Final Technical Report

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Task 3.0:Life-Cycle Database for Wind Energy Systems

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FINAL TECHNICAL REPORT

Sustainable Energy Solutions

DE-FG36-08GO88149

Task 3.0

Life-Cycle Database for Wind Energy Systems

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EXECUTIVE SUMMARY

The benefits of wind energy had previously been captured in the literature at an overview level with relatively low transparency or ability to understand the basis for that information. This has limited improvement and decision-making to larger questions such as wind versus other electrical sources (such as coal-fired plants). This research project has established a substantially different approach which is to add modular, high granularity life cycle inventory (lci) information that can be used by a wide range of decision-makers, seeking environmental improvement.

Results from this project have expanded the understanding and evaluation of the underlying factors that can improve both manufacturing processes and specifically wind generators. The use of life cycle inventory techniques has provided a uniform framework to understand and compare the full range of environmental improvement in manufacturing, hence the concept of green manufacturing. In this project, the focus is on

1. the manufacturing steps that transform materials and chemicals into functioning products
2. the supply chain and end-of-life influences of materials and chemicals used in industry

Results have been applied to wind generators, but also impact the larger U.S. product manufacturing base.

For chemicals and materials, this project has provided a standard format for each lci that contains an overview and description, a process flow diagram, detailed mass balances, detailed energy of unit processes, and an executive summary. This is suitable for integration into other life cycle databases (such as that at NREL), so that broad use can be achieved. The use of representative processes allows unrestricted use of project results. With the framework refined in this project, information gathering was initiated for chemicals and materials in wind generation.

Since manufacturing is one of the most significant parts of the environmental domain for wind generation improvement, this project research has developed a fundamental approach. The emphasis was place on individual unit processes as an organizing framework to understand the life cycle of manufactured products. The rearrangement of unit processes provides an efficient and versatile means of understanding improved manufactured products such as wind generators. The taxonomy and structure of unit process lci were developed in this project. A series of ten unit process lci were developed to sample the major segments of the manufacturing unit process taxonomy.

Technical and economic effectiveness has been a focus of the project research in Task three. The use of repeatable modules for the organization of information on environmental improvement has a long term impact. The information developed can be used and reused in a variety of manufacturing plants and for a range of wind generator sizes and designs. Such a modular approach will lower the cost of life cycle analysis, that is often asked questions of carbon footprint, environmental impact, and sustainability. The use of a website for dissemination, linked to NREL, adds to the economic benefit as more users have access to the lci information.

Benefit to the public has been achieved by a well-attended WSU conference, as well as presentations for the Kansas Wind Energy Commission. Attendees represented public interests, land owners, wind farm developers, those interested in green jobs, and industry. Another benefit to the public is the start of information flow from manufacturers that can inform individuals about products.

Comparison of the Actual Accomplishments with the Goals and Objectives of the Project

The College of Engineering (CoE) at Wichita State University (WSU) has engaged in research and development in the area of wind energy, drawing from advances in technology from the aerospace and power systems industries, and expertise in life cycle analysis. The ***overall objective*** of the proposed effort has been to advance the economy of Kansas through the creation of new knowledge of energy production and products for the advancement of wind energy systems. The impediments to more economical and efficient wind energy systems targeted by this effort include the following: lack of access and integration of sustainable energy technologies (wind) into existing energy infrastructure, high cost of wind energy due to low reliability and high cost of wind-turbine maintenance, and lack of quantifiable environmental impact information. The WSU research addresses those impediments and meets the technology barriers to wind energy identified by the Wind and Hydropower Technologies Program, Department of Energy (Wind Energy Multiyear Program Plan for 2007–2012). Through this award, a CoE consortium of wind energy researchers has been created to provide advice to industry and policy makers, educate students, and offer a portal for information exchange.

To meet the overall objective, five specific goals were pursued. This Final Technical Report addresses one specific goal:

To develop a life cycle database that is accessible to the wind energy research and development community for assessing environmental impacts and making technology decisions throughout the life cycle of a wind energy system.

The Task team developed the life cycle database objective with both format, some of the actual materials, and links to the DOE database. Thus we accomplished the objective of this Task.

Summary Project Activities

Over the project funding period, results from this research have expanded the understanding and evaluation of the underlying factors that can improve both manufacturing processes and specifically wind generators. The use of life cycle inventory techniques has provided a uniform framework to understand and compare the full range of environmental improvement in manufacturing, hence the concept of green manufacturing. In this project, the wind generation research focus is on two important life cycle databases, both of which impact U.S. manufacturing and wind generator development and production. These are subdivided into two research concepts and databases as follows:

1. the manufacturing steps that transform materials and chemicals into functioning products
2. the supply chain and end-of-life influences of materials and chemicals used in industry

Results have been applied to wind generators, but also impact the larger U.S. product manufacturing base.

For chemicals and materials, this project has provided a standard format for each lci that contains an overview and description, a process flow diagram, detailed mass balances, detailed energy of unit processes, and an executive summary. This is suitable for integration into other life cycle databases (such as that at NREL), so that broad use can be achieved. The use of representative processes allows unrestricted use of project results. With the framework refined in this project, information gathering was initiated for chemicals and materials in wind generation.

Since manufacturing is one of the most significant parts of the environmental domain for wind generation improvement, this project research has developed a fundamental approach. The emphasis was place on individual unit processes as an organizing framework to understand the life cycle of manufactured products. The rearrangement of unit processes provides an efficient and versatile means of understanding improved manufactured products such as wind generators. The taxonomy and structure of unit process lci were developed in this project. A series of ten unit process lci were developed to sample the major segments of the manufacturing unit process taxonomy.

These two life cycle research concepts and databases are central to the original hypothesis of Task three: To develop a life cycle database that is accessible to the wind energy research and development community for assessing environmental impacts and making technology decisions throughout the life cycle of a wind energy system.

A similar, modular approach was used to advance the research tasks. That is, we have taken the large scale application and focus of life cycle technology and built the more fundamental modular systems approach. For each part of the research areas for Task 3 this report provides a brief description of results, one detailed report, and a list of the other reports finished.

In research concept 1, unit process life cycle inventories (uplci) are established as the building blocks of manufacturing plants that make products. These may be final products recognized by consumers or subassemblies of such products. These products are the output of a sequence of unit processes that take materials and chemicals into the manufacturing plant and transform these into the output. The unit processes in this sequence are definable machines or operations each of which add value or a change in properties to the unit process inputs. Thus the research of this Task 3 developed the information that allows these lci descriptions to add specific value (such as drilling eight holes of different diameter in a workpiece). The format of this information must be modularized so that additivity of process is simple and direct thus allowing rapid evaluation of the sequence of unit processes that represent the manufacturing of a product. The information in reports are referred to as unit process life cycle inventories (uplci).

The uplci report consists of five major sections

1) Introduction covers the nature of the unit process and pictures describing the value-added step performed. It is often for the non-expert reader.
2) Process energy calculations built typically around three power and time contributions
    a. Stand-by or basic period (often loading and unloading)
    b. Partial-full or idle period (often with movement of portions of the machine)
    c. Full or tip energy period (this is most often the value-added step)

    These equations are supplemented with Tables containing the necessary physical and energy properties to allow individual work pieces to be analyzed, but without the intricate design/construction detail to implement a process

3) Process mass loss equations based on the use of ancillary inputs (like lubricants) and loss of material (such as aluminum milling) from workpieces. If necessary, Tables are included to be used in these calculations.
4) An example of using the uplci. This follows the equations from 2) and 3), Tables in the uplci, and shows the reader how to obtain the overall energy and mass loss results for a specific workpiece and machine.
5) References

It is important to note that a uplci machine description is a reasonable or representative description of a unit process, not a detailed design tool. These evaluations seek the 90:10 rule of information and learned the truth in the adage “do not let perfect get in the way of good enough”. Results from using uplci show where major effects exist and then it will be more economical to refine the results, if needed, to improve the uplci. Transparency in results, assumptions, etc. is extremely important to the effective acquisition and use of lci data by the manufacturing community. Transparency fosters important acceptance, fosters peer review, and contributes directly to quality, verifiable lci results.

Product manufacturing is primarily macro-structure building. This project used the taxonomies of the industrially common manufacturing unit processes (Todd, et. al., 1994; Kalpakjian and Schmid, 2008). These have about 120 basic unit processes.

An example of the drilling uplci is given below in which the numbering and format system is retained to demonstrate the project results.

MR 1 Drilling Process

Unit Process Life Cycle Inventory

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July 23, 2009

I. Drilling Process Summary

Drilling is a frequent unit process in manufacturing as a mass reduction step, creating a hole of a given smoothness. Hence this life cycle heuristic is to establish representative estimates of the energy and mass loss from the drilling unit process in the context of manufacturing operations for products. The drilling unit process life cycle inventory (uplci) profile is for a high production manufacturing operation, defined as the use of processes that generally have high automation and are at the medium to high throughput production compared to all other machines that perform a similar operation. This is consistent with the life cycle goal of estimating energy use and mass losses representative of efficient product manufacturing.

Drilling is a cutting process in which a hole is originated or enlarged by means of a multipoint, fluted, end cutting tool typically aided by cutting fluids. As the drill is rotated and advanced into the workpiece, material is removed in the form of chips that move along the fluted shank of the drill. Chips are produced within the workpiece and move in direction opposite to axial movement of the drill. Although long spiral chips usually result from drilling, adjustment of the feed rate can result in chips with a range of shapes and sizes. Consequently, chip disposal in drilling and the effectiveness of cutting fluids are important. An example drilling machine is given in Figure MR1.1, while the drilling mechanism is illustrated in Figure MR1.2).

Figure MR1.3 shows an overview of the developed environmental-based factors for drilling operations. For a given workpiece (illustrated in Figure MR1.2) the life cycle analysis yields energy use and mass losses as byproducts or wastes.

Figure MR1.1. Computer numerical control (CNC) drilling machine with 3-axis control (Photograph from Haas Automation, Inc. California, USA)

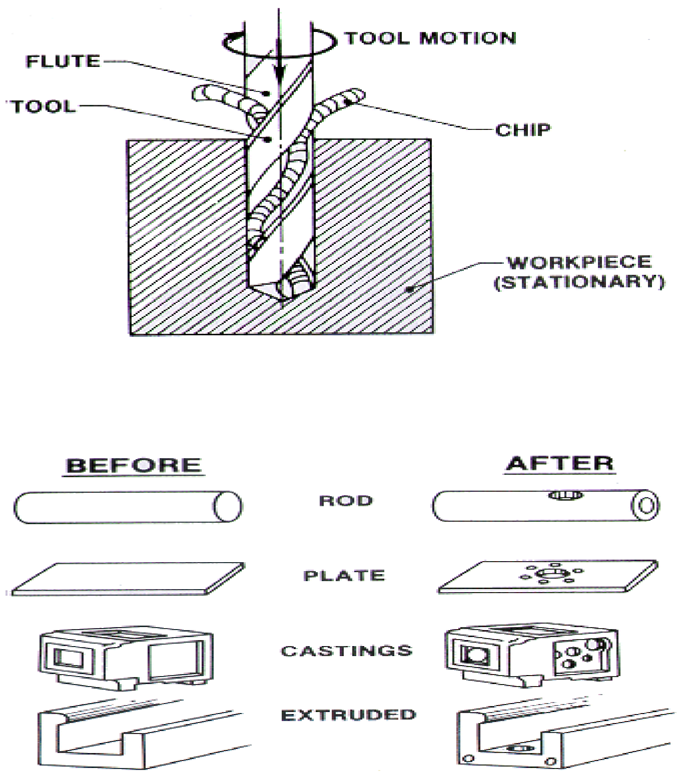


Figure MR1.2. Process Schematic (Todd et al., 1994)

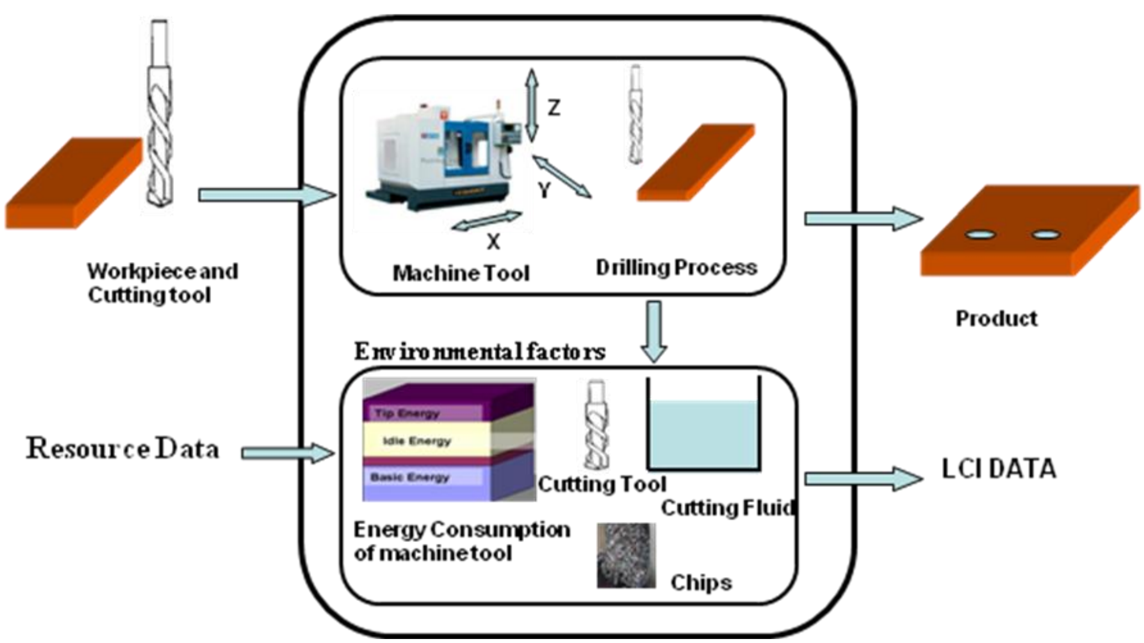


Figure MR1.3. LCI data for drilling process

II. Methodology for Unit Process Life Cycle Inventory Model

In order to assess a manufacturing process efficiently in terms of environmental impact, the concept of a unit operation is applied. The unit process consists of the inputs, process, and outputs of an operation. Each unit process is converting material/chemical inputs into a transformed material/chemical output. The unit process diagram of a drilling process is shown Figure MR1.4.

The transformation of input to output in this report generates five lci characteristics,

a. Input materials
b. Energy required
c. Losses of materials (that may be subsequently recycled or declared waste)
d. Major machine and material variables relating inputs to outputs
e. Resulting characteristics of the output product that often enters the next unit process.

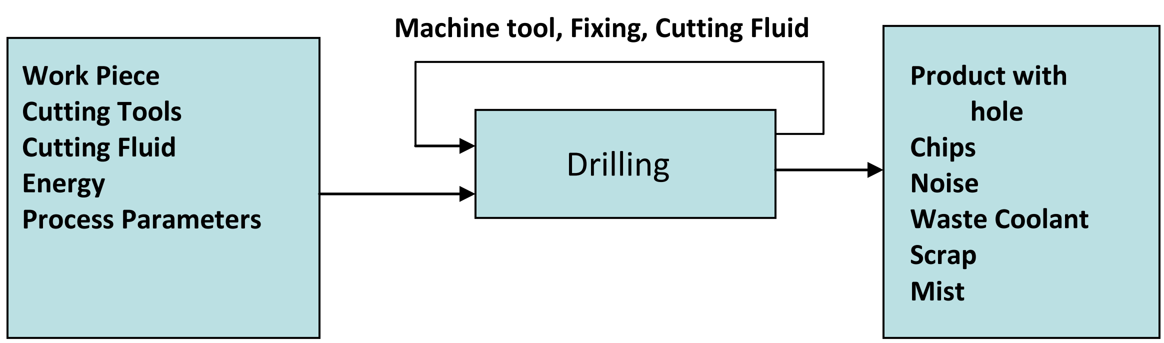


Figure MR1.4. Input-Output diagram of a drilling process

A. Drilling Process Energy Characteristics

Because high production drilling is a semi-continuous process, many of these automated CNC machines have more than three axes. One of the axes is often designed as a rotary table to position the work-piece at some specified angle relative to the spindle. The rotary table permits the cutter to perform drilling on four sides of the part. These machines are classified as horizontal, vertical or universal based on the spindle orientation. The uplci is based on a representative operational sequence, in which

1) Work set-up generally occurs once at the start of a batch in production. Set-up is made on the machine tool as the work piece is introduced into the machine. The work piece is positioned, all drawings and instructions are consulted, and the resulting program is loaded. Typical set-up times are given in Table MR1.1 (Fridriksson, 1979). The total set-up time must be divided by the size of the batch in order to obtain the set-up time per component. The energy consumed during this set-up period is divided by all the parts

processed in that batch and is assumed to be negligible and is discussed in the example below.

2) The power consumption during a campaign for positioning or loading each new piece into the drilling CNC machine, with respect to tool axis is low. Time is required to load the workpiece into the CNC machine and secure it to the fixture. The load time can depend on the size, weight, and complexity of the workpiece, as well as the type of fixture. This is at the level of Basic energy and is labeled Loading.
3) Relative movement of the cutting tool and the workpiece occurs without changing the shape of the part body, referred to as Idle Energy and is labeled Handling. This is the time required for any tasks that occur during the process cycle that do not engage the workpiece. This idle time includes the tool approaching and retracting from the workpiece, tool movements between features, adjusting machine settings, and changing the tools.
4) Drilling of a hole occurs and is labeled Tip Energy.
5) The piece is repositioned for subsequent holes, thus the energy and mass loss per hole is repeated. (Idle Energy for Handling and then Tip Energy for drilling)
6) When all holes are finished, the piece is unloaded and typically sent forward to another manufacturing unit process. This is at the level of Basic Energy and is labeled Unloading.

Table MR1.1. Set-up times for machining operations (Fridriksson, 1979)

Machine tool	**Basic setup time (h)**	**Additional setup per tool (h)**
Horizontal band saw	0.17	---
Manual turret lathe	1.2	0.2
CNC turret lathe	0.5	0.15
Milling machine	1.5	---
Drilling machine	1.0	---
Horizontal-boring machine	1.3	---
Broaching machine	0.6	---
Gear hobbing machine	0.9	---

In this representative unit process, the life cycle characteristics can be determined on a per drilled hole basis or on a full piece (with one or more holes) basis. Since this is a high production process, the start up (at the beginning of a batch or shift) is deemed to be small and not included. In this uplci, there are three typical power levels that will be used, Figure MR1.5. Correspondingly, there are times within the drilling sequence from which these three power levels are used, Figure MR1.5. The overall time per piece is referred to as cycle time and is generally consistent in a batch. Each power level (basic, idle, and drilling) is a reflection of the use of various components or sub-operations, of the CNC machine, Figure MR1.6. The steps 2), 3), 5), and 6) are estimated as representative values for use in this unit process lci and energy required of removing material by drilling, step 4), is measured using specific cutting energy values.

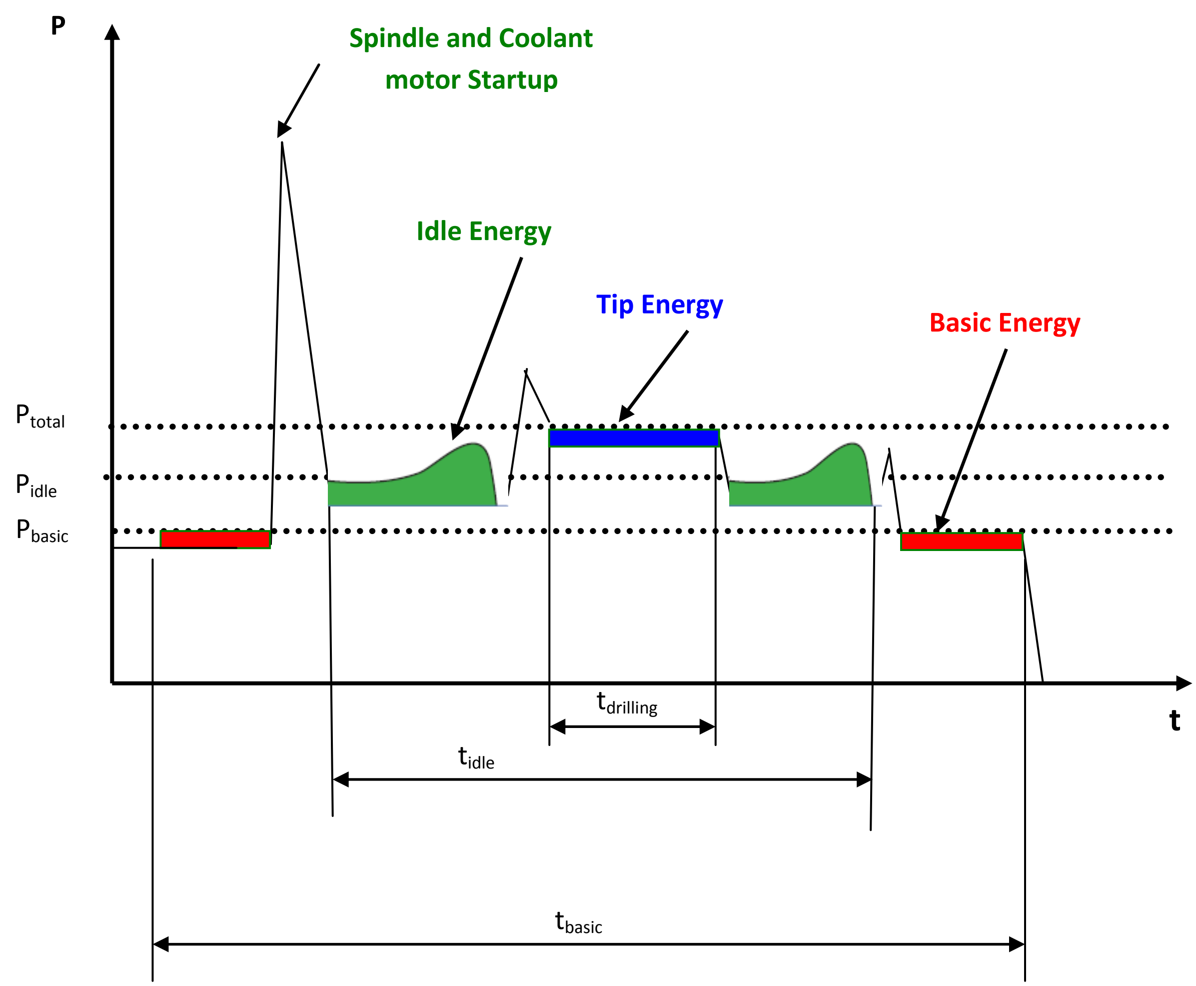


Figure MR1.5. Determination of power characteristics and energy requirements of machine tools.

