the essential elemental compositions including C, H, N, S and O. These analyses are conducted using specialized analytical equipment such as Thermo Gravimetric Analyzer (TGA), CHNSO Elemental Analyzer, and bomb calorimetry that measures the heating/calorific value of the feedstock. Either XRF or inductively coupled plasma (ICP) can be used, respectively, for macro and trace elemental analyses of the mineral/ash. From these analysis, one can infer the unit molecular formula based on a single carbon atom in the form of $\text{CH}_x\text{O}_y\text{N}_z\text{S}_z$ or simply mark the material on the van-Krevelen diagram (O/C vs H/C) that can be directly compared to different grades of coal, biomass, lignite etc.

The issue with SPL is extracting representative and homogenized samples. That can be done by obtaining large chunks of 15kg total mass, crushing and sieving to reach a fine mesh size near $100\mu\text{m}$. Bomb calorimetry and XRF analysis typically require sample mass in the order of several grams, while TGA, Elemental Analyzers, and ICP require samples in the order of one-tenth of a gram or smaller. Therefore, sampling and testing following statistical approach to achieve reproducible statistical representation of the SPL composition is always necessary. In this work four different grades of SPL are presented and these include i) Raw or as received SPL (RSPL), ii) water washed SPL (WWSPL), iii) water washed followed with Acid Treated SPL (ATSPL), and iv) water washed SPL followed with two treatments, primary basic with NaOH and a secondary acidic with H_2SO_4 (FTSPL). More details about the SPL compositions and the heating values are given in the previous experimental and modeling studies [15,16].

Tables 1 summarizes the proximate analyses for the four considered SPL grades as well as their measured calorific values. Their ultimate analysis and inferred unit formula are shown in table 2. These formulas are also presented on Van-Krevelen diagram per Fig. 2. The SPL treatment appears to have solubilized and removed good portion of the mineral contents of the SPL as noticed by the increasing fraction of the fixed carbon particularly the ATSPL and FTSPL and reaching to near anthracite coal grade per figure 2.

Table 1 Proximate Analysis (weight %)

Feedstock	MC %	VM %	FC%	Ash%	Calorific Value (MJ/kg)
RSPL	3.46	6.18	38.96	51.4	12.1
WWSPL	2.4	5.91	40.37	51.32	16.4
ATSPL	2.2	4.78	67.77	25.25	21.2
FTSPL	2.1	0.2	82.86	14.84	28.0

Coal (dry)	0	37.4	54.3	8.3	33.25
------------	---	------	------	-----	-------

Table 2: Ultimate analysis and unit formula representation (dry ash free)

Feedstock	C	O	H	N	S	Unit Formula
RSPL	42.19	55.36	0.616	0.59	1.24	$\text{CH}_{0.168}\text{O}_{0.984}\text{N}_{0.012}\text{S}_{0.011}$
WWSPL	48.08	49.59	0.211	0.4	1.72	$\text{CH}_{0.051}\text{O}_{0.774}\text{N}_{0.007}\text{S}_{0.013}$
ATSPL	72.01	24.83	0.154	0.55	2.46	$\text{CH}_{0.025}\text{O}_{0.259}\text{N}_{0.007}\text{S}_{0.013}$
FTSPL	87.03	9.45	0.21	0.64	2.67	$\text{CH}_{0.028}\text{O}_{0.081}\text{N}_{0.006}\text{S}_{0.012}$
Coal	80.36	12.17	5.08	1.45	0.94	$\text{CH}_{0.729}\text{O}_{0.114}\text{N}_{0.015}\text{S}_{0.004}$