The system boundaries are set to include only the use phase of the machine tool, disregarding production, maintenance and disposal of the machine. Moreover, the functioning of the manufacturing machines is isolated, with the influence of the other elements of the manufacturing system, such as material handling systems, feeding robots, etc. are covered in other uplci reports.

The energy consumption of drilling is calculated as follows:

$$E_{total} = P_{basic} * (t_{basic}) + P_{idle} * (t_{idle}) + P_{drilling} * (t_{drilling}) \quad (1)$$

(Basic energy) (Idle energy) (Drilling energy)

where power and time are illustrated in Figure MR1.5.

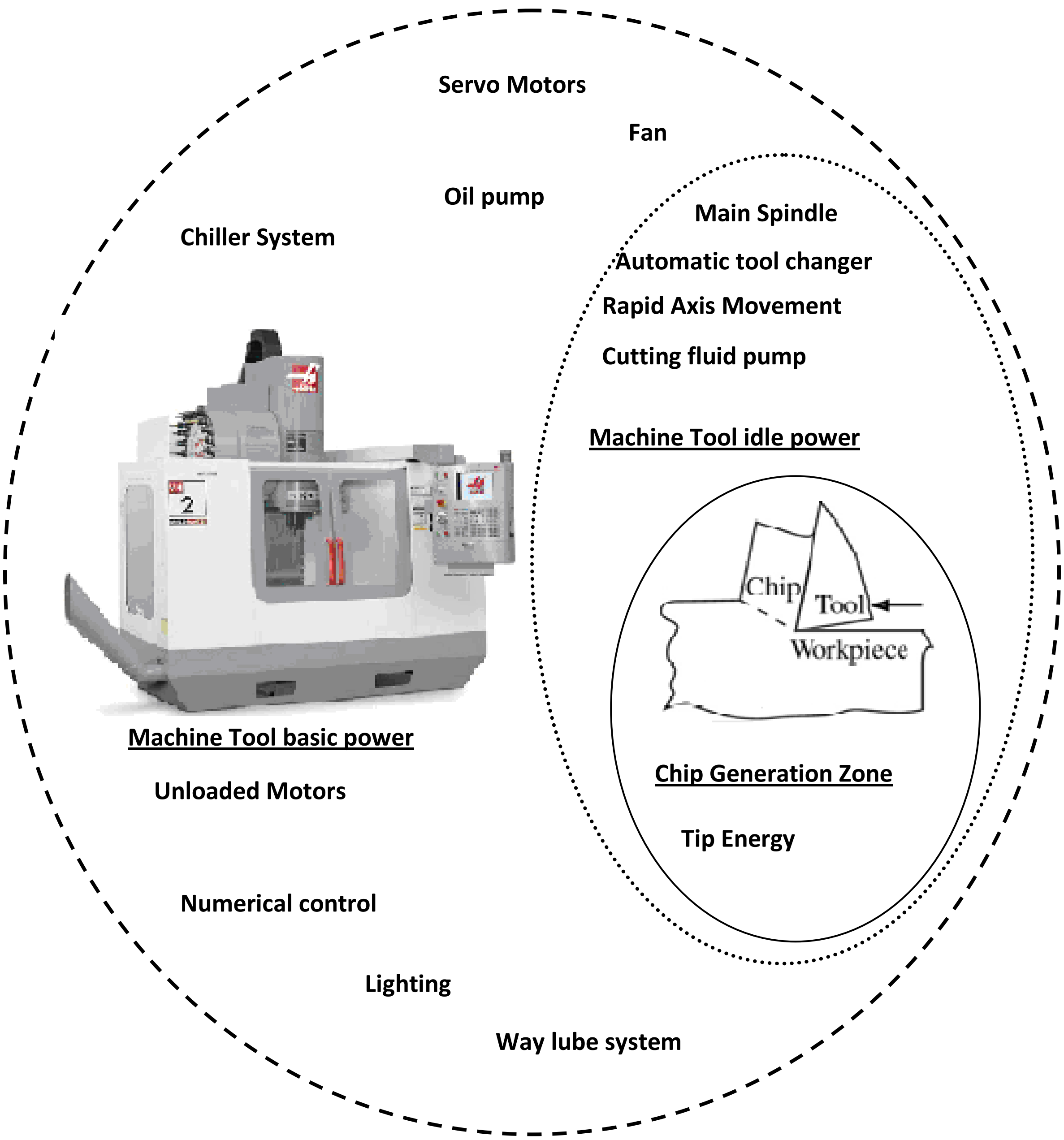


Figure MR 1.6. System boundary of the machining process

III. Parameters Affecting the Energy Required for Drilling

An approximate importance of the many variables in determining the drilling energy requirements was used to rank parameters from most important to lower importance as follows:

1. Workpiece Material properties
2. Feed rate
3. Cutting speed
4. Drilling diameter
5. Drill depth (drilling time)
6. Helix angle
7. Coolant
8. Chisel edge angle
9. Drill wear
10. Geometry and set-up

From this parameter list, only the top 5 were selected for use in this unit process life cycle with the others having lower influence on energy. Energy required for the overall drilling process is also highly dependent on the time taken for idle and basic operations.

A. Drilling Energy

Drilling time ($t_{drilling}$) and power ($P_{drilling}$) must be determined for the drilling energy and are calculated from the more important parameters given above. The calculations are illustrated in Figure MR1.7. Feed for drilling is the axial advance in one revolution of the spindle, f (mm/revolution). The rotational cutting speed, V (m/min), is the rotational speed difference between the cutting tool and the surface of the workpiece it is operating on. V and f are estimated from the material properties, Table MR1.2(a), MR1.2(b) and MR1.3. The rotational speed of the spindle, N, (rev/min), $N = V/(\pi*D)$. Where V = rotational cutting speed, mm/min and D = drill diameter, mm. The rate of drill advance (feed rate), f_r (mm/min) is the product of f*N. For a hole of diameter D, the volume material removal rate (VRR) is $(0.25\pi D^2)*(f_r)$, mm^3/min. In order to drill a through hole, the tool must pass through the thickness of the workpiece.

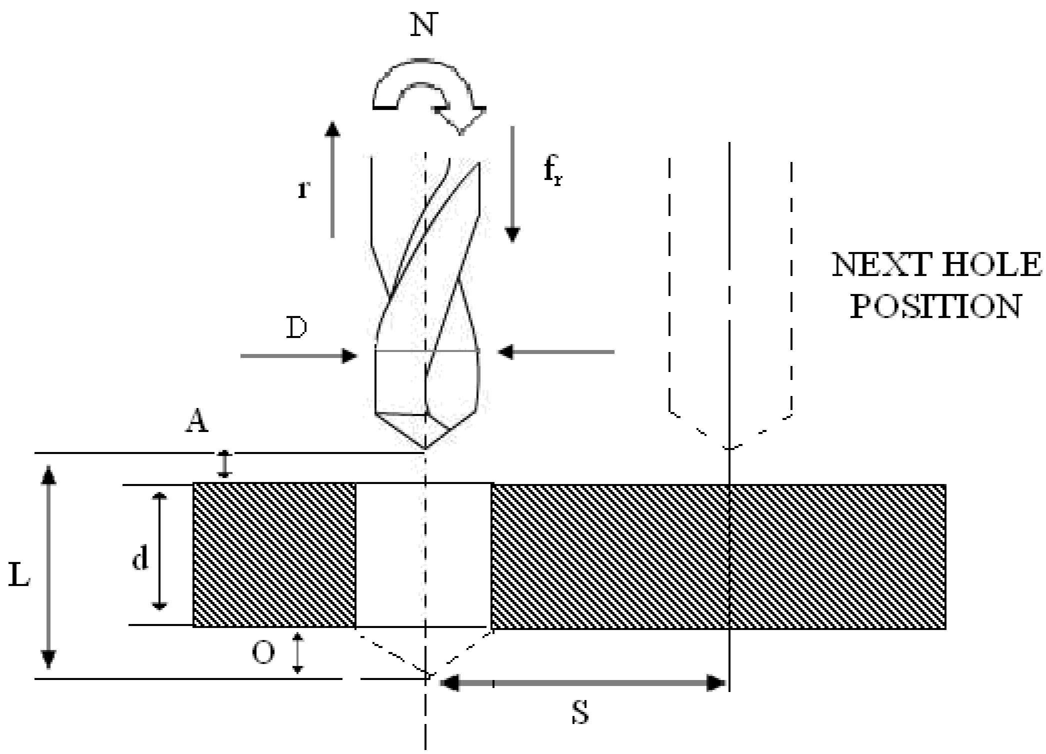


Figure MR1.7. Schematic Diagram of Drilling Process

Drilling time ($t_{drilling}$) is

Time for drilling a through hole t_{drill} = (d)/f*N = d/f_r (2)
Where d = depth of the hole, mm.
f – Feed mm/rev.
N- Spindle speed rpm
f_r – feed rate, mm/min

The drilling energy is thus E (Joule/hole) = drilling time*P_{drill} , (3)

E = drill time*(volume removal rate)*(specific cutting energy, Up, W/mm^3/sec)
E_{drill} (Joule/hole) = t_{drill} *VRR*Up = t_{drill} * P_{drill}

With a given material to be drilled, the specific cutting energy, Up, is given in Table MR1.2(a). Then for that material a representative cutting speed, V is selected from Table MR1.2(a). Then using the hole diameter, D, the spindle speed, N, is calculated =
V/ (π*D). From Table MR1.2 (a and b) for the material being drilled the feed, f is also specified. Then the time for drilling, t_{drill}, is d/(f*N) or d/f_r . The volume removal rate (VRR) is f_r *(0.25π*D^2).

The drilling energy is then calculated from equation 3. Thus with only the material to be drilled, the depth of the hole, and the diameter of the hole, one can calculate the lci drilling energy for one hole. This then must be added to the idle and basic energies, see below.

Table MR1.2(a) Average values of energy per unit material removal rate and recommended speeds and feeds (Erik, 2000; Hoffman, 2001; Joseph, 1989; Kalpakjian, 2008; 9, 10)

Material	Hardness [Brinell hardness number]	Specific cutting energy, *Up* [W/ mm3 per sec] (Hp/ in3 per min)	Cutting Speed, V (m/min, ft/min)	Feed, f	Density (kg/m^3)
Aluminum Alloys(Wrought)	30 – 80	0.76 (0.28)	50 - 120, 175 - 400	Z	2712
	75 – 150	0.76 (0.28)	50 - 120, 175 - 400	Z	
Aluminum (Cast)	40 – 100	0.84 (0.31)	50 - 120, 175 - 400	Z	2560-2640
	70-125	0.84 (0.31)	50 - 120, 175 - 400	Z	
Aluminum (Unalloyed)	80	0.3 (0.11)	50 - 120, 175 - 400	Z	7700-8700
High Silicon Aluminum (10-14% Si)		0.84 (0.31)	50 - 120, 175 - 400	Z	2700-2750
High Silicon Aluminum (14-16% Si)		1.48 (0.55)	50 - 120, 175 - 400	Z	
Malleable Cast Iron (Short Chipping)	110 – 145	1.21 (0.45)	25 - 30, 75 - 100	Z	6800-7800
Malleable Cast Iron (Long Chipping)	200 – 230	1.3 (0.48)	12 - 30, 40 - 75	Y	6800-7800

Grey Cast Iron	180	1.3 (0.48)	20 - 60, 60 - 200	Y	6800-7800
	260	1.48 (0.55)		X	
Nodular Cast Iron	160	1.21 (0.45)	20 – 60, 60 - 200	Y	
	250	2.10 (0.78)		X	6800-7800
Cast Steel (Unalloyed)	150	2.16 (0.8)	20 - 30, 60 - 100	Y	6800-7800
Cast Steel (Low Alloy)	150 – 250	2.51 (0.93)	20 - 30, 60 - 100	Y	6800-7800
Cast Steel (High Alloy)	160 – 200	2.94 (1.09)	20 - 30, 60 - 100	X	6800-7800
Unalloyed Steel	110	1.35 (0.5)	50 - 120, 175 - 400	Z	7850
	150	1.89 (0.81)	20 – 60, 60 - 200	Y	
	310	2.92 (1.08)	15 - 30, 50 -100	X	
Low Alloy Steel	125 – 225	2.51 (0.93)	15 - 20, 50 - 60	Y	7850
	220 – 420	3.29 (1.22)	12 - 15, 40 - 50	X	
High Alloy Steel	150 – 300	2.94 (1.09)	8 - 12, 25 - 40	X	
	250 – 350	4.56 (1.69)	8 - 12, 25 - 40	W	
Hardened Steel	450	4.56 (1.69)	25 - 30, 75 -100	W	
Stainless Steel (Ferritic, Martensitic)	150 – 270	2.81 (1.04)	15 - 24, 50 - 70	X	7480-8000
Stainless Steel (Austenitic)	150 – 275	2.94 (1.09)	24 – 28, 70 - 90	X	7480-8000
Stainless Steel (Quenched and Tempered Martensitic)	275 – 425	2.59 (0.96)	10 – 12, 30 - 40		

				X	
Stainless Steel	150 – 450	3.46 (1.28)	15 – 24, 50 - 70	X	7480-8000
Iron Based Heat Resistant Super Alloy	180 – 230	3.7 (1.37)			7850
	250 – 320	3.86 (1.43)			
Nickel Based Heat Resistant Super Alloy	140 – 300	3.46 (1.28)	6 – 8, 20 - 25	X	8800
	300 – 475	4.21 (1.56)	5 – 6, 15 - 20	W	
Nickel Based Heat Resistant Super Alloy(Cast)	200 – 425	4.21 (1.56)	16 – 18, 55 - 65	W	8800
Cobalt Based Heat Resistant Super Alloy	180 – 230	3.46 (1.28)	5 - 7, 15 - 25	W	8746
	270 – 320	4.21 (1.56)	5 - 7, 15 - 25	W	
Cobalt Based Heat Resistant Super Alloy(Cast)	220 – 425	4.27 (1.58)	5 - 7, 15 - 25	W	8746
Titanium Alloys (Commercially Pure)	110-200	1.51 (0.56)	5 - 6, 15 - 20	X	4500
Titanium Alloys	300-360	1.65 (0.61)	5 - 6, 15 - 20	Y	4500

	275-350	1.67 (0.62)	5 - 6, 15 - 20	W	4500
Copper	125-140	2.70 (1.00)	30 - 80, 100 - 250	Z	8930
Copper alloys	100-150	2.20 (0.80	30 - 80, 100 - 250	Z	8930
Leaded brass	60-120	1.90 (0.70)	30 - 80, 100 - 250		7700-8700
Unleaded brass	50	2.70 (1.00)	30 - 80, 100 - 250		
Magnesium alloys	40-70	0.55 (0.20)	50 - 110, 150 - 350	Z	
	70-160	1.10 (0.40)	50 - 110, 150 - 350	Z	
Refractory alloys(Tantalum, columbium, Molybdenum)	210-230	5.50 (2.00)			10188
Tungsten	320	8.00 (3.00)			19600
Plastics	hard		30, 100		

Table MR1.2(b) Feeds for Materials Listed in Table MR1.2(a) (Erik, 2000; Joseph, 1989)

	Feed (f) in mm/rev (in/rev) for Drill Diameters of				
Code	**3.2 (1/8)**	**6.4 (1/4)**	**12.7 (1/2)**	**19.1(3/4)**	**25.4 (1)**
W	0.038 (0.0015)	0.08 (0.003)	0.089 (0.0035)	0.114 (0.0045)	0.13 (0.005)
X	0.05 (0.002)	0.089 (0.0035)	0.15 (0.006)	0.216 (0.0085)	0.265 (0.0105)
Y	0.08 (0.003)	0.13 (0.005)	0.20 (0.008)	0.267 (0.0105)	0.217 (0.0125)
Z	0.08 (0.003)	0.15 (0.006)	0.25 (0.010)	0.394 (0.0155)	0.483 (0.0190)

Table MR1.3 Recommended speeds and feeds for drilling plastics (Terry and Erik, 2003)

Material	Cutting Speed, V mm/min, in/min	Nominal hole diameter, mm					
		1.5	3	6	12.5	19	25
Thermoplastics		Feed, f, mm/revolution					
Polyethylene	45-60, 150-200	0.05	0.08	0.13	0.25	0.38	0.5
Polypropylene							
TFE fluorocarbon							
Butyrate							
High impact styrene	45-60, 150-200	0.05	0.1	0.13	0.15	0.15	0.2
Acrylontrille-styrene							
Modified acrylic							
Nylon	45-60, 150-200	0.05	0.08	0.13	0.2	0.25	0.3
Acetals							
Polycarbonate							
Acrylics	45-60, 150-200	0.02	0.05	0.1	0.2	0.25	0.3
Polystyrenes	45-60, 150-200	0.02	0.05	0.08	0.1	0.13	0.15
Thermosets							
Paper or cotton base	60-120, 200-480	0.05	0.08	0.13	0.15	0.25	0.3
Homopolymers	45-60, 150-200	0.05	0.08	0.1	0.15	0.25	0.3
Fiber glass, graphitized and asbestos base	60-75, 200-300	0.05	0.08	0.13	0.2	0.25	0.3

B. Idle Energy

Energy-consuming peripheral equipment included in idle power (P_{idle}) are shown in Figure MR1.6. In the machining praxis it is known as “run-time mode” (Abele et al., 2005). The average idle power (P_{idle}) of automated CNC machines is between 1,200 and 15,000 watt*. (* This information is from the CNC manufacturing companies, see Appendix 1). The handling power characterizes the load case when there is relative movement of the tool and the work-piece without changing the shape of the body (e.g. rapid axis movement, spindle motor, coolant, tool changer) - Handling.

The idle time (t_{idle}) is the sum of the handling time ($t_{handling}$) and the drilling time (calculated above as t_{drill}, equation 2), see Figure MR1.5. For CNC drill machines, the handling times are the air time of tool moving from home position to approach point, approach, overtravel, retraction after drilling, and traverse, if needed to other holes in the same work piece. Approximate Handling time will vary from 0.1 to 10 min. We can calculate the handling times and energy as follows.

$$\text{Idle time} = [\text{time}_{handling} + \text{time}_{drill}] \quad (4)$$

Drilling tool moves from the home position to the approach point at vertical traverse rate, VTR and it can be defined as the air time_1. This distance would be in the range of 10 to 30 mm. During the drilling process, the tool is considered to be at an offset of 0.3 times the hole diameter above the work piece and so the approach distance is 0.3D. We also assume the overtravel below the hole is 0.3D. These forward distances are at the feed rate, f_r. After reaching the overtravel point, the drill retraces back to an offset position, but at a faster rate called the vertical traverse rate, VTR. The retraction time is estimated from the sum of the approach, overtravel, and drill distances, d, and the traverse rate, VTR.

Time for handling is

$$\text{Air time}_1 + \text{Approach/overtravel times} + \text{retraction times} = \text{time}_{handling} \quad (5)$$

The drilling time (for distance d) was previously calculated and is not included in the handling time.

To this idle time must be added the time to traverse to the next hole (if needed) and this is (hole spacing)/traverse speed, as given by the CNC manufacturer. The example given later in this uplci lists such traverse speed data for use in any representative drilling scenarios.

From these calculations the idle energy for a single hole is

$$E\ (\text{Joule/hole})_{idle} = [t_{handling} + t_{drill}] * P_{idle} \quad (6)$$

Thus with just the hole diameter, the information used in calculating t_{drill}, and the representative idle power (1,200 – 15,000 watts), one can calculate the idle energy for this drilling unit process.

C. Basic Energy

The basic power of a machine tool is the demand under running conditions in "stand-by mode". Energy-consuming peripheral equipment included in basic power are shown in Figure MR1.6. There is no relative movement between the tool and the work-piece, but all components that accomplish the readiness for operation (e.g. Machine control unit (MCU), unloaded motors, servo motors, pumps) are still running at no load power consumption. Most of the automated CNC machine tools are not switched off when not drilling and have a constant basic power. The average basic power P_{basic} of automated CNC machines is between 800 and 8,000 watt* (* From CNC manufacturing companies the basic power ranges from 1/8th to 1/4th of the maximum machine power, (see Manufacturers Reference Data in Appendix). The largest consumer is the hydraulic power unit. Hydraulic power units are the driving force for motors, which includes chiller system, way lube system and unloaded motors.

From Figure MR 1.5, the basic time is given by

$$T_{basic} = t_{load/unload} + t_{handling} + t_{drill} \quad (7)$$

where $t_{handling} + t_{drill} = t_{idle}$ as determined in equation 4.

An exhaustive study of loading and unloading times has been made by Fridriksson, 1979; it is found that these times can be estimated quite accurately for a particular machine tool and work-holding device if the weight of the workpiece is known. Some of Fridriksson, 1979 results are showed in Table MR1.4, which can be used to estimate machine loading and unloading times. For drilling representative work-holding devices are vise, jigs, parallels, V-blocks and rotary table. To these times must be added the times for cleaning the workholding devices etc.

Thus the energy for loading and unloading is given by

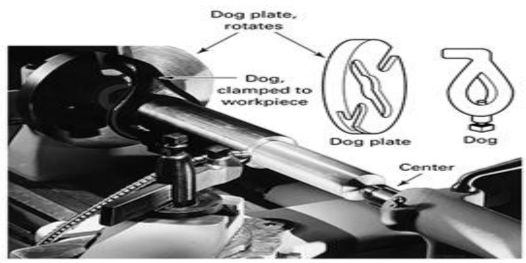
Basic energy, t_{basic} = [$time_{load/unload}$ + $time_{idle}$]*P_{basic} (8)

Where $time_{idle}$ is given in earlier sections and $time_{load/unload}$ is from Table MR1.4. P_{basic} is in the range of 800 to 8,000 watts.

Thus the uplci user must add some reasonable value from Table MR1.4 for the load/unload times and can then use the $time_{idle}$ to determine the Basic energy

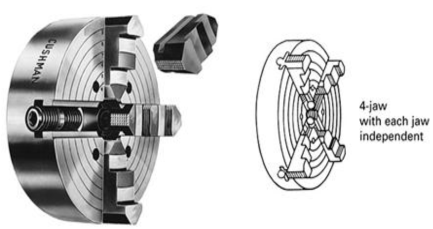
Table MR 1.4. Sum of the Loading Times and Unloading Times (sec) versus Workpiece weight (Fredriksson, 1979) (load and unload times are assumed equal)

	Workpiece Weight				
Holding Device	**0-0.2** **0-0.4**	**0.2-4.5** **0.4-10**	**4.5-14** **10-30**	**14-27 (kg)** **30-60 (lb)**	**Crane**
Angle Plate	27.6	34.9	43.5	72.1	276.5
					
Between Centers, with dog	25.6	40.2	57.4	97.8	247.8



Between Centers, no dog	13.5	18.6	24.1	35.3	73.1
Chuck, universal	16.0	23.3	31.9	52.9	--

Chuck, independent (4 jaws)	34.0	41.3	49.9	70.9	--

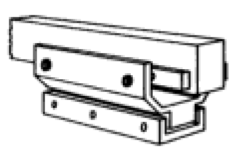


Clamp on table (3 clamps)	28.8	33.9	39.4	58.7	264.6

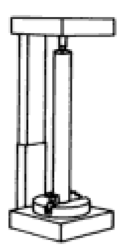
Collet	10.3	15.4	20.9	--	--

Faceplate (3 clamps)	31.9	43.3	58.0	82.1	196.2

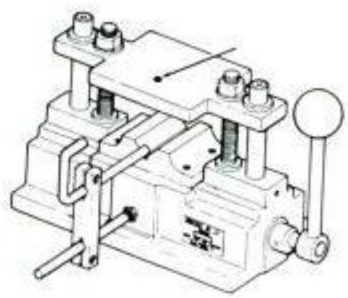

Fixture, horizontal (3 screws)	25.8	33.1	41.7	69.4	274.7



Fixture vertical (3 screws)	27.2	38.6	53.3	--	--



Hand-held	1.4	6.5	12.0	--	--
Jig	25.8	33.1	41.7	--	--



Magnet table	2.6	5.2	8.4	--	--

Parallels	14.2	19.3	24.8	67.0	354.3

Rotary table or

Index plate (3 clamps)	28.8	36.1	44.7	72.4	277.7

“V” Blocks	25.0	30.1	35.6	77.8	365.1

Vise	13.5	18.6	24.1	39.6	174.2

In summary, the unit process life cycle inventory energy use is given by

$$E_{total} = P_{basic} * (t_{basic}) + P_{idle} * (t_{idle}) + P_{drilling} * (t_{drilling}) \quad (9)$$

This follows the power diagram in Figure MR 1.5. With only the following information the unit process life cycle energy for drilling can be estimated.

1. material of part being manufactured
2. diameter, number of holes, and location
3. hole depth to be drilled
4. Table MR1.4

IV. Method of Quantification for Mass Loss

The mass loss streams in drilling process, identified with the associated process performance measures, are depicted in the Figure MR1.8 below.

		Drilling
Waste Stream	Gas/Aerosol	• Cutting fluid mist • Dust (dry machining)
	Solid	• Chips, worn tools
	Liquid	• Spent cutting fluids

Figure MR1.8. Waste Streams in drilling process

A. Lci for Material Mass Loss Calculations

The workpiece material loss after drilling a hole can be specified as chip mass (m_s). Metal chips are accumulated, and cutting fluid is separated from these. The chip mass (m_s) can be calculated by multiplying the volume of material removed ($V_{removal}$) by the density of the workpiece material ρ.

Density of the material can be attained from the material property list as shown in Table MR1.2(a), kg/m^3.

Volume of the material removed for a hole = $V_{removal} = \frac{\pi D^2}{4} * d$ [mm^3] (10)

Where

D = Diameter of the hole in mm,

d = depth of the hole in mm.

Chip mass (m_s) = $V_{removal}$ * ρ * (1 m^3/1 E+09 mm^3) [kg] (11)

B. Lci for Cutting Fluid Waste Calculations

For drilling operations, cutting fluids can be used to allow higher cutting speeds, to prolong the cutting tool life, and to some extent reduce the tool - work surface friction during machining. The fluid is used as a coolant and also lubricates the cutting surfaces and the most common method is referred to as flooding (23). Table MR1.5 shows the recommended cutting fluid for drilling operation. Cutting fluid is constantly recycled within the CNC machine until the properties become inadequate. The dilution fluid (water) is also supplied at regular intervals due to loss through evaporation and spillage.

Table MR1.5. Cutting fluid recommendations for drilling operation (Hoffman et al., 2001)

Material	Drilling (most of these cutting fluids are aqueous suspensions)
Aluminum	Soluble Oil (75 to 90 percent water). Or 10 Percent Lard oil with 90 percent mineral oil.
Alloy Steels	Soluble oil
Brass	Soluble oil (75 to 90 percent water). Or 30 percent Lard oil with 70

	percent Mineral oil.
Tool steels and Low carbon Steels	Soluble Oil
Copper	Soluble Oil
Monel Metal	Soluble oil
Cast iron	Dry
Malleable Iron	Soluble Oil
Bronze	Soluble oil
Magnesium	60-second Mineral Oil

The service of a cutting fluid provided to one CNC machine tool for one year was considered as the functional unit. It is assumed that the number of parts produced per unit time will not vary depending on the cutting fluid replacement. The drilling time associated with one year of production was based on the schedule of 102 hr of drilling/week for 42 weeks/year from one of the most comprehensive cooling fluid machining studies (Andres et al., 2008). From (Andres et al., 2008) a single CNC machine using cutting fluid required an individual pump to circulate the fluid from a 55 gallon (208L) tank to the cutting zone. The 208L/machine is recycled within process until it is disposed of after two weeks. Assuming cutting fluid is used 204 hr/ 2 weeks, then the cutting fluid loss is 208L/ (204*60) per minute. Which is 0.017 L/min or about 17 g/min as the effective loss of cutting fluid due to degradation. The coolant is about 70wt% - 95 wt% water, so at 85wt% water, the coolant oil loss is 15wt% or 2.5 g cutting oil/min. With the machining time for drilling a hole the mass loss of coolant oil can be calculated.

There is also a fugitive emissions factor here that could account for aerosol losses. Wlaschitz and Hoflinger (2007) measured aerosolized loss of cutting fluid from a rotating machining tool under flooding conditions. For a cutting fluid use of 5,700 g/min, the aerosol oil loss was about 0.0053 g/min and water loss of 0.1 g/min. Other losses from spills and carry off (drag-out) on workpieces were not included at this time.

C. Lci for Lubricant Oil Waste Calculations

Lubricant oil is mainly used for a spindle and a slide way. Minute amount of oil is infused to the spindle part and the slide way at fixed intervals. From the CNC manufacturing companies it is found that lubricant oil is replaced only 2-3 times of the life of the machine. It is assumed that the life of the machine is around 20 years. Since it is negligible lubricant oil loss is not considered for this study.

D. Cutting Tool usage

Drilling processes often require regular replacement of cutting tools. The tool life is a time for a newly sharpened tool that cuts satisfactorily before it becomes necessary to remove it for regrinding or replacement. Worn tools contribute significantly to the waste in the form of wear particles and a worn tool at the end of tool life. The wear particles usually are carried away by the cutting fluid. From an environmental perspective the cutting tools remaining at the end of the tool life are of importance as they are often disposed off and hence are a burden to the environment. The worn tool can be identified by the process performance in terms of the cutting forces, energy consumed, and surface finish. For simplification regrinding of the tools are not considered.

V. Case Study on Drilling

In this report we analyze the detailed energy consumption calculations in drilling process. The machining process is performed on Jeenxi Technology 4-axis CNC machine (JHV – 1500) in a high production mode. The machine specifications are listed below:

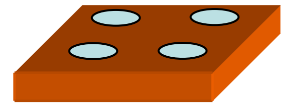
Table MR1.6. Specifications of JHV – 1500 CNC Machine

Model	**JHV - 1500**	
TRAVEL	Liner	
X axis Travel (mm)	1500	
Y axis Travel (mm)	750	
Z axis Travel (mm)	700	
Distance from the table to spindle nose (mm)	120 – 820	
TABLE		
Table dimensions, mm	1650 x 750	
Max. load of table (kg)	1000	
SPINDLE (rpm)	8000	
Spindle Taper	BT - 40	BT - 40
Spindle Speed (rpm)	8000, 10000	10000, 12000, 15000

Spindle Drive	Belt type	Direct type
Spindle Motor (kw)	7.5 / 11	7.5 / 11
Spindle Cooling	Oil Cooler	
FEED RATE		
Rapid Traverse (X,Y) (m/min), HTR	30	
Rapid Traverse (Z) (m/min), VTR	24	
Cutting Feed rate (mm/min), f_r	1 – 15000	
3 Axes motor output (X, Y, Z) (kw)	4.0 / 4.0 / 7.0	
A.T.C		
Magazine Type	Carosel	Arm
Tool Magazine Capacity (pcs)	16	24
Max. Tool Diameter (mm)	100 / 150	80 / 150
Max. Tool Length (mm)	300	300
Max. Tool Weight (kg)	7	7
Tool Selection	Fixed type	Random
OTHER		
Maximum Power Consumption (KW)	30	
Floor Space (L x W x H)	4100 x 2640 x 2810 mm	
Machine Weight (kg)	11000	

A. Product Details:

For this example we are assuming a grey cast iron (BHN 180) as the work piece. The work piece is a square block of dimensions 100 mm x 100 mm x 50 mm (L x H x B). The objective of the study is to analyze the energy consumption in drilling 4 symmetrical holes of 19 mm diameter through the thickness of the work piece. The product dimensions are shown in Figure MR1.9. From the dimensions and the density from Table MR1.2(a), the weight of the workpiece is 3.6 kg.



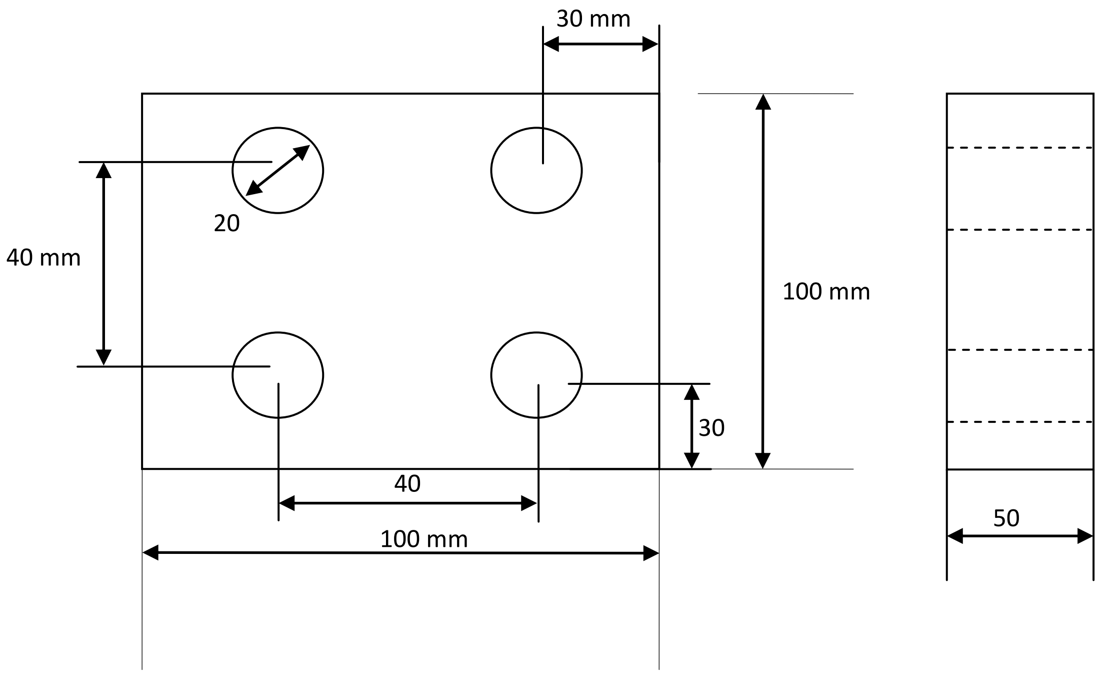


Figure MR 1.9. Dimensions of the Work piece

B. Cutting Parameters:

The machining conditions and the cutting parameters are listed in Table MR1.7.

Table MR1.7. Cutting Parameters for Example Case

Cutting Conditions	
Drill Diameter (D)	19.1 mm
Cutting Speed (V), Table MR1.2(a)	25 m/min
Feed (f), Table MR1.2(b)	0.267 mm/rev
Spindle Speed (N) = V/πD	417 rpm
Feed rate (f_r) = f*N	111 mm/min
Volume removal rate (VRR) = $0.25\pi D^2 f_r$	31,800 mm^3/min
Depth of hole (Workpiece Thickness)	50 mm
Rapid Horizontal Traverse rate, HTR,	30

(horizontal, X,Y) (m/min)	
Rapid Vertical Traverse rate, VTR (vertical, Z) (m/min)	24

C. Machining Process

Before drilling holes on the work piece in a CNC machine, it is important to set the co-ordinate axes of the machine with respect to the work piece. The left bottom hole on the top surface is considered as the origin (reference point). All dimensions are considered with reference to the origin. The direction along the length and breadth are taken as positive X and Y axis respectively. The vertical plane perpendicular to the work piece is considered as the Z-axis. The direction inwards the work piece is taken as negative.

During the drilling process the tool is considered to be at an offset of 6mm (0.3 times the diameter of the tool) above the work piece. Every time while drilling a hole the tool comes down from a height of 6mm before drilling a hole with 6 mm overtravel. For a 50 mm workpiece thickness, it retracts 62 mm back to the offset position after completing the drilling process. The feeds and speed are stated in Table MR1.7.

D. Time, Power, and Energy calculations per hole

The total processing time can be divided into the 3 sub groups of basic time, idle time, and drilling time.

Drilling Time:

The time for drilling or enlarging a through hole of length 50 (mm) is determined by

$$t_{drilling} = d/f*N = d/f_r \quad \text{(min)}$$

Where d is the workpiece thickness of the given hole in mm, f is the feed in mm/rev, and N is the drill rotational speed in rev/min.
d = depth of the cut = 50mm

Time to drill a hole will be,

$$t_{drilling} = (50)/ 111$$

$$= 0.45 \text{ min/hole} = 27 \text{ sec/hole}$$

Machining Power for each hole,

$$p_{drilling} = VRR * \text{Specific cutting energy}$$

VRR from Table MR1.7 = 31,800 mm^3/min and specific cutting energy, Up, from Table MR1.2(a) = 1.3 W/mm^3/sec

$$p_{drilling} = (31,800/60) *1.3 = 0.69 \text{ kW}$$

Tip Energy required per hole is $e_{drilling} = p_{drilling} * t_{drilling}$ = 0.69 * 27 = 19 kJ/hole

Handling Time:

Time required for the cutter to move from home position to approach point (25mm) is essentially drilling in air. The air time of the rapid traverse speed to approach is

$$t_{a1} = 25/ \text{(traverse speed)}$$

$$t_{a1} = 25/ 24000 \text{ mm/min}$$

$$= 0.001 \text{ min} = 0.06 \text{ sec (neglect)}$$

Time required for the drill to move from offset position to work piece location is called approach time and is essentially drilling in air. The air time of the approach is

$$t_a = 0.3*D/f_r$$

$$t_a = 5.7/ 111 \text{ mm/min}$$

$$= 0.05 \text{ min} = 3 \text{ sec}$$

Following this logic, the air time for a single hole, when not cutting the workpiece, is the approach plus overtravel distance which are repeated when the drill retracts, the handling distance is

(0.3D + 0.3D)+ (0.3D + 50mm thickness + 0.3D)

(approach + overtravel) + (retraction)

$t_a = [(0.3*D)+(0.3*D)]/(f_r) + [(0.3D + d + 0.3D)]/VTR$

$t_a = [(0.3*19.1)+(0.3*19.1)]/(111) + [(5.7+50+5.7)]/24,000$ mm/min

= 0.106 min = 6.3 sec

For a single hole there is no traverse to other workpiece holes.

Idle power of the machine can be calculated based on the individual power specifications of the machine.

$$P_{idle} = P_{spindle} + P_{coolant} + P_{axis}$$

The assumed values are

$P_{coolant}$ = 1 kW (~1.5 hp); $P_{spindle}$ = 4 kW (~5 hp); P_{axis} = 5 kW (~7 hp)

(These assumed values are from the CNC manufacturing companies, see Appendix 1)

To convert a horse power rating (HP) to Watts (W) simply multiply the horsepower rating by 746

Idle power for the process is

$$P_{idle} = P_{spindle} + P_{coolant} + P_{axis}$$

$$= 4 + 1 + 5$$

$$= 10 \text{ kW}$$

Total Idle time for 1 hole $t_{idle} = t_a + t_{drilling} = 6.3 + 27$

$= 33$ sec

Total Energy during the idle process per hole is,

$$e_{idle} = P_{idle} * t_{idle}$$

$$= 10*33$$

$$= 330 \text{ kJ/hole}$$

Load/unload Time:

The total basic time can be determined based on the following assumptions for this example:

- The workholding device used for clamping the workpiece is a simple vise, Table MR1.4.

- The total time required to mount the work piece on the vise manually is thus 9.3 sec.
- After completing the drilling process on a single workpiece, the machine is cleaned using pneumatic cleaners or air blowers. The time required to clean the machine is assumed to be 0.4 min (25 sec).
- The machined part has to be removed manually from the fixture. The time required to remove the material from the fixture is assumed to be 9.3 sec.

Therefore, load/unload processes time for this study is,

$$T_{l/u} = \text{loading time} + \text{cleaning time} + \text{unloading time}$$

$$= 9.3 + 25 + 9.3$$

$$= 44 \text{ sec}$$

Basic power of the machine can be assumed as the 25% of the machine maximum in the manufacturer specifications. Therefore the power consumed during the basic process is,

$$P_{basic} = 7.5 \text{ kW}$$

Energy consumed during this process is,

$$E_{basic} = P_{basic} * t_{basic}$$

The basic time for the process to drill 1 hole can be taken as the sum of idle time (which contains machining time) and load/unload times, i.e.

$$T_{basic} = T_{l/u} + t_{idle}$$

$$= 44 + 33$$

$$= 77 \text{ sec}$$

$e_{basic\ per\ hole}$ = 7.5* 77 = 577.5 kJ per hole

Total Energy required for drilling 1 hole can be determined as,

$$e_{process} = e_{drilling} + e_{idle} + e_{basic}$$

$$=19 + 330 + 577.5$$

$$= 926.5 \text{ kJ/ one hole}$$

Power required for machine utilization during drilling per hole is,

$$P_{mtotal} = e_{process} / t_{total}$$

$$= 926.5/77 = 12.03 \text{ kW.}$$

E. Time, Power and Energy calculations drilling 4 holes

Drilling Time:

The time required to drill 4 holes is considered as the drilling time.