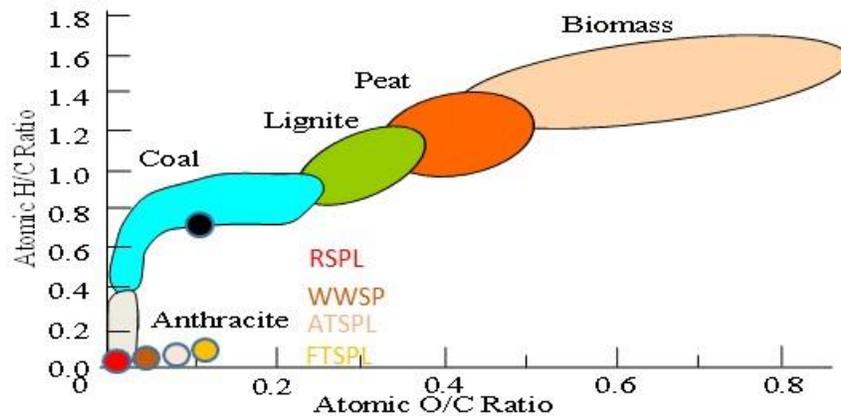


Fig. 2 Van-Krevelen diagram representation and the location of the different types of SPL grades

The coal properties are given according to MacPhee [17] of bituminous type and characterized with heating value (LHV) of 32.3 MJ/kg. In general, the SPL is characterized with low volatile fraction and Heating values compared to the baseline bituminous coal.

2.2 Gasification modeling: The assumption of equilibrium is amenable to high temperature gasification and specifically in entrained flow gasification (EFG) than the lower temperature such as fixed & moving bed and fluidized bed technologies [18,19]. EFG technology is popular and used by BBP, Hitachi, MHI, Prenflo, SCGP, E-Gas and Texaco with the advantage of lower tar, CO_2 , and CH_4 and offer flexibility of feedstock, but at the price of smaller particle size requirements [20]. The feedstock is typically crushed and pulverized to ensure its complete carbon conversion. It can be admitted as wet-slurry or dry-solid into the EFG. The EFG can also be of two types, i.e. non-slagging or slagging, depending on downstream plan for bottoming ash further treatment and usage or for safe disposal as vitrified stable minerals [21].

Wang et al in Fig. 3 illustrated the reaction time scale inside the gasifier and its dependency on the operation pressure and temperature that suggested the position of equilibrium which falls within the range of operation of the EFG temperature range [22].

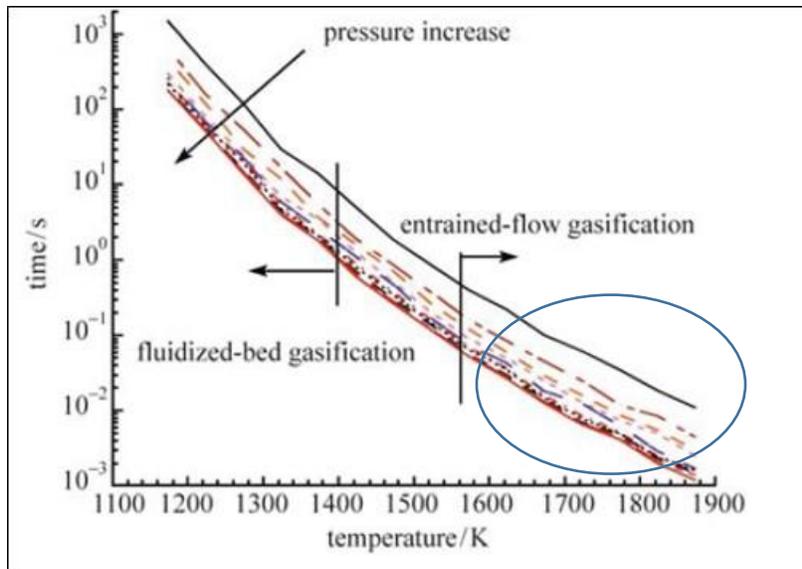


Fig. 3. Reaction equilibrium time scale in function of temperature as well as pressure of the gasifier

At the condition of the EFGs the time of the reactions is greatly reduced to be safely considered in equilibrium operation range. For instance, when operating the EFG at 1573K/1300°C the reaction time for the production of syngas is about 0.1s which is essentially less than the average residence time inside the gasifier, i.e. in the order of several seconds [22]. Therefore equilibrium modeling of EFGs is justifiable at their operational temperature. One also can remark, from the Wang et al work, the pronounced influence of the temperature over that of the pressure.