The time for drilling or enlarging a through hole of length 50 (mm) is determined by

$$t_{drilling} = d/f*N = d/f_r \quad \text{(min)}$$

Where d is the total drill travel necessary for making the given hole in mm, f is the feed in mm/rev, and N is the drill rotational speed in rev/min.
d = depth of the cut = 50mm

Time to drill a hole will be,

$$t_{drilling} = (50)/111$$

$$= 0.45 \text{ min/hole} = 27 \text{ sec/hole}$$

Machining Power for each hole,

$$p_{drilling} = VRR * \text{Specific cutting energy}$$

VRR from Table MR1.7 = 31,800 mm^3/min (530 mm^3/sec and specific cutting energy, Up, from Table MR1.2(a) = 1.3 W/mm^3/sec

$$p_{drilling} = 530 *1.3 = 0.69 \text{ kW}$$

The total drilling time for 4 holes is,

$$T_{drilling} = 0.45 \text{ min} * 4$$

$$= 1.80 \text{ min} = 108 \text{ sec}$$

Machining power for drilling 4 holes is,

$$P_{drilling} = 0.69 \text{ kW}$$

Tip Energy required to drill 4 holes is $E_{drilling} = P_{drilling} * T_{drilling} = 0.69 * (108) = 75$ kJ

Handling Time:

The air time for 4 holes is four times that for the single hole

$$T_a = t_a * 4 = 6.3 * 4$$

$= 25$ sec

Because this is a multi-hole workpiece, the tool moves rapidly from one hole to other. The traverse time from manufacturers specifications, Appendix 1, is 30m/min, Table MR1.7. In order to calculate the tool total rapid traverse time, we assume the tool to move linearly (neglecting the effect of tool rotation), 160 mm (4 holes, 40mm apart).

$$T_t = \text{Total rapid traverse/ traverse speed}$$

$$= 160/30{,}000\text{mm/min}$$

$$= 0.005 \text{ min} = 0.32 \text{ sec}$$

Thus compared to the handling times of 108 sec, we can neglect the traverse time to multiple holes for rapid axis movement for this high production case.

Total idle time for the machine during a high production campaign can be determined as described in the following. The total idle time and drilling time for drilling 4 holes of the machine is,

$$T_{idle} = T_a + T_{drilling}$$

$$= 25 + 108$$

$$= 133 \text{ sec}$$

Idle power of the machine can be calculated based on the individual power specifications of the machine.

$$P_{idle} = P_{spindle} + P_{coolant} + P_{axis}$$

The assumed values are

$P_{coolant}$ = 1 kW (~1.5 hp); $P_{spindle}$ = 4 kW (~5 hp); P_{axis} = 5 kW (~7 hp)

(These assumed values are from the CNC manufacturing companies, see Appendix 1)

To convert a horse power rating (HP) to Watts (W) simply multiply the horsepower rating by 746

Idle power for the process is

$$P_{idle} = P_{spindle} + P_{coolant} + P_{axis}$$

$$= 4 + 1 + 5$$

$$= 10 \text{ kW}$$

Total Idle time for 4 holes $T_{idle} = T_a + T_m + T_t$, where T_t is negligible

$= 133$ sec

Total Energy during the idle process for 4 holes is,

$$E_{idle} = P_{idle} * T_{idle}$$

$$= 10*133$$

$$= 1{,}330 \text{ kJ}$$

Load/unload Time:

The load/unload processes time for this study is,

$$T_{l/u} = \text{loading time} + \text{cleaning time} + \text{unloading time}$$

$$= 9.3 + 25 + 9.3$$

$$= 44 \text{ sec}$$

Basic power of the machine can be assumed as the 25% of the machine maximum in the manufacturer specifications. Therefore the power consumed during the basic process is,

$$P_{basic} = 7.5 \text{ kW}$$

Energy consumed during this process is,

$$E_{basic} = P_{basic} * T_{basic}$$

The basic time for the process to drill 4 holes can be taken as the sum of idle time (which contains machining time) and load/unload times, i.e.

$$T_{basic} = T_{l/u} + T_{idle}$$

$$= 44 + 133$$

$$= 177 \text{ sec}$$

$E_{basic} = 7.5 * 177 = 1{,}328$ kJ for 4 holes

Total Energy required for drilling 4 holes can be determined as,

$$E_{process} = E_{drilling} + E_{idle} + E_{basic}$$

$$=75 + 1{,}330 +1{,}328$$

$$= 2{,}733 \text{ kJ/ 4 holes}$$

This energy is 680 kJ/hole or slightly lower (due to only one load/unload cycle for four holes) than the 926 kJ/hole for a workpiece requiring only one hole.

Power required for machine utilization during drilling process is,

$$P_{mtotal} = E_{process} / T_{total}$$

$$= 15.4 \text{ kW}$$

The total time for this four-hole piece is about 177 sec (2.95 min). If we look at typical set-up times, Table MR1.1, of about one hour then for a batch of greater than 200 pieces, the set-up times is less than 10% of the time and energy of the actual overall drilling of the workpiece. Thus for smaller batches than 200 pieces, set-up might need to be included.

F. Lci Material mass loss calculations

Volume of the material removed for a hole = $V_{removal} = \frac{\pi D^2}{4} * d$ [mm^3]

$$= \mathbf{14{,}169\ mm^3}$$

Chip mass (m_s) = $V_{removal} * \rho$ [kg]

$$m_s = 14{,}169 * 7{,}300 * 10^{-9}$$

$$\mathbf{= 0.10\ kg/hole}$$

G. Lci for Cutting fluid waste calculations

From (Andres et al., 2008) a single CNC machine using cutting fluid required an individual pump to circulate the fluid from a 55 gallon (208L) tank to the cutting zone. The 208L/machine is recycled within process until it is disposed of after two weeks. Assuming cutting fluid is used 204 hr/ 2 weeks, then the cutting fluid loss is 208L/ (204*60) per minute, which is 0.017 L/min or about 17 g/min. The coolant is about 70wt% - 95 wt% water, so at 85wt% water, the coolant oil loss is 15wt% or 2.5 g cutting oil/min (= 0.042 g/sec).

Drilling time per hole t_m = 27 sec

Mass loss of the coolant = 0.042*27 = 1.1 g cutting oil/hole

Mass loss of the coolant for 4 holes = 0.042 *27 * 4 = 4.5 g cutting oil/4 holes.

The fugitive loss is 0.1 g cutting oil/min or 0.18 g cutting oil/4 holes

VI. Summary

This report presented the models, approaches, and measures used to represent the environmental life cycle of drilling unit operations referred to as the unit process life cycle inventory. The five major environmental-based results are energy consumption, metal chips removed, cutting fluid, lubricant oil, and cutting tool. With only the following information the unit process life cycle energy for drilling can be estimated.

1. material of part being manufactured
2. diameter, number of holes, and location
3. hole depth to be drilled
4. Table MR1.4

The life cycle of drilling is based on a typical high production scenario (on a CNC drilling machine) to reflect industrial manufacturing practices.

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VIII. Appendices

A. Manufacturers Reference Data

The methodology that has been followed for collecting technical information on CNC machines has been largely based in the following:

The documentation of the CNC machine and the technical assistances collected from the manufacturing companies through internet. Several interviews with the service personnel of the different CNC manufacturing companies have been carried out. After collecting the information from the different companies it has been put together in the relevant document that describes the different approaches the different companies have regarding the technical information on the CNC machines. Telephone conversations allowed us to learn more about basic power and idle power. Companies that involved in our telephone conversations are Bridge port, Fadal, Hass and Jeenxi. These companies' manufactures different sizes of CNC machines, but this report shows the lower, mid and highest level of sizes. For our case study we picked machine at the highest-level.

Specifications	JEENXI TECHNOLOGY		
Model Number	JHV – 850	JHV – 1020	JHV – 1500
Spindle Speed	8000 rpm	8000 rpm	8000 rpm
Spindle Drive	Belt/Direct type	Belt/Direct	Belt/Direct type
Spindle Motor	5.5/7.5 kw	7.5/11 kw	7.5/ 11 kw
Rapid Traverse (X,Y)	30 m/min	30 m/min	30 m/min
Rapid Traverse (Z)	20 m/min	20 m/min	24 m/min
Cutting Feed rate	1 – 15000 mm/min	1 – 15000 mm/min	1 – 15000 mm/min

3 Axes motor output(X,Y,Z)	1.8/ 1.8/ 2.5	1.8/ 1.8/ 2.5	4.0/ 4.0/ 7.0
Power Consumption	20 KVA	20KVA	40 KVA

Specifications	HAAS		
Model Number	**VF- 7**	**VM - 2**	**MDC**
Spindle Speed	7500 rpm	12,000 rpm	7,500 rpm
Spindle Drive	Belt/Direct type	Inline direct drive	Direct speed belt drive
Max Torque	75 ft-lb@1400	75 ft-lb@1400	75 ft-lb@1400
With Gearbox	250 ft-lb@ 450	-	-
Spindle motor max rating	20 hp	30 hp	20 hp
Axis Motor max thrust	3400 lb	3,400 lb	2,500 lb
Rapids on X-axis	600 ipm	710 ipm	1,000 ipm
Rapid on Y & Z Axes	600 ipm	710 ipm	1,000 ipm
Max Cutting	500ipm	500 ipm	833 ipm
Power Consumption(min)	200 – 250 VAC 380 – 480 VAC	200 – 250 VAC 380 – 480 VAC	200 – 250 VAC 380 – 480 VAC

Specifications	KAFO		
Model Number	**VMC – 850**	**VMC – 137**	**VMC - 21100**
Spindle speed (Belt)	8000 rpm	8,000/10,000 rpm	6000/8000 rpm
Spindle speed (Gear)	4000/7000 rpm	4000/7000 rpm	4000/7000 rpm
Rapid Traverse (X, Y)	590.55 ipm	787.4 ipm	393.7 ipm
Rapid Traverse (Z)	472.44 ipm	787.40 ipm	393.7 ipm

Cutting feed rate	236.22 ipm	393.7 ipm	393.7 ipm
Spindle drive motor	7.5/ 10 hp	15/ 20 hp	15/20 hp
X,Y,Z axis drive motor	a12, a12, a12	a22, a22, a30	a30, a30, a30
Power consumption	20 KVA	25 KVA	35 KVA

Specifications	BRIDGE PORT		
Model Number	XR 760	XR 1270 HP	XR 1500 HPD
Spindle Speed(Belted)	9000/15000 rpm	-	-
Fanuc Motor Power	25/25 hp	-	-
Heidenhain Motor Power	28/28 hp	-	-
Spindle Speed(Directly coupled)	15000 rpm	15000 rpm	375 – 7500 rpm (Gear Box)
Fanuc Motor Power	30 hp	40 hp	40 hp
Heidenhain Motor Power	33 hp	34 hp	40 hp
Rapid Traverse (X,Y)	1692 ipm	1417 ipm	1417 ipm
Rapid Traverse (Z)	1417 ipm	1417 ipm	1417 ipm
Cutting Feed rate	787 ipm	787 ipm	787 ipm
Power	30 KVA	40 KVA	40 KVA

Specifications	FADAL		
Model Number	VMC 4020	VMC 6030	VMC 6535 HTX
Spindle Speed	10 - 10,000 rpm	10 - 10,000 rpm	6000 rpm
Spindle Drive	Automatic Mechanical	Automatic Mechanical	Automatic Electric

	Vector Drive	Vector Drive	Vector Drive
Rapid Traverse (X,Y)	900 ipm	400 ipm	900 ipm
Rapid Traverse (Z)	700 ipm	400 ipm	700 ipm
Cutting Feed rate	600 ipm	400 ipm	600 ipm
Motor Power	10 hp	14.7 hp	29.5 hp
Air Pressure Required	80 – 120 psi	80 – 120 psi	80 – 100 psi

Specifications	TTC		
Model Number	**TTC-630**	**TMC 500**	**XR 1500 HPD**
Spindle Speed(Belted)	4000 rpm	6000	-
Spindle Motor Power	15/20 KW	5/7 KW	-
X Axis Motor Power	2.8 KW	-	-
Z Axis Motor Power	2.8 KW	15000 rpm	375 – 7500 rpm (Gear Box)
Coolant Pump Motor Power	1 KW	40 hp	40 hp
ATC Motor Power	12.6 KW	34 hp	40 hp
Rapid Traverse (X,Y)	197 mm/min	1417 ipm	1417 ipm
Rapid Traverse (Z)	630 mm/min	1417 ipm	1417 ipm
Total Driving Power	40 KW	787 ipm	787 ipm
Hydraulic Pump	1.1 KW	40 KVA	40 KVA

The development of the format, the accessible information sources, the use of metric and English units, and the parameters for examples were developed. This required an extensive amount of time since input from potential users and those who might generate further uplci had to be obtained. The goal was to have a generic format that was suitable for all the current processes in the taxonomy, but would also be used with emerging unit processes at research and development organizations. The generic format will allow comparisons and direct exchange of information in the future. The completed uplci reports are listed in Table 1. Another five are in draft form.

The results from this grant have been used in a number of Conferences to expand the community of engineers and companies developing uplci from the taxonomy. The generic format is critical to efficient development of the entire set of unit processes by the large community of potential users.

Table 1 Unit process life cycle reports in current funding cycle

1. Drilling
2. Milling
3. Turning
4. Shearing
5. Submerged arc welding
6. Gas metal arc welding
7. Brakeforming
8. Punch Press

In research concept 2, the emphasis was on the materials and chemicals that enter the unit processes described above in research concept 1. That is, an entire wind generator is a complex assembly of parts and subassemblies, all of which began back in the supply chain as refined materials and chemicals. These are the inputs to the various product manufacturing plants. However these materials and chemicals (such as aluminum or epoxy) are the end point of a further supply chain back to natural resources from the globe. Thus the emphasis in research concept 2 is to develop and refine the life cycle inventory structure so that a useful database for wind generation is constructed. Such a database should capture the most frequently used materials in wind generators, but not necessarily by virtue of the largest mass used. The objective is to have the largest cluster of materials and chemicals such that all of the manufacturers of the sub parts in a wind generator can use the lci to seek improvement. This is a more transparent and distributed approach that can achieve greater effort at environmental improvement in wind generation.

The following is a description of the inputs needed to create a life cycle inventory profile of a material or chemical manufacturing process. It is meant to be representative of this product manufacturing and is not a detailed engineering design or construction description. The collection of this information can be by the staff of the manufacturing plant or by one of the life cycle team. The life cycle inventory (lci) steps are as follows:

1. Create a process flow diagram (PFD) with blocks for the major unit processes.

2. Prepare a Table that shows the ingredients, chemicals, and materials that are inputs to the process and where on the PFD these enter the process. These inputs are on a dry weight or undiluted basis. Use the Chemical Abstract Service (CAS) number for each chemical name. It is important to avoid tradenames and state the best estimate of what is the ingredient. These are expressed as mass per unit time (like day, hr, or year). Any major water, solvents, or similar additional materials are also listed in the same mass per unit time basis. There are no firm rules for very small inputs as these may or may not be important. The best rule is to list the masses of inputs down to about 0.5 wt % of the product weight. Then for any others below this, just make a list with no mass.
3. Prepare a Table that shows all products, co-products, or byproducts. Again, dry or undiluted basis is to be used and the same format of mass per unit time as the inputs should be used. The location of all outputs must be shown in this Table or on the PFD. All water, solvents, etc. outputs are to be also shown.
4. Prepare a Table that shows all chemical or material losses and respective locations of these losses on the PFD. These losses are usually wastes. The general mass of inputs minus the mass of products (co-products and byproducts) will equal the chemical/material losses. The same dry basis and mass per unit time formats as the inputs and product outputs should be used.
5. Finally, an energy Table is to be produced. The goal is to estimate the energy for each of the major unit process blocks shown in the PFD. The energy must be estimated for the process when the mass inputs and product outputs are at the levels specified in 2) and 3) above. This then relates energy to a specific level of inputs or product manufacturing. The first step is to put the approximate temperature (unless it is room temperature) and pressure (unless it is one atmosphere) on the streams going in and out of the major unit processes on the PFD.

   The energy is next estimated for each process in six possible energy types described below. The sum of these energies equals the total energy of the particular unit process and the sum of all the unit process energies must equal the total process energy for the manufacturing of a specific product.

   a. Overhead energy: While it is not often measured or known, an estimate of the overhead energy use (that is, when the manufacturing plant is not running for an extended period of time (no product output), what energy is still required for the plant electricity, steam, natural gas, etc?).
   b. Electrical energy (the preferable data are amps drawn and the voltages when the unit process throughput at the level described in 2) and 3) above). If this measurement is not possible, then the horsepower rating of the machine is needed. When all the major unit process horsepower values are collected for the plant, the kwh for a month (if that is the billing or measuring cycle) and the overall product manufactured for that cycle are used.
   c. Steam use by each unit process (lb per unit time) and some estimate of the steam temperature and pressure. If steam use by unit process cannot be estimated, then total steam use per unit time for the total manufacturing process should be given and a best guess as to the % that goes to each unit process must be made.

d. Other heat transfer fluids, like Dowtherm, (estimated lb/unit time and temperature)
e. Any very high temperature heating by direct flame use of natural gas or fuel combustion. Note, this is not the fuel used to make steam, but rather any other very high temperature process, like a kiln.
f. Cooling is any heat removed from the process by cooling heat exchangers, refrigeration, air cooling, etc. If heat removal is not known, the inlet and outlet temperature of the process material being cooled can be listed along with the process material mass flow rate.

An example of the lci for aluminum oxide as a part of the supply chain for aluminum is given below in which the numbering and format system is retained to demonstrate the project results.

Aluminum oxide, metallurgical grade

CONTENTS OF FACTORY GATE TO FACTORY GATE

LIFE CYCLE INVENTORY SUMMARY

IX. Chemistry

Primary reaction:

$$Al(OH)_3 + Na^+ + OH^- \longleftrightarrow Na^+ + Al(OH)_4^- \quad (1)*$$

$$2Al(OH)_3 \rightarrow Al_2O_3 + 3H_2O \quad (1a)$$

*Gibbsitic bauxite

Desilication reactions: (desilication is used to lower SiO_2 content to below 0.6 g/L)

$$4Al_2Si_2O_5(OH)_4 + 24NaOH \rightarrow 8NaAlO_2 + 8Na_2SiO_3 + 20H_2O \quad (2)$$

kaolin + sodium hydroxide → sodium silicate + water

$$8NaAlO_2 + 8Na_2SiO_3 + 5Al_2O_3 + 10SiO_2 + 3H_2O \rightarrow 3[Na_8Al_6Si_6O_{24}(OH)_2] \quad (3)$$

Net desilication (R1 + R2)

$$4Al_2Si_2O_5(OH)_4 + 24NaOH + 5Al_2O_3 + 10SiO_2 \rightarrow 17H_2O + 3[Na_8Al_6Si_6O_{24}(OH)_2]^* \quad (4)$$

Notes: $[Na_8Al_6Si_6O_{24}(OH)_2]$ is referred to as Bayer desilication product 1 in this GTG document.

In the mass balance Table, $Al(OH)_3$ as a reactant rather than Al_2O_3. Thus the substitution 5 Al_2O_3 + 15 H_2O = 10 $Al(OH)_3$

Additional desilication

$$8NaOH + 6Al(OH)_3 + 6SiO_2 + CO_2 \rightarrow (Na_2O.Al_2O_3.2SiO_2.2H_2O)_3Na_2CO_3 + 7H_2O \quad (4a)$$

Notes: $(Na_2O.Al_2O_3.2SiO_2.2H_2O)_3Na_2CO_3$ is referred to as Bayer desilication product 2 in this GTG document

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Side reactions: (loss of NaOH through carbonate formation)

$$2NaOH + CO_2 \rightarrow Na_2CO_3 + H_2O \quad (5)$$

$$Na_2CO_3 + Ca(OH)_2 \rightarrow CaCO_3 + 2NaOH \quad (6)^{a,b}$$

$$CaO + H_2O \rightarrow Ca(OH)_2 \quad (7)^{a}$$

Net reaction (5-7) $$CaO + CO_2 \rightarrow CaCO_3 \quad (8)$$

a CaO is added to recover NaOH from the Na_2CO_3 formed in side reaction 5.

b This reaction when done inside the dissolution tank is called inside causticization. This is typically done only for ores that dissolve easily (US 2,981,600)

X. Process Summary

A. *Literature*

World bauxite production in 2000 was 49 million tons. Some bauxite is used with no further processing in applications such as fillers or flame retardants for carpets. Most bauxite is purified to a hydroxide, and the Bayer process is used in nearly all cases (Kirk Othmer, 2002). Of the hydroxide product, about 85% was calcined to aluminum oxide (metallurgical grade alumina) (Kirk Othmer, 2002). The remainder is used as feedstock to the aluminum chemicals industry. In this GTG, we model the Bayer process and include calcination to produce a metallurgical grade product.

After mining and preparation (blending and grinding), the process has five primary steps: digestion, separation, washing, precipitation, and calcination (Kirk Othmer, 2002; Ullmann's 2002). Processing conditions depend on the availability of cheap electricity and the ore characteristics. Our bauxite mining GTG does not include grinding, and thus, it is included in this report. The bauxite ore (defined in mining GTG, and input to this GTG) contains 47.8% alumina (based on Clarendon mine in Jamaica). The weight percents of other materials are 2.6% SiO_2, 17.6% Fe_2O_3, 2.3% TiO_2, 2.4% clay (assumed to be kaolin, $4Al_2Si_2O_5(OH)_4$), and 27.3% loss on ignition (water). Bauxite is typically comprised of a mixture of gibbsite (Al_2O_3*$3H_2O$), boehmite (Al_2O_3*H_2O), and diaspore (Al_2O_3*H_2O). Assuming that the material lost on ignition is water, the aluminum oxide and water portion is 75.1 kg/100kg bauxite. Of this, 47.8 kg (63%) is aluminum oxide. This is roughly the aluminum oxide content of gibbsite. Thus we assume that the ore is primarily composed of Gibbsite and select operating conditions accordingly.

Process flow diagrams are given by Kirk Othmer (2002), Austin (1984), and Ullmann's (2002). The Bayer process flow sheet from Kirk Othmer (2002) is reproduced in Figure 1. The ore is wet ground, mixed with calcium oxide, and fed to the digester. The sodium hydroxide solution is recycled. However, the side reactions result in a net consumption of NaOH, so that it needs to be replenished. After digestion, the pressure is reduced, and the solution is filtered to remove a red mud. According to Ullmann's, the pressure is reduced in an adiabatic flash. The evaporated steam is used to preheat the recycled NaOH liquor, but in this report is catalogued as potential heat recovery. After filtering, impurities the rich liquor is cooled and aluminum hydroxide ($Al(OH)_3$) is precipitated. The lean liquor is heated (exchange with heat on cooling the rich liquor) and purified.

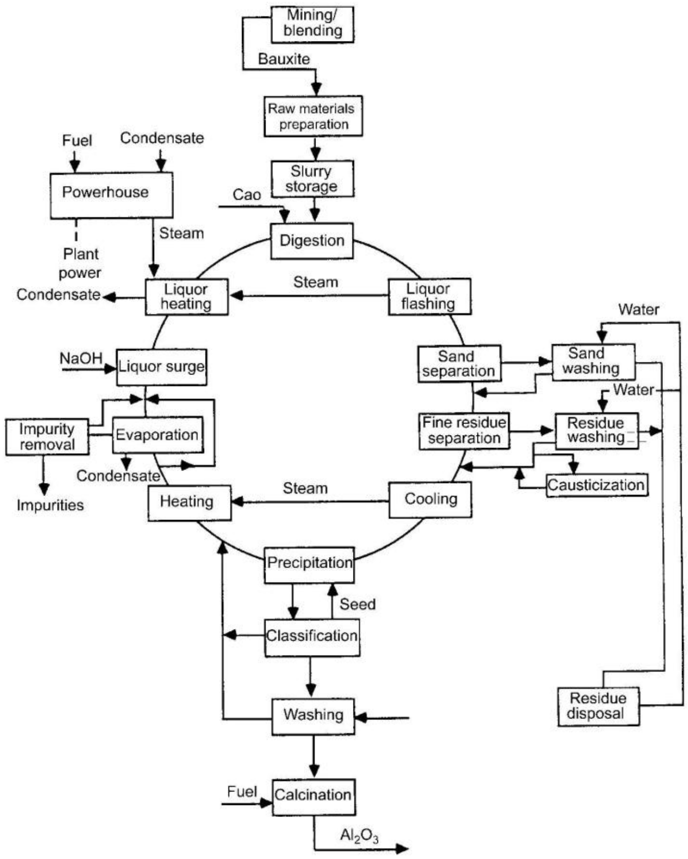

Fig. 1. Bayer process flow sheet.

Figure 1. Bayer process flow sheet from Kirk Othmer (2002)

Grinding

Bauxite is wet ground to 100mesh (150 microns) (Austin, 1984). The Bond work index for bauxite is 9.45 kWhr per metric tonne. Thus, the energy to grind to 150 microns is E = 10 * Wi $(1/(Xp)^{0.5})$ = 28 MJ/metric tonne. According to Ullmann's, wet grinding is usually done, and the feed is controlled so that the solids content in the grinding mill is 45 to 55%. We use a solids content of 50% in this GTG report.

Lime addition

Calcium monoxide is used in the Bayer process for causticization of sodium carbonate (reactions 6 and 7) and in some desilication reactions. The SiO_2 is partially soluble in the digestion mixture. Various desilication reactions have been shown in the literature. We include reactions 4 and 4a to show desilication. Another desilication reaction that is mentioned in the literature, but not included in this GTG is CaO + SiO_2 --> 2CaO*SiO2 (dicalcium silicate).

In some cases, the NaOH is formed in situ by adding $NaCO_3$ and CaO rather than using NaOH as an input. Although, sodium is now typically added as NaOH, $NaCO_3$ is formed by several reactions in the Bayer process: NaOH reacts directly with dissolved CO_2, $CaCO_3$ in the bauxite input is converted to Na_2CO_3, and organics in the bauxite are oxidized and lead to Na_2CO_3. In the case of gibbsitic ores, the $NaCO_3$ (added directly or formed by reaction with CO_2) can be converted to NaOH in the digester (inside causticization) (US 2,375,342). For Al(OH) type ores, this practice does not work as well, and $NaCO_3$ must be removed by other methods. In this GTG, we use CaO to convert Na_2CO_3 formed by reaction with CO_2. The sodium input to the process is NaOH, and we do not include any consumption of CaO for desilication.

Wellington and Valcin (2007) and Marciano et al. (2006) give values for the Na_2CO_3 concentration in the Bayer process. Wellington and Valcin (2007) provide concentrations of spent liquor from a Jamaican alumina refinery. The amount of caustic divided by the amount of caustic plus carbonate (C/S ratio) is about 0.76. In this ratio, C is defined as the Na_2CO_3 content in NaOH plus $NaAl(OH)_4$. The denominator, S, is defined as C plus the Na_2CO_3 content in Na_2CO_3. During causticization experiments, the C/S ratio was increased to 0.88. Marciano et al. (2006) give the Na_2O content in caustic (C) as 160 g/L and the Na_2O content of carbonate as 28 g/L. The C/S ratio for is thus calculated as 160/188 = 0.85. We use a C/S ratio of 0.8 in this GTG, and add enough CaO to increase C/S to 0.88 during each cycle. This gives a CaO consumption of 143 kg/1000kg of Al_2O_3produced. Ecoinvent and Buwal 250 each show 90 kg of CaO used per 1000 kg of Al_2O_3, and NREL shows 46 kg CaO per 1000 kg Al_2O_3.

NaOH balance

Sodium hydroxide transformations in the Bayer cycle are shown in Figure 2. Sodium hydroxide is consumed in desilication reactions and exits the process in waste streams. The majority of the consumption is due to the desilication reactions and depends on the amount Si in the ore in the form of silica (SiO_2) and kaolin ($Al_2O_3(SiO_2)_2(H2O)_2$). Based on the ore composition used in this GTG, 74 kg of NaOH are consumed in reactions. Additional sodium (10 kg of NaOH content) exits as NaOH or sodium aluminate in the red mud and product streams. On a basis of 1000 kg of Al_2O_3 product, 795 kg of the NaOH is converted to sodium aluminate. Of this, 791 kg is converted back to NaOH and recycled. During each cycle, 205 kg of NaOH are converted to Na_2CO_3. Carbon dioxide for this conversion is supplied by absorption from air or from organic materials in the ore (Ullmann's, 2002).

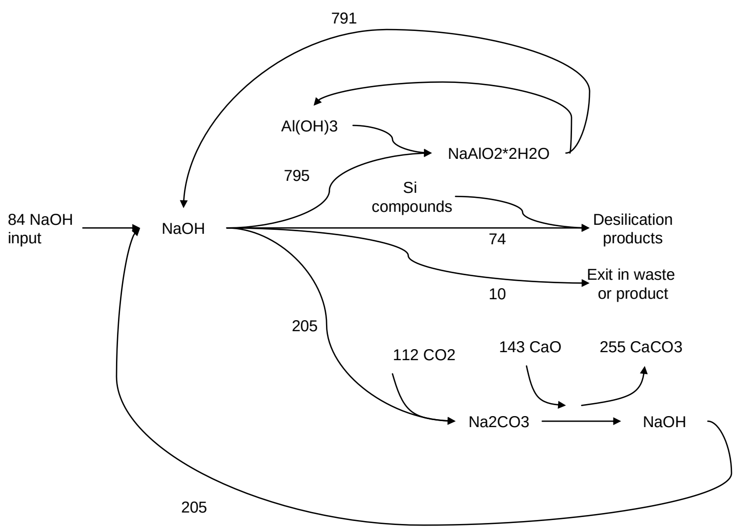

Figure 2. Sodium hydroxide balance

Digestion

Typical temperatures and NaOH concentrations for digestion are shown in Table 1. There is some flexibility in using heat or NaOH. For instance, Ullmann's (2002) gives conditions for Boehmite ore in Europe and in America. In America, the NaOH concentration and dilution rate are the same as for the Gibbsitic process. Thus, a higher temperature is required to dissolve the ore. In Europe, a lower temperature and higher NaOH concentration are used. The most economically efficient mode of operation depends on the price of utilities and raw materials. In this GTG, we use the average values for Gibbsitic ore. The alumina to caustic ratio (A/C), defined as the alumina content in g/L Al_2O_3 to caustic content in g/L of Na_2CO_3, is typically 0.5 to 0.75 (US 4,511,542). In this GTG, the ratio is 110/145*106/80 = 0.57. The concentration of NaOH in Table 1 is based on the total Na content in the solution, whether it is free caustic (NaOH), carbonate, or sodium aluminate. The free caustic of the 'pregnant liquor' can be as low as 5 g/L to as high as 150 g/L (US 20040052706). We assume an NaOH concentration of 145 g/L in the digester (including Na content of NaOH plus sodium aluminate). The quantity of free caustic (NaOH only) after the digestion is 57 g/L.

The clay (2.4 wt%) is assumed to be kaolin, and is digested according to reaction (2). Reaction (3) shows additional silica (2.6 wt%) and alumina combining with the products of reaction (2) to form a silicate precipitate specified as the product of reaction 3 (Ullmann's, 2002). The ratio of silica to kaolin in the feed is greater than the stoichiometric ratio in reaction 4. Therefore, an additional desilication reaction (4a) is used to convert the balance of silica.

The time required for digestion is specified as 10-20 minutes (U.S. 4,661,328), 20-30 minutes (US 2,701,752), and 2.5 to 3 hrs (U.S. 2,066,209). We assume a digestion time of 1 hr, and assume a low-intensity agitation.

Sodium hydroxide is not consumed in the primary reaction. It is used to dissolve the $Al(OH)_3$ in the digestion process, and is regenerated in the crystallization. However, sodium hydroxide is lost directly in the waste streams and indirectly by reaction. Both sodium carbonate, and various sodium containing desilication products exit in the waste stream. According to US 4,486,393, 15 to 25% of the cost of the Bayer process is for sodium hydroxide. Using the desilication reactions (4 and 4a) and silica content in Jamaican ore, the sodium hydroxide consumption is 74 kg/1000 kg Al_2O_3. An additional 9.6 kg NaOH /1000kg Al_2O_3 are required due to mass losses in the waste streams and product. This compares to 19, 34, and 74 kg NaOH/1000kg Al_2O_3 for BUWAL, Ecoinvent, and NREL, respectively.

Table 1. Digestion conditions.

Ore type	Source	T, oC	Concentration of NaOH, g NaOH/L	P, atm	Concentration of Al_2O_3, g/L	Yield of liquor, g Al_2O_3/L
Gibbsitic	Kirk Othmer (2002)	140	155-175	moderate		
Gibbsitic	Ullmann's (2002)	142	105-145		90-130	Increasing from 50 to > 65. Some claim 100.
Boehmite	Kirk Othmer (2002)	200-250		34 atm		
Boehmite, European	Ullmann's, 2002)	200	150-250		120-160	
Boehmite, American conditions	Ullmann's (2002)	237	105-145		90-130	

Diasporic	Kirk Othmer (2002)	higher	260-390	higher		
Diasporic	Ullmann's (2002)	262	150-250		100-150	
American process	US 6391277		155			70
European process	US 6391277		180			80
						71 with 15% fines fraction
Used in this GTG (Gibbsitic ore)		141	145 (average of Ullmann's and Kirk Othmer)	4.1 atm	110	58

Flashing

The rich liquor is typically flashed to atmospheric pressure. This accomplishes cooling with steam generation for use in preheating the lean liquor. In addition, it removes a portion of the water, which is required for crystallization. For lower temperature digesters (145 ^{o}C) as few as three stages are used in the flash. For higher temperatures (242 ^{o}C), as many as 10 stages are used to perform the flash. We use a low temperature. For the purpose of determining the amount of water flashed as steam, we show a single stage flash. The flashed steam is cooled to 25 ^{o}C with heat recovery. Ullmann's states that about 10% of the water is evaporated in each cooling area (a lower amount for low temperature digestion, and a higher amount for higher temperature digestion). In this GTG, the evaporation rate is 8.6% in the flash.

Filtration/purification

The crystallized silicates as well as the iron and titanium oxides are insoluble, and are filtered. The iron oxide dominates and gives the mud a red color. The solids distribution is typically bimodal. Up to half of the solids are in excess of 100 microns and are termed sand. The remainder of the solids are typically under 10 microns. The sands can be separated in cyclones, and the smaller particles are typically removed in a raking thickener device. For the cyclone separation, we assume a single pass through a cyclone with a pressure drop of 4 atm (Perry's gives 0.3 to 4 atm for cyclone separation). For the rake classifiers, Perry's gives a HP rating of 0.25 to 25 for a feed rate of 5 to 350 tons/hr. We use a power of 25 HP per 350 tons/hr (0.2 MJ/metric ton feed). The overflow from the rake thickener contains 0.3 g/L solids (Ullmann's, 2002). Starch or other flocculants are added at 0.5 to 3 kg/tonne of bauxite (Ullmann's, 2002). In this GTG, we show 3 kg of starch per tonne bauxite into the process. After the rake classifier, a final polish filtration is often performed. This can be achieved with a gravity filter (passing solution through a layer of sand, for instance) or pressure filtration (US 4,789,485). Either solution requires a pump to achieve the required pressure as an energy input. We assume a height of 3 meters for a gravity driven solution.

Washing of red mud

The red mud contains 35-50 % ferric oxide and 6 to 10% sodium oxides (US 3,776,717). In this GTG, the percentage is based on the feed composition, and the red mud contains 41% ferric oxide. Other components in the red mud include the desilication products, calcium carbonate and minor impurities. Typically the red mud is considered a waste; although it can be utilized as a source material for sodium or iron production as discussed in US 3,776,717. In this GTG, we consider the red mud a waste material. When the mud leaves the cyclone and rake classifier, it contains a liquid portion that contains dissolved sodium and aluminum. Typically, the red mud would be washed to recover the dissolved sodium and aluminum and reduce raw material costs. The extent of washing depends on an economic trade-off. As more water is used in the wash to achieve a higher recovery, the energy requirement to evaporate the water increases. Ullmann's (2002) states that drum vacuum type filters are often used in the wash stage to increase the solids content to 50 - 60 wt%. A mass balance shows that two wash stages with 55% solids output is more effective than 6 wash stages with 20% solids (Ullmann's, 2002). In this GTG report, we estimate recovery based on three stages of vacuum filter washing with 57 volume % solids as an output and two stages.

Crystallization (precipitation)

The filtered solution is cooled from 375 K to 335-345 K. We use 340 K (67 oC) in this GTG report. This cooling is usually done in a flash system under vacuum, and the steam is used to heat the cooled stripped liquor. Alternatively, a standard liquid-liquid heat exchanger can be used. We show a standard heat exchanger for cooling and use our standard model of heat recovery. Precipitators are typically vertical cylinders 30 m high and 10 m in diameter (Ullmann's, 2002; Kirk Othmer, 2002) and are continuously stirred. In modern plants, crystal growth is done by a series of 10-14 precipitators (Kirk Othmer, 2002). At 70 ^{o}C, the time required to reduce the Al_2O_3 concentration from 100 to 65 g/l is 10 hours (Ullmann's, 2002). Increased crystallization time can reduce the Al_2O_3 concentration in the supernatant. At 30 hours, the Al_2O_3 in the supernatant is 45 g/l at 50 oC and 55 g/l at 60 oC (Ullmann's, 2002). US 2,701,752 gives a precipitation time of 36 to 48 hrs, and Konigsberger (2008) gives a crystallization time of at least one day. In this GTG, the mixing energy is based on 30 hours of low agitation. After the crystal growth, the crystals are classified. Liquid-solid cyclones are often used for this classification. The smaller crystals are recycled to seed the first precipitator. At 50 ^{o}C, after 10 hours, the solution has 55 g/l Al_2O_3 (Ullmann's, 2002). US 2,852,343 states that generally about 50% of the dissolved alumina content is precipitated, while the balance remains in the liquor and is recycled. In this GTG report, 52% of the Al_2O_3 content crystallizes per pass, and the Al_2O_3 content (as sodium aluminate) in the recycled liquor is 53 g/L.

Water balance and treatment of weak liquor

After crystallization, the weak liquor must be treated, heated, and recycled to the digestion stage. Process water is added both to the grinding section and is used to wash the red mud waste streams. The waste is washed to recover dissolved bauxite in the entrained water. With each cycle, the water added must be removed by evaporation. Some water is removed during the flash to lower pressure. However, additional evaporation is typically needed. Additionally, organics are added mostly as part of the bauxite ore, and these organics can build up in the liquor. Treatments such as 'liquor-burning,' wet oxidation, ultraviolet irradiation, and nanofiltration have been described in order to treat the liquor (US 20040052706). US 4,789,485 suggests removing both organic and inorganic impurities by using polymeric flocculants prior to filtration.

Ullmann's (2002) gives the evaporation requirement as 5.3 t of water per tonne of Al_2O_3. However, it is not clear if this includes water from the flash. Kirk Othmer (2002) states that evaporation over and above that attained by flash cooling is usually required. This indicates that extra evaporation is sometimes not required, or that the flash cooling can provide a substantial amount of the evaporation. Evaporation also serves to concentrate impurities, if these are to be removed prior to recycle. Based on the flash calculations, and water requirements for washing the red mud and crystals, the additional evaporation requirement is 2.1 kg water per kg of Al_2O_3. This is accomplished with a 4-stage multi-effect evaporator.

Calcination

The crystallized $Al(OH)_3$ is washed using vacuum filters (Kirk-Othmer, 2002). The wash sequence is countercurrent, and the filters are horizontal rotating drums (Ullmann's, 2002). We show a pre-filtration followed by a countercurrent wash with two stages. After washing, the crystals are calcined at 1380K (Ullmann's, 2002; Kirk Othmer, 2002). As the aluminum hydroxide is heated, the crystal structure changes, eventually leading to α-alumina at high enough temperatures. According to Konigsberger (2008), air flows countercurrent to the solids in the calciner. We show 5.2 kg of air per kg of alumina, in order to remove 510 kg of free water and 520 kg of bound water (in $Al(OH)_3$). Without heat recovery, the calcination efficiency is 51%.

Using our standard heuristics for heat recovery, the net calcination energy (calcination input minus heat recovered in HX 6 and 7 is 3.5 GJ/tonne product. Ullmann's (2002) states that currently used stationary calciners require 3.1 GJ of heating fuel/tonne product.

Net energy / energy conservation

The Bayer plant utilizes a large amount of heat energy, and the HH cell for aluminum production uses a large quantity of electricity. Thus, cogeneration of steam and power is usually part of the Bayer plant (Kirk Othmer, 2002). Cogeneration enables efficiencies of > 85% compared to a typical efficiency of 35% in public utilities. It is not stated directly, but this co-generation is likely combining the electricity requirements of Hall-Heroult process with the steam requirements of the Bayer process. We do not include the co-generation efficiencies in this GTG. Ullmann's (2002) states that the steam produced in flashing the hot digestion liquor is used to preheat the digester inputs. In our model, the digester requires 4200 MJ/hr of heat. The enthalpy available in the flashed steam (HX 2) is -3980 MJ. Of this, 25% (990 MJ/hr) is recovered. The sum of the energy inputs to this GTG is 23,300 MJ/hr. However after recovery, the net energy requirement is 12,100 MJ/hr with a 1000kg Al_2O_3 /hr basis. Including an efficiency of 0.85 for generating steam gives a net energy of 13,500 MJ/1000kg Al_2O_3. According to Konigsberger (2008), the current best practice based on an Australian report is 9,500 MJ/1000 kg of Al_2O_3. Green and Choate (2003) give an energy requirement of 13,500 MJ/1000 kg of Al_2O_3 for the Bayer refining process. Ullmann's (2002) citing an article from 1983 states that 16 MJ are typically required per kg of Al2O3, and that the worldwide range is 7.4 to 33 MJ/kg.

Purity

The largest contaminant is sodium as sodium hydroxide or sodium aluminate. The sodium content is measured as kg of Na_2O. For metal making purposes, the Na_2O content of the alumina product should not be higher than 0.4 to 0.5 wt% (Ullmann's, 2002). Other contaminants are: SiO_2 (< 0.02%), iron oxide, calcium, lithium, gallium, phosphate, and organic matter. We include 0.4wt% Na_2O as an impurity in the form of sodium hydroxide and sodium aluminate crystals. The overall purity is 99 wt % Al_2O_3.

B. LCI design

Bauxite, 2390 kg/hr, and 143 kg of calcium monoxide are ground to 150 microns with 2390 kg of water (50% solids content). The slurry is pumped to 4 atm, combined with recycled liquor and 84 kg of fresh sodium hydroxide (in water) in a digester. The digester operates at 141 ^oC with low agitation and has a residence time of 10 hours. During digestion, alumina is converted to soluble sodium aluminate and silica is combined into sodium- and aluminum-containing crystals.