In general, there are two main approaches for developing a gasification model, i) the Equilibrium constant method (ECM) and ii) the Element potential method (EPM). In this work, we consider the ECM following several published works [23,24,]. These models apply elemental balance, methanation reaction, water gas shift, Boudouard reaction, and energy balance. They are simple to code and easily understood in determining the equilibrium species concentrations and the temperature and pressure products conditions [19]. The main assumption is that the process takes infinite residence time under chemical and thermodynamic equilibrium [25,26]. For that, reaction kinetics are neglected and no intermediate species is accounted for as the model lack the concept of time, mixing and geometry to provide special distribution of species. Nevertheless, the gasifier metrics such as GE and conversion under “best” case scenario are evaluated. Practically, the operation is subjected to heat losses, kinetic limitations, localized flow turbulence and variation in special and temporal species distribution, yielding lower efficiencies than the equilibrium assumption.

During gasification of hydrocarbons, oxygen is depleted in a series of heterogeneous and homogeneous reactions as summarized in table 3. Therefore, R1 through R3 reactions do not contribute to the equilibrium composition, and only the last three reactions are considered during equilibrium. In these reactions, the solid carbon feedstock is consumed and the products are limited to CO, CO₂, CH₄, H₂, H₂O and Ash.

Table 3. Gasification reaction of the main species and their corresponding heat of reactions

Reaction#	Reaction Stoichiometry	Reaction energy (MJ/kmol)	Description
-----------	------------------------	---------------------------	-------------

R1	$C + \frac{1}{2}O_2 \rightarrow CO$	-111	Carbon combustion reaction
R2	$CO + \frac{1}{2}O_2 \rightarrow CO_2$	-283	CO combustion
R3	$H_2 + \frac{1}{2}O_2 \rightarrow H_2O$	-242	H ₂ combustion
R4	$C + H_2O \leftrightarrow CO + H_2$	+131	Steam gasification, reforming
R5	$C + CO_2 \leftrightarrow 2CO$	+173	Boudouard reaction
R6	$C + 2H_2 \leftrightarrow CH_4$	-75	Methanation reaction

Additionally, the traces of Nitrogen and Sulfur and the formation of N₂, NH₃, COS, and H₂S are considered simultaneously. The objective is to solve for these 10 species as well as oxygen ratio per feedstock, and steam ratio per feedstock during gasification at a specified temperature and pressure. Therefore, a total of 12 unknowns are generated, governed by 12 equations; the *five* elemental balance of each of C, O, H, N, and S, the *one* total heat balance, the *three* equilibrium reaction of Water-gas (R4), Boudouard (R5) and Methanation (R6), and, finally, the *three* formation of NH₃, COS, and H₂S. Each of above reaction equations is independent, and has an associated equilibrium equation in terms the concentration K_c or the partial pressure K_p as follows:

$$K_c(T) = \frac{[C]^c [D]^d}{[A]^a [B]^b} \quad \text{or} \quad K_p(T) = \frac{P_C^c \cdot P_D^d}{P_A^a \cdot P_B^b} \quad (5)$$

with $K_c(T) = K_p(T) \cdot (RT)^{c+d-a-b}$, [X] representing the molar concentration of species X and K_c expressed Arrheniusly as:

$$k_c(T) = A_r T^{\beta_r} e^{-\frac{E_r}{RT}} \quad (6)$$

Where A is the pre-exponent constant, β is temperature exponent constant, E_r is the activation energy which is quoted to the Gibbs free energy of the reaction, R is the universal gas constant ($R = 8.313 \text{ kJ/kmol} \cdot \text{K}$), T is the reaction absolute temperature. The steady form of the energy equation is written as:

$$\sum_{i=1}^{n \text{ product}} \dot{n}_i h_i = \sum_{i=1}^{n \text{ reactant}} \dot{n}_i h_i + \dot{Q} \quad (7)$$

Where n is the number of moles and the “dot” indicates time rate. h is the enthalpy term and includes the formation and sensible enthalpies. The 9 species (χ_{CO_2} , χ_{CO} , χ_{H_2} , χ_{CH_4} , χ_{N_2} , χ_{NH_3} , χ_{H_2S} , χ_{COS} , χ_{H_2O} , oxygen ratio per feedstock, and steam ratio per feedstock) can be solved iteratively. The feedstock is defined according to its proximate and ultimate composition in addition to its lower heating value as shown in Tables 1 and 2, leading to the evaluation of the molar or mass fractions of each as well as the moderator steam and oxidizer molar ratio to that of the feedstock. The baseline coal is common bituminous grade. The analyses are carried out at a fixed pressure of 30 bars and at sweeping values of temperature between 750°C and 1550°C. Additional to species distribution the cold gasification efficiency (GE) has been evaluated without accounting for any of the product sensible heat. GE is defined as the ratio of the yield syngas accumulative heating value to the measured SPL heating value with any extra heat.

3. Preliminary Results:

The gasification model is validated against a baseline coal stream as depicted in Fig.4. This has a general consensus in published literature. This results in best CG efficiency of 77% at a temperature of 1300 °C with corresponding molar fractions for CO, H₂ and CH₄ of 0.595, 0.377, and 0.007, respectively, and oxidizer and moderator molar ratio of 1.84 and 1.32 respectively. The trends is systematic and reasonable as the increase of temperature favors the endothermic reactions – steam gasification reaction and Boudouard reaction – and, thus, is in agreement with *Le Chatelie Principle*. The decrease of CO₂ and steam as well as the decrease of methane are in accordance with the same principle. The

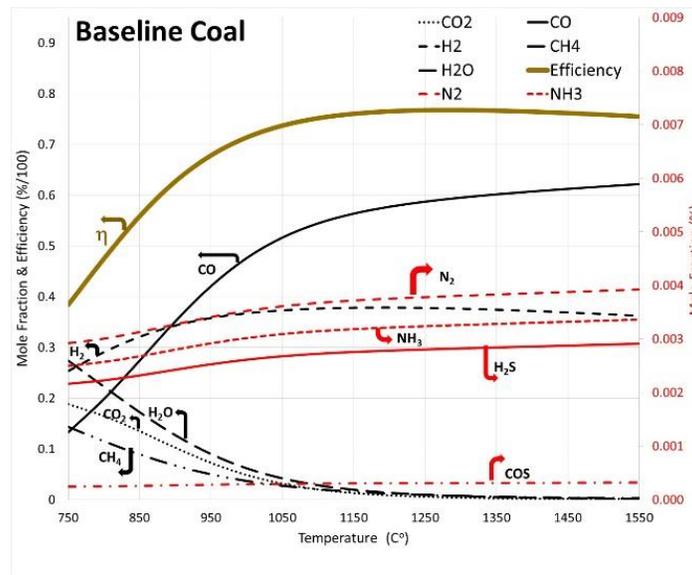


Fig. 5. Model results to the gasification of the baseline coal

Fig. 6 depicts the gasification results for the WWSPL feedstock. It reflects different temperature trends from that described for the coal. Although CO and H₂ dominate the molar fraction, H₂ production is on the decline and that led to a very low gasification efficiency of 39% at a rather high temperature of 1450 °C. The corresponding molar ratios of the oxidizer and moderators respectively were 0.0141 and 0.417 and that corresponds to X_{CO} of 0.804 and X_{H₂} 0.178. Therefore, even though a good syngas fraction is produced, the process seems more of a pyrolysis than a gasification and much of the energy needed in the process led to low GE. This due to the unfit composition of the feedstock with a large fraction of Ash per its proximate analysis coupled with a very large fraction of oxygen signifying an oxidized compound that always reflect lower heating value to be gasified. It should be also noted that lower temperatures (<1450) resulted in negative values for the oxidizer and moderator ratios signifying the inability to gasify and unreliability of the model results at these temperatures.