The rich liquor is sent to an adiabatic flash, which reduces the pressure to 1 atm, and the temperature to 100 ^{o}C. In this process about 8.6% of the water is evaporated, producing steam, which serves as a heat supply. The cooled liquor is then filtered by a hydrocyclone and a rake classifier. The red mud solids are then pre-filtered with a vacuum drum and washed in a 2-stage counter-current was with vacuum filters on each stage. This wash requires adding 377 kg of water in order to recover 86% of the free sodium and sodium aluminate content in the underflow. The liquor from the rake classifier is put through a gravity bed filter to remove some remaining solids and combined with the wash fluid. A heat exchanger lowers the temperature to 67 ^{o}C with heat recovery. Multi-stage crystallizers are used to crystallize $Al(OH)_3$ from the rich liquor. This process requires low agitation for 10 hours, and about 52% of the aluminum content is crystallized. Additional cooling is used to lower the temperature to 50 ^{o}C during crystallization. Hydrocyclones classify the crystals, so that the larger crystals are sent to purification, and some of the smaller crystals (10%) are recycled to seed the crystallization. The recirculating spent liquor is sent to a 4-stage multi-effect evaporator to remove excess water, and recycled to the digester. The larger crystals are pre-filtered with a vacuum drum and purified by a 3-stage counter-current wash with vacuum filtration between stages. The washed crystals are calcined at 1100 ^{o}C. 5.2 kg of air are used per kg of alumina during the calcination process, and heat is recovered from the hot gases exiting the calciner and the hot alumina as it cools. Although not shown here, heat from the hot alumina is recovered by preheating the air that is used in the calciner.

C. References

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D. *Critical parameters*

Conversion / Yield information from both reactors			
		Conversion of or Yield from Bauxite	Conversion of or Yield from Al2O3 content in bauxite
Total yield of Process: (% yield produced by the overall process based on reactant input to process)	From mass balance	44.5 (2.25 kg bauxite per kg of purified alumina)	93%
Notes:			

Product purity			
	Al2O3	Na2O content	Comments
Used here	99%	0.4%	
Ullmann's, 2002		0.4 - 0.5%	

XI. Summary of LCI Information

Inputs					
Input UID	Input Name	Input Flow	Input purity	Units	Comments
UIDCO2FromAir	CO2 from air	116		[kg/hr]	Used for desilication
1305-78-8	calcium monoxide	143		[kg/hr]	Added to convert Na2CO3 to NaOH
1310-73-2	Sodium hydroxide	83.6		[kg/hr]	
UIDBauxiteAtUSPort	bauxite, at US port	2246		[kg/hr]	
	Total	2590		[kg/hr]	
Non-reacting inputs					
UID	Name	Flow	Purity	Units	Comments
7732-18-5	Water	3918		[kg/hr]	
UIDO2FromAir	Oxygen from air	1215		[kg/hr]	
UIDN2FromAir	Nitrogen from air	4000		[kg/hr]	
	Total	9133		[kg/hr]	
Ancillary inputs					
UID	Name	Flow	Purity	Units	Comments
UIDCornStarch	corn starch	6.74		[kg/hr]	
	Total	6.74		[kg/hr]	

Products					
Product UID	Product Name	Product Flow	Purity	Units	Comments
1344-28-1	Aluminum oxide	1000	98.9	[kg/hr]	
	Total	1000		[kg/hr]	
Benign Outflows					
UID	Name	Flow	Purity	Units	Comments
7732-18-5	Water	4526		[kg/hr]	
7782-44-7	Oxygen	1215		[kg/hr]	
7727-37-9	Nitrogen	4000		[kg/hr]	
	Total	9741		[kg/hr]	

Chemical Emissions							
Emission UID	Emission Name	Gas Flow	Liquid Flow	Solid Flow	Solvent Flow	Units	Comments
UIDBayerRedMud	bayer red mud	0	0	987	0	[kg/hr]	
Totals		0	0	987	0	[kg/hr]	
Mass Balance							
Total inputs		1.17e+4					
Total outflows		1.17e+4					
Net input		0.585					

Energy use			
Energy type	Amount	Comments	
electricity	2806	[MJ/hr]	
heating steam	9342	[MJ/hr]	
heating natural gas	1.26e+4	[MJ/hr]	
Net input requirement	2.47e+4	[MJ/hr]	Net of energies input to system
cooling water	-2.05e+4	[MJ/hr]	
potential recovery	-1.12e+4	[MJ/hr]	
Net energy	1.35e+4	[MJ/hr]	Net input requirement - potential recovery

XII. Process Diagram Interpretation Sheet

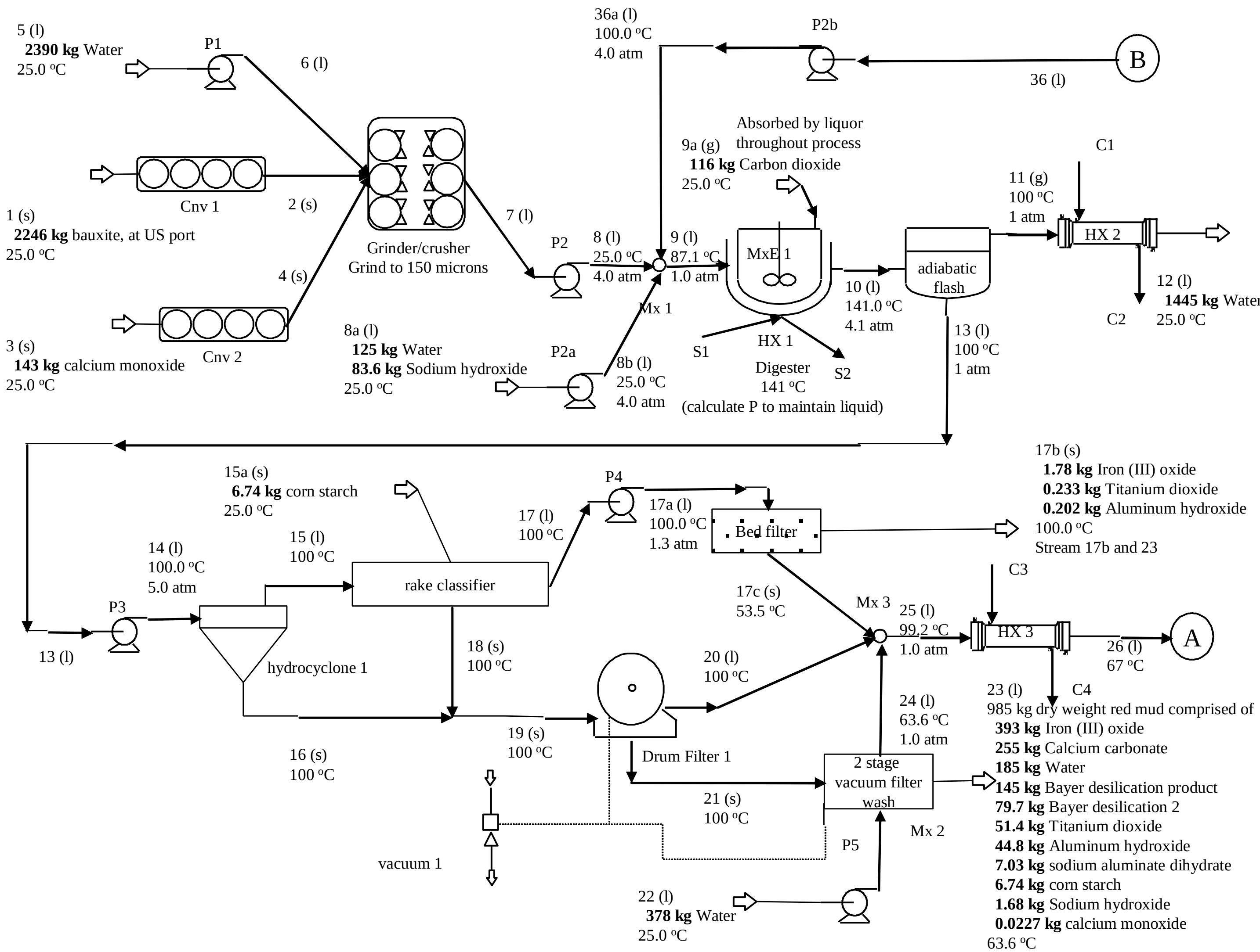
1) As much as possible, standard symbols are used for all unit processes.
2) Only overall input and output chemicals are labeled on these diagrams. All intermediate information is given on the attached Process Mass Balance sheet
3) The physical state of most streams is shown (gas, g; liquid, l; solid, s)
4) The process numbering is as follows,
    - generally numbers progress from the start to the end of the process
    - numbers are used for process streams
    - C i , i = 1,..n are used for all cooling non-contact streams
    - S j, j = 1,...n are used for all steam heating non-contact streams
5) Recycle streams are shown with dotted lines

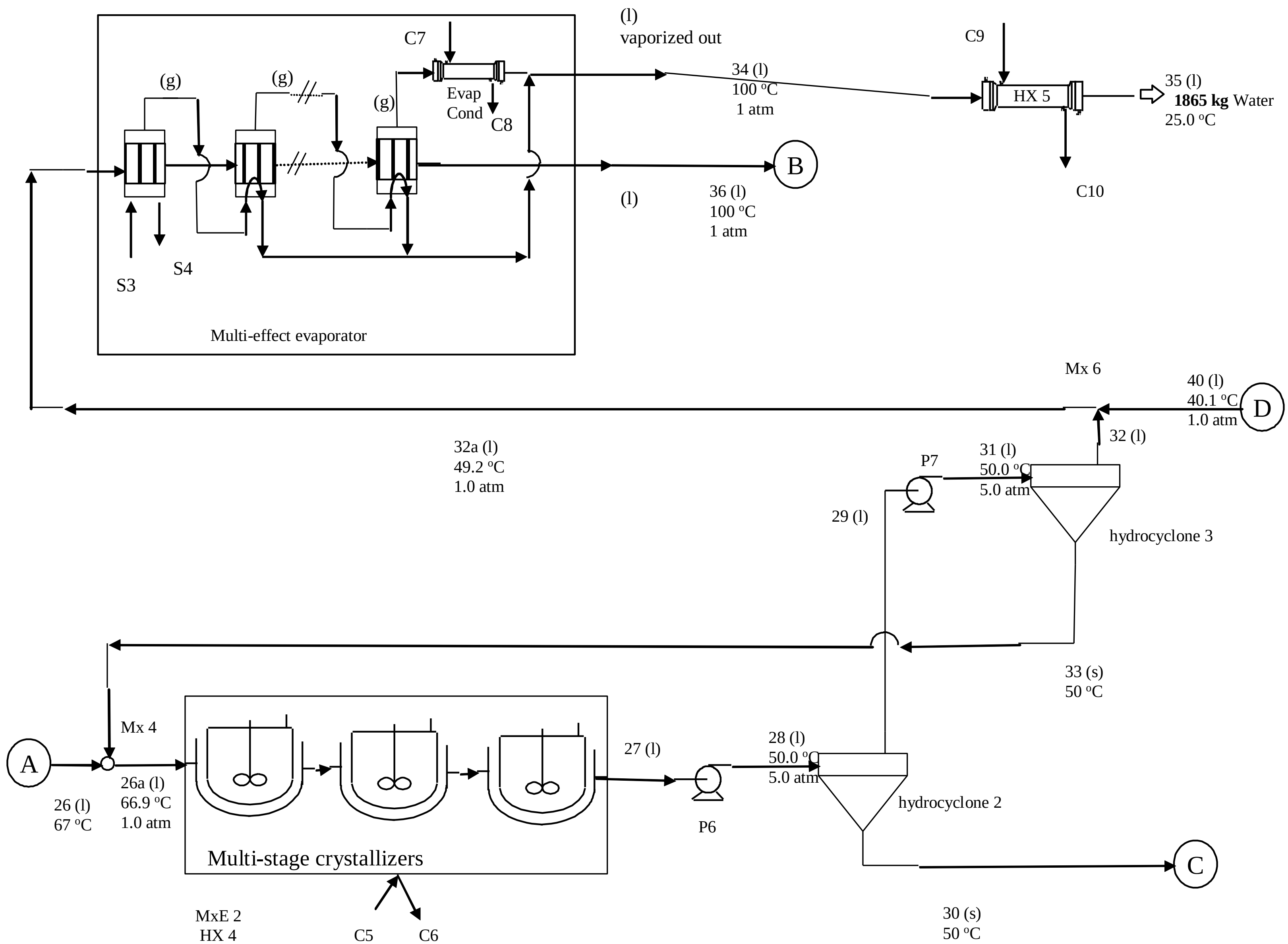
For most streams, the temperature and pressure are shown, if the pressures are greater than 1 atm

Process Diagram or Boundary of LCI

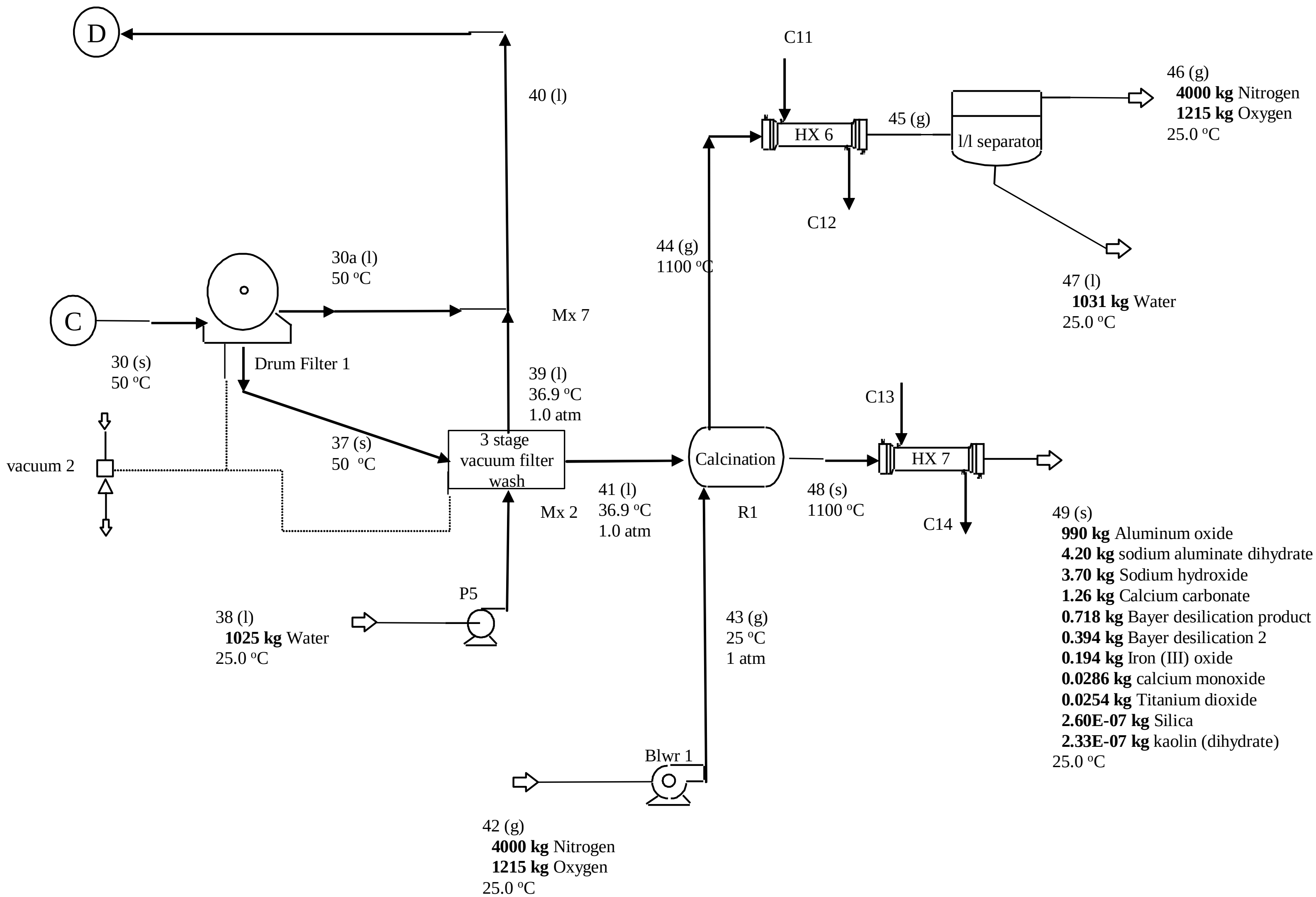
Steam enters the process as a gas at 207 °C and leaves as a liquid at 207 °C. Cooling water enters at 20 °C and leaves at 50 °C.

Unless otherwise indicated, all processes are at 1 atm and 25°C.





C7
(l)
vaporized out
C9
(g)
(g)
(g)
Evap
Cond
C8
34 (l)
100 ºC
1 atm
35 (l)
1865 kg Water
25.0 ºC
HX 5
B
(l)
36 (l)
100 ºC
1 atm
C10
S3
S4
Multi-effect evaporator
Mx 6
40 (l)
40.1 ºC
1.0 atm
D
32 (l)
32a (l)
49.2 ºC
1.0 atm
P7
31 (l)
50.0 ºC
5.0 atm
29 (l)
hydrocyclone 3
33 (s)
50 ºC
Mx 4
A
26 (l)
67 ºC
26a (l)
66.9 ºC
1.0 atm
27 (l)
28 (l)
50.0 ºC
5.0 atm
hydrocyclone 2
P6
Multi-stage crystallizers
C
MxE 2
HX 4
C5
C6
30 (s)
50 ºC



Fugitive Losses (Total) (g)
no fugitives

Stream 17b and 23 are counted as a red mud waste

XIII. Mass Balance of Chemicals in Each Process Stream

All flow rates are given in kg / hr

Physical state of chemical losses:

Gas
Liquid
Solid

	Comments	Streams	Temp [C]	P	Phase	Total Flow	Water	bauxite, at US port	Sodium hydroxide	calcium monoxide	Aluminum hydroxide	Aluminum oxide	kaolin (dihydrate)	Silica	Titanium dioxide	Iron (III) oxide	sodium aluminate dihydrate	Bayer desilication product	Calcium carbonate	Carbon dioxide	Bayer desilication 2	Nitrogen	Oxygen	corn starch
Input		1	25.0	1.00	s	2246		2246																
		1Composition				2246	613					1074	53.9	58.4	51.7	395								
		2	25.0	1.00	s	2246	44.8				1642		53.9	58.4	51.7	395								
Input		3	25.0	1.00	s	143				143														
		4	25.0	1.00	s	143				143														
Input		5	25.0	1.00	l	2390	2390																	
		6	25.0	1.00	l	2390	2390																	
		7	25.0	1.00	l	4780	2435	0	0	143	1642	0	53.9	58.4	51.7	395	0	0	0	0	0	0	0	0
		8	25.0	4.00	l	4780	2435	0	0	143	1642	0	53.9	58.4	51.7	395	0	0	0	0	0	0	0	0
		Stream 36:Recycle input	50.0	1.00	l	1.81E+04	1.41E+04		1850	14.3	29.0						2100	0.0127	0.0223	0	6.97E-03			
		Stream 36:Recycle calculated				1.81E+04	1.41E+04	0	1850	14.3	29.3	0	4.13E-09	4.60E-09	4.50E-04	3.44E-03	2100	0.0127	0.0223	0	6.97E-03	0	0	0
		Stream 36:Recycle residue				-0.562	0	0	-2.39E-03	0.0520	-0.294	0	-4.13E-09	-4.60E-09	-4.50E-04	-3.44E-03	-0.314	-2.54E-08	-4.46E-08	0	-1.39E-08	0	0	0
Input		8a	25.0	1.00	l	209	125		83.6															
		8b	25.0	4.00	l	209	125		83.6															
Al2O3, g/L	110	9	87.1	1.00	l	2.31E+04	1.67E+04	0	1934	158	1671	0	53.9	58.4	51.7	395	2100	0.0127	0.0223	0	6.97E-03	0	0	0
Input		9a	25.0	1.00	g	116														116				

	Comments	Streams	Temp [C]	P	Phase	Total Flow	Water	bauxite, at US port	Sodium hydroxide	calcium monoxide	Aluminum hydroxide	Aluminum oxide	kaolin (dihydrate)	Silica	Titanium dioxide	Iron (III) oxide	sodium aluminate dihydrate	Bayer desilication product	Calcium carbonate	Carbon dioxide	Bayer desilication 2	Nitrogen	Oxygen	corn starch
		R dissolution stoichiometry							-1.00		-1.00						1.00							
		R dissolution kg/hr				0			-795		-1550						2345							
		R dissolution kgmol/hr							-19.9		-19.9						19.9							
		R desilication stoichiometry					32.0		-24.0		-10.0		-4.00	-10.0				3.00						
		R desilication kg/hr				0	30.1		-50.2		-40.7		-53.9	-31.3				146						
		R desilication kgmol/hr					1.67		-1.25		-0.522		-0.209	-0.522				0.157						
		R desilication 2 stoichiometry					7.00		-8.00		-6.00			-6.00						-1.00	1.00			
		R desilication 2 kg/hr				0	9.47		-24.1		-35.2			-27.1						-3.31	80.1			
		R desilication 2 kgmol/hr				-0.977	0.526		-0.601		-0.451			-0.451						-0.0752	0.0752			
		R carbonate formation stoichiometry								-1.00									1.00	-1.00				
		R carbonate formation kg/hr				0				-143									256	-113				
		R carbonate formation kgmol/hr								-2.56									2.56	-2.56				
free NaOH, g/L	57.8	10	141	4.10	l	2.32E+04	1.67E+04	0	1064	14.3	45.0	0	0	0	51.7	395	4445	146	256	0	80.1	0	0	0
		11	100	1.00	g	1445	1445																	
Waste		12	25.0	1.00	l	-1445	-1445	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
-0.756		13	100	1.00	l	2.18E+04	1.53E+04	0	1064	14.3	45.0	0	0	0	51.7	395	4445	146	256		80.1	0	0	0
Volume solids in,L	257	14	100	5.00	l	2.18E+04	1.53E+04	0	1064	14.3	45.0	0	0	0	51.7	395	4445	146	256	0	80.1	0	0	0
Efficiency	0.500					type, solvent, solute, solid	solvent		solute	solute	solid		solid	solid	solid	solid	solute	solid	solid		solid			
Volume solids underflow,L	129					density	0.995	0	2.13	3.34	2.42	0	0	0	4.23	5.25	3.98	4.00	2.71	0	4.00	0	0	0

	Comments	Streams	Temp [C]	P	Phase	Total Flow	Water	bauxite, at US port	Sodium hydroxide	calcium monoxide	Aluminum hydroxide	Aluminum oxide	kaolin (dihydrate)	Silica	Titanium dioxide	Iron (III) oxide	sodium aluminate dihydrate	Bayer desilication product	Calcium carbonate	Carbon dioxide	Bayer desilication 2	Nitrogen	Oxygen	corn starch
Volume liquids, L	157	15	100	1.00	l	2.11E+04	1.51E+04	0	1054	14.2	22.5	0	0	0	25.8	198	4404	73.0	128	0	40.1	0	0	0
V Uo, L	157	16	100	1.00	s	680	141	0	9.87	0.133	22.5	0	0	0	25.8	198	41.2	73.0	128	0	40.1	0	0	0
		17	100	1.00	l	2.03E+04	1.49E+04	0	1040	14.0	0.225	0	0	0	0.258	1.98	4342	0.730	1.28	0	0.401	0	0	
Input		15a	25.0	1.00	s	6.74																		6.74
	0.991	17a	100	1.29	l	2.03E+04	1.49E+04	0	1040	14.0	0.225	0	0	0	0.258	1.98	4342	0.730	1.28	0	0.401	0	0	0
Waste		17b	100	1.00	s	-2.21	0	0	0	0	-0.202	0	0	0	-0.233	-1.78	0	0	0	0	0	0	0	0
		17c	100	1.00	s	2.03E+04	1.49E+04	0	1040	14.0	0.0225	0	0	0	0.0258	0.198	4342	0.730	1.28	0	0.401	0	0	0
		18	100	1.00	s	778	212		14.8	0.200	22.3		0	0	25.6	196	61.8	72.3	127		39.7			6.74
Drum filter 1, % solid	57.5	19	100	1.00	s	1458	354	0	24.7	0.333	44.8	0	0	0	51.4	393	103	145	255	0	79.7	0	0	6.74
Volume liquids, L	189	20	100	1.00	l	250	184	0	12.8	0.173	0	0	0	0	0	0	53.5	0	0	0	0	0	0	0
Uo (volume in), L	189	21	100	1.00	s	1208	170		11.9	0.160	44.8		0	0	51.4	393	49.5	145	255		79.7			6.74
O (volume solvent)	380					type, solvent, solute, solid	solvent		solute	solute	solid		solid	solid	solid	solid	solute	solid	solid		solid			
xn/xo (solutes)	0.142					density	0.995	0	2.13	3.34	2.42	0	0	0	4.23	5.25	3.98	4.00	2.71	0	4.00	0	0	
Input		22	25.0	1.00	l	378	378																	
Waste		23	63.6	1.00	l	-1170	-185	0	-1.68	-0.0227	-44.8	0	0	0	-51.4	-393	-7.03	-145	-255	0	-79.7	0	0	-6.74
U check	Correct	24	63.6	1.00	l	415	362	0	10.2	0.137	0	0	0	0	0	0	42.5	0	0	0	0	0	0	0
		wash_total_out	63.6				548	0	11.9	0.160	44.8	0	0	0	51.4	393	49.5	145	255	0	79.7	0	0	
		25	99.2	1.00	l	2.10E+04	1.54E+04	0	1063	14.3	0.0225	0	0	0	0.0258	0.198	4438	0.730	1.28	0	0.401	0	0	0
		26	67.0	1.00	l	2.10E+04	1.54E+04	0	1063	14.3	0.0225	0	0	0	0.0258	0.198	4438	0.730	1.28	0	0.401	0	0	0
recycle seed crystals		Stream 33:Recycle				241	70.6	0	8.37	0.0646	153	0	2.42E-	2.70E-	5.13E-	3.93E-	9.49	0.0145	0.0257	0	7.95E-			

	Comments	Streams	Temp [C]	P	Phase	Total Flow	Water	bauxite, at US port	Sodium hydroxide	calcium monoxide	Aluminum hydroxide	Aluminum oxide	kaolin (dihydrate)	Silica	Titanium dioxide	Iron (III) oxide	sodium aluminate dihydrate	Bayer desilication product	Calcium carbonate	Carbon dioxide	Bayer desilication 2	Nitrogen	Oxygen	corn starch
		input											07	07	04	03					03			
		Stream 33:Recycle calculated				242	70.5	0	8.46	0.0653	153	0	4.75E-09	5.29E-09	5.16E-04	3.95E-03	9.60	0.0146	0.0256	0	8.01E-03	0	0	0
		Stream 33:Recycle residue				-0.0643	0.0878	0	-0.0828	-7.16E-04	0.0423	0	2.37E-07	2.64E-07	-3.33E-06	-2.55E-05	-0.111	-1.02E-04	5.02E-05	0	-5.59E-05	0	0	0
		26a	66.9	1.00	l	2.12E+04	1.55E+04	0	1071	14.4	153	0	2.42E-07	2.70E-07	0.0263	0.202	4448	0.745	1.31	0	0.409	0	0	0
		R crystallization stoichiometry							1.00		1.00						-1.00							
		R crystallization kg/hr				0			791		1543						-2334							
		R crystallization kgmol/hr							19.8		19.8						-19.8							
Al2O3, g/L	53.7	27	50.0	1.00	l	2.12E+04	1.55E+04	0	1862	14.4	1696	0	2.42E-07	2.70E-07	0.0263	0.202	2114	0.745	1.31	0	0.409	0	0	0
Volume solids in,L	701	28	50.0	5.00	l	2.12E+04	1.55E+04	0	1862	14.4	1696	0	2.42E-07	2.70E-07	0.0263	0.202	2114	0.745	1.31	0	0.409	0	0	0
Efficiency	0.980					type, solvent, solute, solid	solvent		solute	solute	solid		solid	solid	solid	solid	solute	solid	solid		solid			
Volume solids underflow,L	687					density	0.995	0	2.13	3.34	2.42	0	2.59	2.33	4.23	5.25	3.98	4.00	2.71	0	4.00	0	0	0
Volume liquids, L	840	29	50.0	1.00	l	1.87E+04	1.48E+04	0	1770	13.7	156	0	4.84E-09	5.40E-09	5.27E-04	4.03E-03	2010	0.0149	0.0261	0	8.17E-03	0	0	0
V Uo, L	840	30	50.0	1.00	s	2506	767	0	92.0	0.711	1540	0	2.37E-07	2.64E-07	0.0258	0.198	104	0.730	1.28	0	0.400	0	0	0
Volume solids in,L	64.5	31	50.0	5.00	l	1.87E+04	1.48E+04	0	1770	13.7	156	0	4.84E-09	5.40E-09	5.27E-04	4.03E-03	2010	0.0149	0.0261	0	8.17E-03	0	0	0
Efficiency	0.980					type, solvent,	solvent		solute	solute	solid		solid	solid	solid	solid	solute	solid	solid		solid			

	Comments	Streams	Temp [C]	P	Phase	Total Flow	Water	bauxite, at US port	Sodium hydroxide	calcium monoxide	Aluminum hydroxide	Aluminum oxide	kaolin (dihydrate)	Silica	Titanium dioxide	Iron (III) oxide	sodium aluminate dihydrate	Bayer desilication product	Calcium carbonate	Carbon dioxide	Bayer desilication 2	Nitrogen	Oxygen	corn starch
						solute, solid																		
Volume solids underflow,L	63.2					density	0.995	0	2.13	3.34	2.42	0	2.59	2.33	4.23	5.25	3.98	4.00	2.71	0	4.00	0	0	0
Volume liquids, L	77.2	32	50.0	1.00	l	1.85E+04	1.47E+04	0	1762	13.6	3.12	0	9.68E-11	1.08E-10	1.05E-05	8.06E-05	2000	2.98E-04	5.23E-04	0	1.63E-04	0	0	0
V Uo, L	77.2	33	50.0	1.00	s	242	70.5	0	8.46	0.0653	153	0	4.75E-09	5.29E-09	5.16E-04	3.95E-03	9.60	0.0146	0.0256	0	8.01E-03	0	0	0
		Stream 40:Recycle input				1500	1284	0	88.3	0.682	26.2	0	4.03E-09	4.49E-09	4.39E-04	3.36E-03	100	0.0124	0.0218	0	6.81E-03			
		Stream 40:Recycle calculated				1500	1284	0	88.3	0.682	26.2	0	4.03E-09	4.49E-09	4.39E-04	3.36E-03	100	0.0124	0.0218	0	6.81E-03	0	0	0
		Stream 40:Recycle residue				0.0390	-4.09E-03	0	0.0129	-1.56E-05	0	0	0	0	1.20E-07	9.20E-07	0.0302	2.34E-06	-1.86E-06	0	1.28E-06	0	0	0
		32a	49.2	1.00	l	2.00E+04	1.60E+04	0	1850	14.3	29.3	0	4.13E-09	4.60E-09	4.50E-04	3.44E-03	2100	0.0127	0.0223	0	6.97E-03	0	0	0
		34	100	1.00	l	1865	1865	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Waste		35	25.0	1.00	l	-1865	-1865	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		36	100	1.00	l	1.81E+04	1.41E+04	0	1850	14.3	29.3	0	4.13E-09	4.60E-09	4.50E-04	3.44E-03	2100	0.0127	0.0223	0	6.97E-03	0	0	0
		36a	100	4.00	l	1.81E+04	1.41E+04	0	1850	14.3	29.3	0	4.13E-09	4.60E-09	4.50E-04	3.44E-03	2100	0.0127	0.0223	0	6.97E-03	0	0	0
Volume solids in,L	637	30	50.0	1.00	s	2506	767	0	92.0	0.711	1540	0	2.37E-07	2.64E-07	0.0258	0.198	104	0.730	1.28	0	0.400	0	0	0
Efficiency	0.983	solvent	solute	solid		type, solvent, solute, solid	solvent		solute	solute	solid		solid	solid	solid	solid	solute	solid	solid		solid			
Volume solids underflow,L	626					density	0.995	0	2.13	3.34	2.42	0	2.59	2.33	4.23	5.25	3.98	4.00	2.71	0	4.00	0	0	0

	Comments	Streams	Temp [C]	P	Phase	Total Flow	Water	bauxite, at US port	Sodium hydroxide	calcium monoxide	Aluminum hydroxide	Aluminum oxide	kaolin (dihydrate)	Silica	Titanium dioxide	Iron (III) oxide	sodium aluminate dihydrate	Bayer desilication product	Calcium carbonate	Carbon dioxide	Bayer desilication 2	Nitrogen	Oxygen	corn starch
Volume liquids, L	512	30a	50.0	1.00	l	402	299	0	35.9	0.277	26.2	0	4.03E-09	4.49E-09	4.39E-04	3.36E-03	40.8	0.0124	0.0218	0	6.81E-03	0	0	0
V Uo, L	512	37	50.0	1.00	s	2104	468	0	56.1	0.433	1513	0	2.33E-07	2.60E-07	0.0254	0.194	63.7	0.718	1.26	0	0.394	0	0	0
Uo (volume in), L	512	37	50.0	1.00	s	2104	468	0	56.1	0.433	1513	0	2.33E-07	2.60E-07	0.0254	0.194	63.7	0.718	1.26	0	0.394	0	0	0
O (volume solvent)	1030					type, solvent, solute, solid	solvent		solute	solute	solid		solid	solid	solid	solid	solute	solid	solid		solid			
xn/xo (solutes)	0.0659					density	0.995	0	2.13	3.34	2.42	0	2.59	2.33	4.23	5.25	3.98	4.00	2.71	0	4.00	0	0	0
Input		38	25.0	1.00	l	1025	1025																	
		41	36.9	1.00	l	2031	507	0	3.70	0.0286	1513	0	2.33E-07	2.60E-07	0.0254	0.194	4.20	0.718	1.26	0	0.394	0	0	0
U check	Correct	39	36.9	1.00	l	1097	985	0	52.4	0.405	0	0	0	0	0	0	59.5	0	0	0	0	0	0	0
		wash2_total_out	36.9				1492	0	56.1	0.433	1513	0	2.33E-07	2.60E-07	0.0254	0.194	63.7	0.718	1.26	0	0.394	0	0	0
		40	40.1	1.00	l	1500	1284	0	88.3	0.682	26.2	0	4.03E-09	4.49E-09	4.39E-04	3.36E-03	100	0.0124	0.0218	0	6.81E-03	0	0	0
Input		42	25.0	1.00	g	5215																4000	1215	
		43	25.0	1.00	g	5215																4000	1215	
R1	1513	kg	Aluminum hydroxide			is converted in rxn 1 (100 % of reactor input)																		
		Input to reactor			:	7246	507	0	3.70	0.0286	1513	0	2.33E-07	2.60E-07	0.0254	0.194	4.20	0.718	1.26	0	0.394	4000	1215	0
		R1 Reaction Coefficient 1			:		3.00				-2.00	1.00												
		R1 Conversion 1 [kg/hr]			:	0	524				-1513	990												

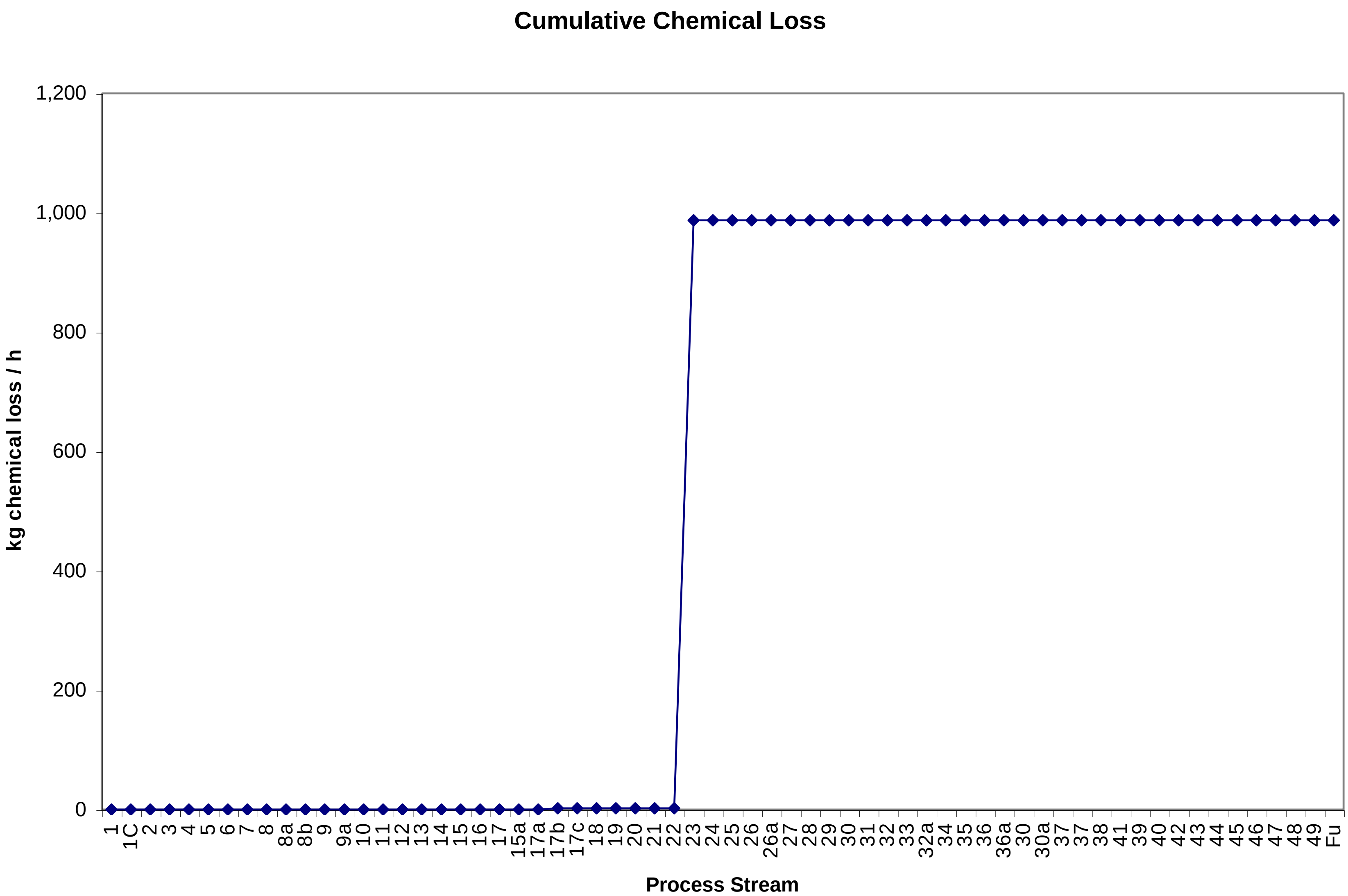
	Comments	Streams	Temp [C]	P	Phase	Total Flow	Water	bauxite, at US port	Sodium hydroxide	calcium monoxide	Aluminum hydroxide	Aluminum oxide	kaolin (dihydrate)	Silica	Titanium dioxide	Iron (III) oxide	sodium aluminate dihydrate	Bayer desilication product	Calcium carbonate	Carbon dioxide	Bayer desilication 2	Nitrogen	Oxygen	corn starch
		R1 Conversion 1 [kgmol/hr]			:	9.70	29.1				-19.4	9.70												
		Flow out of reactor			:	7246	1031	0	3.70	0.0286	0	990	2.33E-07	2.60E-07	0.0254	0.194	4.20	0.718	1.26	0	0.394	4000	1215	0
		Primary product			:	Aluminum oxide																		
		Total conversion			:		-13.4	-0	-0	-0	NA	NA	NA	NA	NA	NA	NA	NA	NA	-0	NA	-0	-0	-0
		Per pass conversion			:		NA		-0	-0	100	NA	-0	-0	-0	-0	-0	-0	-0		-0	-0	-0	
		Total yield from reactor			:							100												
		44	1100	1.00	g	6246	1031															4000	1215	
		45	25.0	1.00	l	6246	1031															4000	1215	
Waste		46	25.0	1.00	g	-5215	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-4000	-1215	0
Waste		47	25.0	1.00	l	-1031	-1031	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		48	1100	1.00	s	1000	0	0	3.70	0.0286	0	990	2.33E-07	2.60E-07	0.0254	0.194	4.20	0.718	1.26	0	0.394	0	0	0
Main product		49	25.0	1.00	s	-1000	0	0	-3.70	-0.0286	0	-990	-2.33E-07	-2.60E-07	-0.0254	-0.194	-4.20	-0.718	-1.26	0	-0.394	0	0	0
		Product purity (%)				0.989		Na2O	3.97															
		Main product				Aluminum oxide																		
		Overall Rxn coefficients																						
		Total yield of process (from reactant)										NA												
Waste		Fugitive Losses (Total)			g	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		Input Sum				1.17E+04	3918	2246	83.6	143	0	0	0	0	0	0	0	0	0	116	0	4000	1215	6.74
		Fugitive Replacement of Reactants				0																		

	Comments	Streams	Temp [C]	P	Phase	Total Flow	Water	bauxite, at US port	Sodium hydroxide	calcium monoxide	Aluminum hydroxide	Aluminum oxide	kaolin (dihydrate)	Silica	Titanium dioxide	Iron (III) oxide	sodium aluminate dihydrate	Bayer desilication product	Calcium carbonate	Carbon dioxide	Bayer desilication 2	Nitrogen	Oxygen	corn starch
		Total Input (Input + Fugitive Replacement)				1.17E+04	3918	2246	83.6	143	0	0	0	0	0	0	0	0	0	116	0	4000	1215	6.74
		Product Sum				1000	0	0	3.70	0.0286	0	990	2.33E-07	2.60E-07	0.0254	0.194	4.20	0.718	1.26	0	0.394	0	0	0
		Main product flow				1000	0	0	3.70	0.0286	0	990	2.33E-07	2.60E-07	0.0254	0.194	4.20	0.718	1.26	0	0.394	0	0	0
		Net Input (in - out, omitting fugitives)				0.587																		