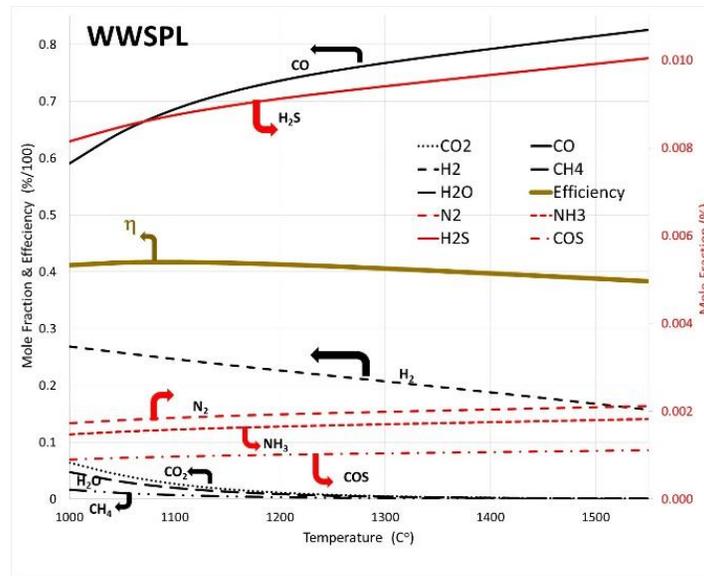


Fig. 6. Model results to the gasification of WWSPL

The SPL results of the treated ATSP and FTSP, respectively, revealed GE of 65%, and 75% with corresponding syngas (CO & H₂) molar fractions at 0.769 & 0.159, and 0.730 & 0.218 at temperatures of 1100 °C, and 1150 °C. The corresponding oxidizer and moderator molar ratio for ATSP and FTSP are 1.29E & 1.02 and equal moles of 1.97 & 1.97, respectively. Compared to the values for baseline coal, these results suggest the potential and feasibility of gasification of only the treated SPL.

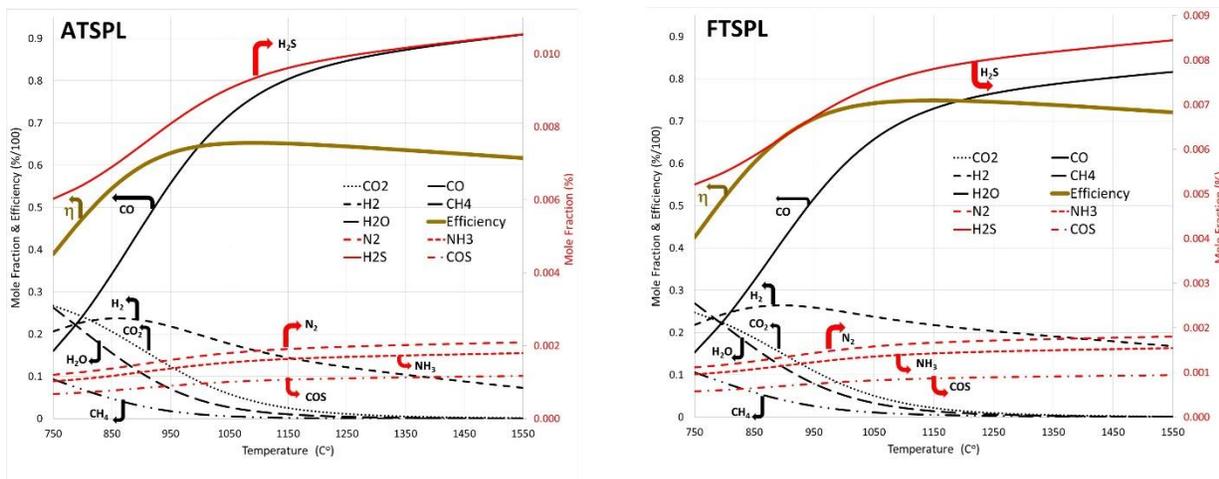


Fig. 7. Model results to the gasification of the treated ATSP and FTSP

4. Conclusion:

Aluminum industry produces an alarming and increasing amount of hazardous, none recyclable, solid waste known as spent pot lining that grew to 2Mt annually. This waste can be sorted into two cuts with one being carbonaceous and the other inorganic. In this work, the technical feasibility of gasification of SPL through

equilibrium modeling following different levels of treatment was conducted. The model considers 11 species including the molar ratio of the moderator steam (H₂O) and the oxidizer (O₂) in addition to the molar fractions of CO, H₂, CH₄, N₂, NH₃, H₂S, COS, H₂O and Ash. The process metrics are assessed via the produced syngas fraction (CO and H₂), gasification efficiency (GE) and in comparison to the gasification of a baseline bituminous coal. The gasification model is validated against a baseline coal stream which has a general consensus in published results, i.e. near 77% GE and molar fractions for CO, H₂ and CH₄ of 0.595, 0.377, and 0.007, respectively at a temperature of 1300 °C and with moderator molar of 1.84 and oxidizer molar of 1.32. The SPL results for each of the WWSPL, ATSPL, FTSPL, respectively, revealed GE of 40%, 65%, and 75% with corresponding syngas (CO & H₂) molar fractions at 0.804 & 0.178, 0.769 & 0.159, and 0.730 & 0.218 at temperatures of 1450 °C, 1100 °C, and 1150 °C. These results suggest the potential and feasibility of gasification of only the treated SPL.

5. Acknowledgment

The support of Khalifa University of Science and Technology (KUST) is highly acknowledged. The technical support also from the Center of Excellence for Solid Waste at Ain Shams University is equally acknowledged. We also thank our colleagues at Sharjah University.

6. References

- [1] Chen Xi-ping. Latest status of processing technologies for spent potlining from aluminium smelters. *Light Metals* 2011;12:21 -25.
- [2] Haiying Liu, Jinling Wang, Shifu Shen, Youfa Luo, Study on process mineralogy of a used cathode of carbon block from electrolytic aluminum factory, *Procedia Environmental Sciences* 16 (2012) 749 – 757
- [3] Gunasegaram DR, Molennar D. Towards improved energy efficiency in the electrical connections of Hall-Héroult cell through finite element analysis (FEA) modeling. *J Clean Prod* 2015;93:174–92
- [4] George Hollywell and Raymond Breault, An overview of useful methods to treat, recover, or recycle spent potlining, *JOM* 65, No11 (2013), 1441-1451.
- [5] Regain Processing Technology, <http://www.regainmaterials.com/aluminium-smeltingindustry/regain-spl-solution/spl-processing-technology>, retrieved on 8n August 2017
- [6] Chanaan F, Eby E. Best demonstrated available technology (bdat) background document for spent aluminum potliners –K088. Environ Protect Agency 2000.
- [7] Harald Arnljot Øye, Discussion of Industrial Spent Pot Lining Treatment, *Travaux* 46, Proceedings of 35th International ICSOBA Conference, Hamburg, Germany, 2 – 5 October, 2017.
- [8] Venâncio LCA, Souza JAS, Macedo EN, Nazareno J, Quaresma N, Paiva AEM. Residues recycling: reducing costs and helping the environment. *JOM* 2010;62(9):41–5
- [9] Gomes V, Drumond PZ, Neto JOP, Lira AR. Co-processing at cement plant of spent potlining from aluminum industry. In: Tomsett A, Johnson J, editors. *Essential readings in lightmetals: electrode technology for aluminum production* (4). Hoboken: John Wiley & Sons; 2013. p. 1057–63.
- [10] Renó MLG, Torres FM, Silva RJ, Santos JJCS, Melo MLNM. Energy analyses in cement production applying waste fuel and mineralizer. *Energy Convers Manag* 2013;75:98–104.
- [11] Regain Processing Technology, <http://www.regainmaterials.com/aluminium-smeltingindustry/regain-spl-solution/spl-processing-technology>, retrieved on 8n August 2017
- [12] Von Krüger P. Use of spent potlining (SPL) in ferro silicomanganese smelting. In: Lindsay SJ, editor. *Light metals 2011*. Hoboken: John Wiley & Sons; 2011. p. 275–80.
- [13] Shi Z, Li W, Hu X, Ren B, Gao B, Wang Z. Recovery of carbon and cryolite from spent pot lining of aluminium reduction cells by chemical leaching. *Trans Nonferrous Met Soc China* 2012;22:222–7. and
- [14] Tetronics website: <http://tetronics.com/our-solutions/hazardous-material-treatment/spent-potliner/>, retrieved on 7 August 2017.
- [15] P. D. Indurkar, Optimization in the treatment of Spent Pot Lining - A Hazardous Waste Made Safe. Master Thesis, 2014.
- [16] Chaouki Ghenai I, Abrar Inayat, Abdallah Shanableh, Eman Al Sarairah, and Isam Janajreh. *Combustion And Emissions Analysis Of Spent Pot Lining (Spl) as Alternative Fuel In Cement Industry*, Science of Total Environment, in the press, 2019
- [17] J.E. Macphee, M. Sellier, M. Jermy, and E. Tadulan, CFD modeling of pulverized coal combustion in rotary lime kiln, 7th Int. Conference on CFD in Minerals and Process Industries, CSIRO Melbourne, Australia, December 9-11, 2009.
- [18] S Shabbar, I Janajreh, Thermodynamic equilibrium analysis of coal gasification using Gibbs energy minimization method *Energy conversion and management* 65, 755-763
- [19] Talab, I., et al., Numerical Modeling of Coal Tire-Shred Co-Gasification. *JJMIE*, 2010. 4(1).
- [20] I Adeyemi, I Janajreh, Modeling of the entrained flow gasification: Kinetics-based ASPEN Plus model, *Renewable Energy* 82, 77-84, 2012
- [21] IA Adeyemi, I Janajreh, Detailed Kinetics-Based Entrained Flow Gasification Modeling of Utah Bituminous Coal and Waste Construction Wood Using Aspen Plus, *ICREGA'14-Renewable Energy: Generation and Applications*, 607-622, 2014
- [22] Wang, Z., et al., Syngas composition study. *Frontiers of Energy and Power Engineering in China*, 2009. 3(3): p. 369-372.
- [23] Jarungthammachote S, Dutta A. Equilibrium modeling of gasification: Gibbs free energy minimization approach and its application to spouted bed and spout-fluid bed gasifiers. *Energy Convers Manage* 2008;49(6):1345–56.
- [24] Jarungthammachote S, Dutta A. Thermodynamic equilibrium model and second law analysis of a downdraft waste gasifier. *Energy* 2007;32(9):1660–9.
- [25] Prins, M.J., K.J. Ptasinski, and F.J.J.G. Janssen, From coal to biomass gasification: Comparison of thermodynamic efficiency. *Energy*, 2007. 32(7): p. 1248-1259.

[26] de Souza-Santos, M.L., Solid fuels combustion and gasification : modeling, simulation, and equipment operation. Mechanical engineering. Vol. 180. 2004, New York: Marcel Dekker. 439.