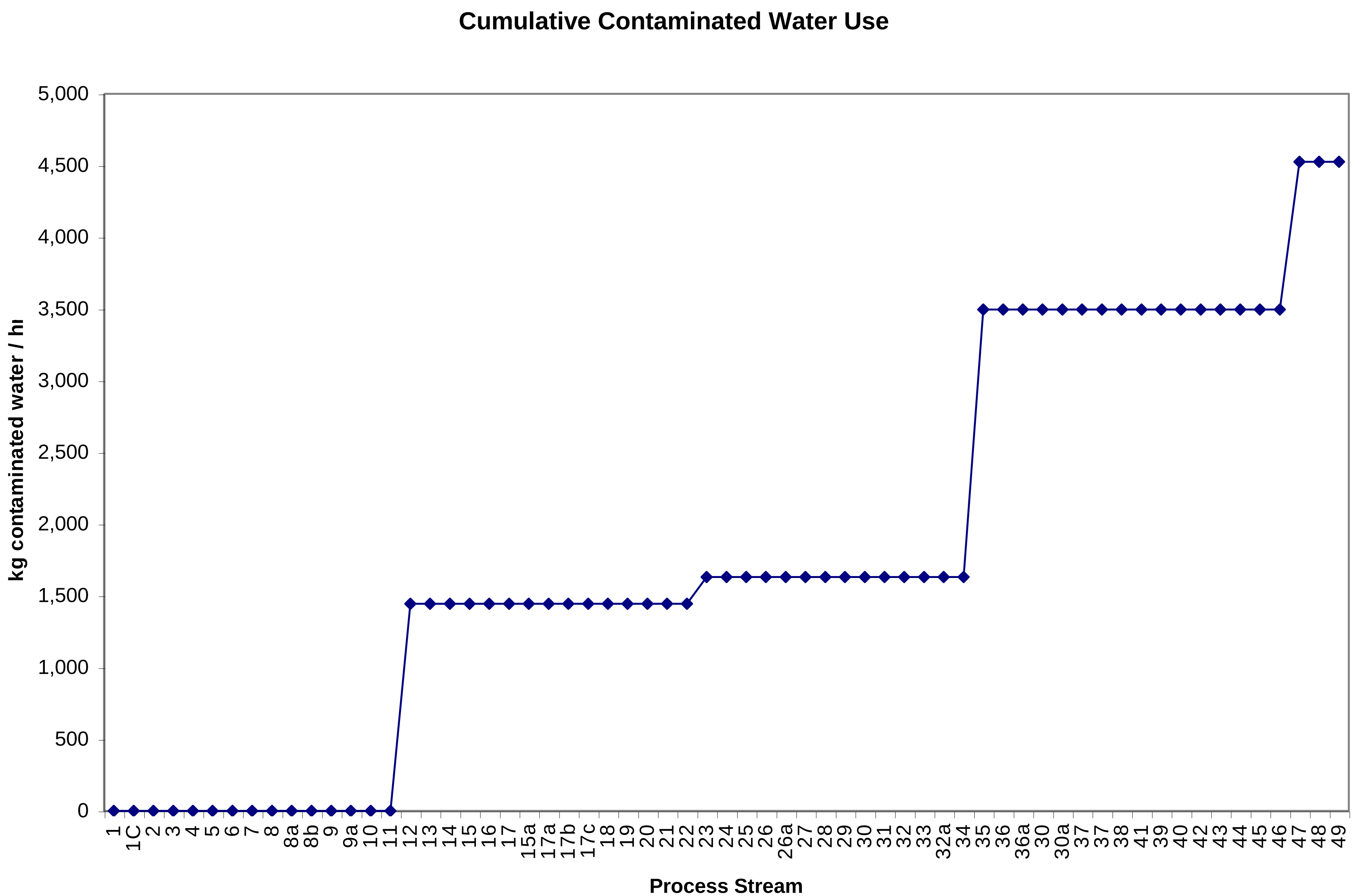
	Comments	Streams	Temp [C]	P	Phase	Total Flow	Steam	Water
Input		C1	20.0	1.00	l	2.69E+04		2.69E+04
Cooling out		C2	50.0	1.00	l	-2.69E+04	0	-2.69E+04
Input		C3	20.0	1.00	l	1.58E+04		1.58E+04
Cooling out		C4	50.0	1.00	l	-1.58E+04	0	-1.58E+04
Input		C5	20.0	1.00	l	8318		8318
Cooling out		C6	50.0	1.00	l	-8318	0	-8318
Input		C7	20.0	1.00	l	1686		1686
Cooling out		C8	50.0	1.00	l	-1686	0	-1686
Input		C9	20.0	1.00	l	3969		3969

Cooling out		C10	50.0	1.00	l	-3969	0	-3969
Input		C11	20.0	1.00	l	7.62E+04		7.62E+04
Cooling out		C12	50.0	1.00	l	-7.62E+04	0	-7.62E+04
Input		C13	20.0	1.00	l	5682		5682
Cooling out		C14	50.0	1.00	l	-5682	0	-5682
Input		S1	207	1.00	l	2583	2583	
Steam out		S2	207	1.00	l	-2583	-2583	0
Input		S3	207	1.00	l	2303	2303	
Steam out		S4	207	1.00	l	-2303	-2303	0

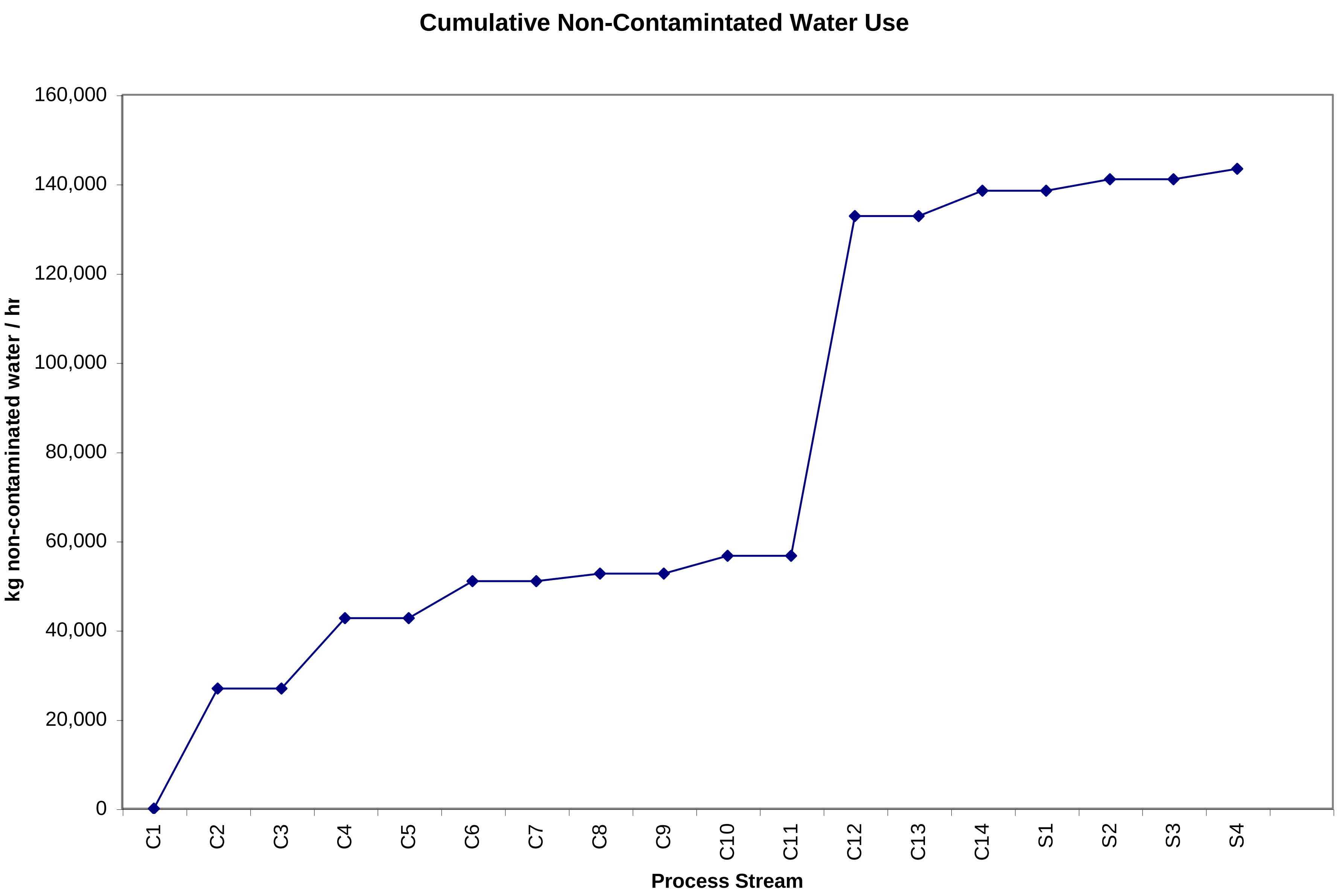
XIV. Graph of Cumulative Chemical Losses through Manufacturing Process



XV.Graph of Cumulative Contaminated Water Use / Emission through Manufacturing Process



XVI. Graph of Cumulative Non-Contaminated Water Use / Emission through Manufacturing Process



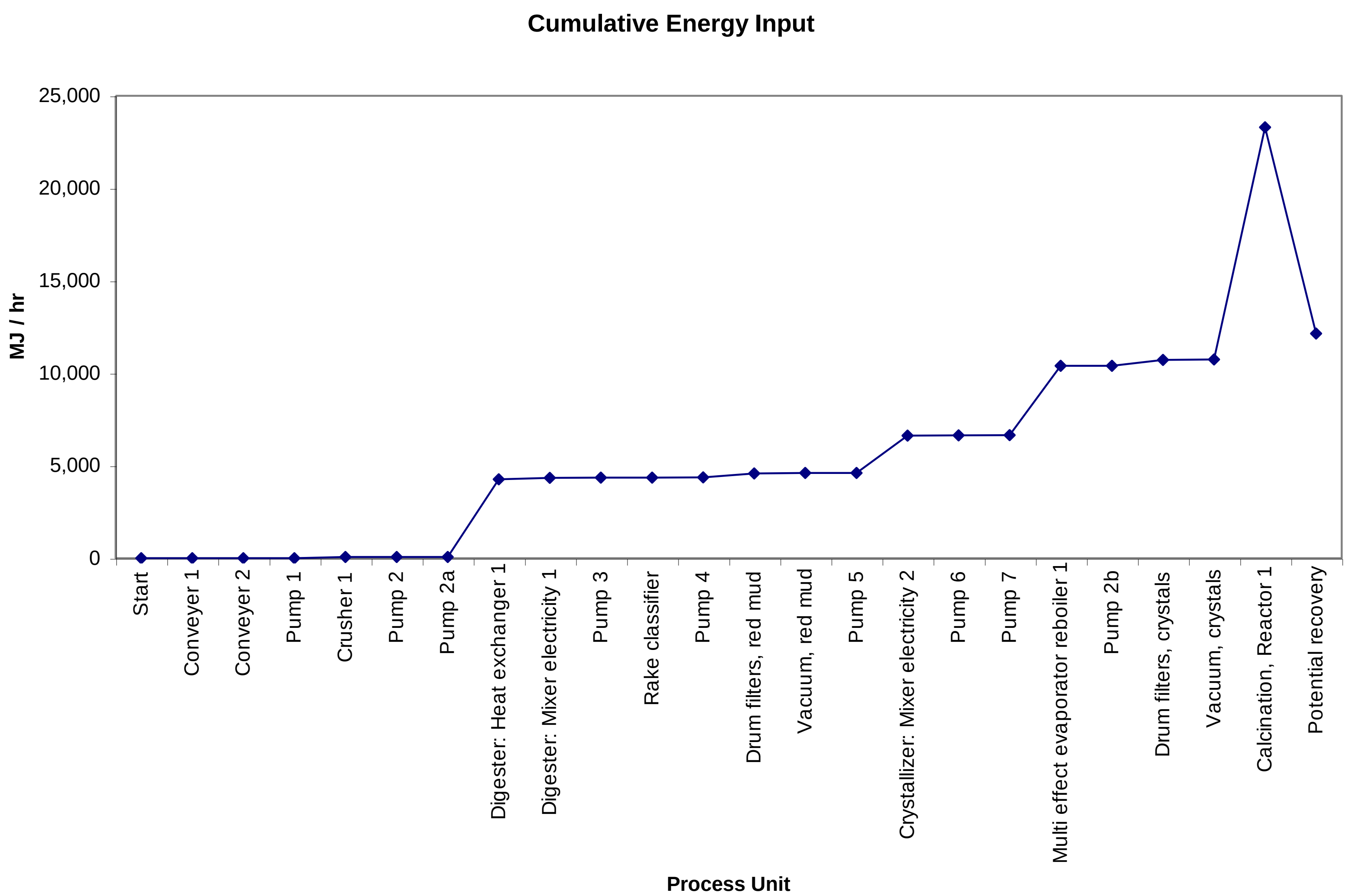
XVII. Energy Input for each Unit Process, Cumulative Energy Requirements, Cooling Requirements (exotherms), and Assumed Heat Recovery from Hot Streams Receiving Cooling

Energy Input [MJ / hr]						Cooling Requirements [MJ / hr]							
Process Diagram Label	Unit	Energy input [MJ / 1000 kg Product]	Cumulative energy [MJ / 1000 kg	To [C] (Used to determine	Energy Type	Process diagram label	Unit	Energy Loss	Cumulative cooling water energy	Tef [C] (for recovery	Recovery Efficiency	Energy Recovered	Cumulative recovered [MJ / 1000 kg Product]
Cnv1	Conveyer 1	0.147	0.147		E	Hx2	Heat exchanger 2	-3976	-3976	100	0.250	-994	-994
Cnv2	Conveyer 2	0.0182	0.166		E	Hx3	Heat exchanger 3	-2326	-6303	99.2	0.250	-582	-1576
P1	Pump 1	0.141	0.307		E	Hx4	Heat exchanger 4	-1228	-7531	66.9	0.250	-307	-1883
Crsh1	Crusher 1	65.7	66.0		E	MEvp1	Multi effect evaporator condenser 1	-249	-7780	100	0.250	-62.3	-1945
P2	Pump 2	2.78	68.7		E	Hx5	Heat exchanger 5	-586	-8366	100	0.250	-147	-2091
P2a	Pump 2a	0.108	68.9		E	Hx6	Heat exchanger 6	-1.12E+04	-1.96E+04	1100	0.750	-8435	-1.05E+04
Hx1	Digester: Heat exchanger 1	4198	4267	141	S	Hx7	Heat exchanger 7	-839	-2.05E+04	1100	0.750	-629	-1.12E+04
MxE1	Digester: Mixer electricity 1	73.5	4340		E								
P3	Pump 3	16.6	4357		E								
NA	Rake classifier	4.21	4361	0	E								
P4	Pump 4	2.30	4363		E								
NA	Drum filters, red mud	219	4582	0	E								

NA	Vacuum, red mud	25.2	4607	0	E								
P5	Pump 5	3.30E-05	4607		E								
MxE2	Crystallizer: Mixer electricity 2	2016	6623		E								
P6	Pump 6	16.1	6639		E								
P7	Pump 7	13.9	6653		E								
MEvp1	Multi effect evaporator reboiler 1	3742	10395	100	S								
P2b	Pump 2b	10.3	10406		E								
NA	Drum filters, crystals	316	10721	0	E								
NA	Vacuum, crystals	25.2	10746	0	E								
R1	Calcination, Reactor 1	1.26E+04	2.33E+04	1100	G								
	Potential recovery	-1.12E+04	1.21E+04										
	Net energy		1.21E+04				Potential recovery:						-1.12E+04
	Electricity	2806	E	[MJ/hr]									
	DowTherm	0	D	[MJ/hr]			Adiabatic flash residual			-.756	MJ/hr		
	Heating steam	7940	S	[MJ/hr]			Drum filters	50 MJ/1000 kg in for rotating each filter					
	Direct fuel use	0	F	[MJ/hr]			Vacuum	7 kWhr per wash / filter set					

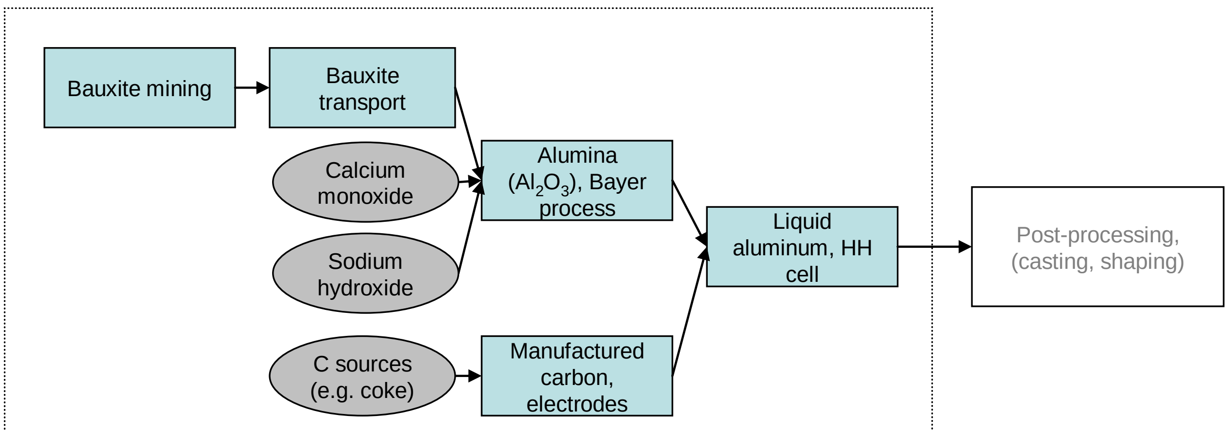
	Heating natural gas	1.26E+04	G	[MJ/hr]									
	Diesel process	0	Ds	[MJ/hr]			calcination, net energy			3489	MJ/hr		
	Undefined	0	U	[MJ/hr]									
	Heating coal	0	C	[MJ/hr]									
	Energy input requirement	2.33E+04		[MJ/hr]									
	Cooling water	-2.05E+04		[MJ/hr]									
	Cooling refrigeration			[MJ/hr]									
	Potential heat recovery	-1.12E+04		[MJ/hr]									
	Net energy	1.21E+04		[MJ/hr]									

XVIII. Graph of Cumulative Energy Requirements



The individual lci are referred to as gate-to-gate (gtg) which means a single plant or process to make a specific chemical or material. These gtg lci are joined together on the basis of mass flows to provide a profile of the entire supply chain prior to a material or chemical going into a product manufacturing plant (research concept 1). Figure 1 provides the supply chain (also referred to as the cradle-to-gate, ctg) for aluminum.

Figure 1. Gate-to-gates specific to aluminum production. gtgs specific to aluminum production are represented by rectangles. The ovals represent cradle-to-gates of commodity inputs.



In research concept 2, a number of lci were produced or used to construct the current database for materials and chemicals of wind generator manufacturing. These are on the WSU website and linked to the NREL website. Table 2 is a list of these lci gtg.

Some conditions of the information and the U.S. manufacturing base have represented problems or changes in the research initially proposed. Overall, there has not been a significant departure from the objectives or approach. First, the emphasis on defining generic frameworks has taken a greater effort and longer time. This was a result of 1) the need to integrate this effort with the global IMS (Intelligent Manufacturing Systems) initiative that began after this WSU project had started and 2) the process of building a network of uplci developers was limited by suitable Conferences as a venue for networking. Second, an area that restricted progress on Task 3 was the low number of U.S. manufacturers of wind generators. This has made the use of information and the critical review to be less and hence to take more time. Third, the access to industrial practices in product manufacturing is surprisingly small compared to industrial practice information sources in material and chemical manufacturing. This suggested we use more general benchmark information initially, but may have to develop specific industrial sites for further information.

Table 2. Chemical lci gtg for wind generator manufacturing in current funding cycle

Aluminum	liquid aluminum, HH cell
	aluminum oxide, Bayer
	bauxite shipping (at US Port)
	bauxite mining
	manufactured amorphous carbon
	calcium monoxide
	calcium carbonate
	sodium hydroxide
	sodium chloride
	coal tar from coking
	sulfuric acid
	sulfur trioxide
	sulfur
	petroleum coke
	water
	coal
Steel	liquid steel
	iron
	coke, metallurgical
	Iron pellets, 65 Fe, at mill, US
	oxygen, air separation
	natural gas
	calcium monoxide
	calcium carbonate
	sulfuric acid
	sulfur trioxide
	sulfur
	steel scrap
Carbon fiber	carbon fiber with epoxy
	carbon fiber, high strengh
	epoxy for carbon fiber
	pan precursor
	acrylonitrile
	ammonia
	propylene
	naphtha
	nitrogen (distillation of air, byproduct
	natural gas
	sulfuric acid
	sulfur trioxide
Epoxy	acetone
	bisphenol A
	benzene
	pyrolysis gas
	reformate, from naphtha
	oxygen
	hydrogen chloride
	chlorine
	ethylene
	phenol
	epichlorohydrin
	allyl chloride
	propylene
	calcium monoxide
	calcium carbonate
Glass fiber	borix oxide
	boric acid
	borax
	silica
	aluminum oxide
	bauxite, at US port
	bauxite, at mine
	calcium monoxide
	calcium carbonate
	sodium hydroxide
	sodium hchloride
	sulfuric acid
	sulfur trioxide
	sulfur
	calcium carbonate

Resolution of the limitations above have helped us achieve the major goals of the research in Task 3. The impact of what has been completed in Task 3 has been to establish this research at the early stage of a global effort to examine manufacturing environmental footprints as a first stage in seeking improvements. This project has made it easier and more transparent to estimate the larger, more distant effects of decision-making in wind generator manufacturing. These estimates are still imprecise because a more complete set of uplci and chemical/material lci are not available. This research project has now expanded to a larger community of developers for uplci (now five additional universities) with faculty beginning to use this generic framework.. They will continue to publish these and utilize the results of the entire database as suitable products are defined.

References cited (not already listed in drilling uplc or aluminum gtg lci)

1. Kalpakjian, S.; and Schmid, S. (2008) *Manufacturing Processes for Engineering Materials,* 5th Edition, Prentice Hall.

2. Todd, R.; Allen, D.; and Alting, L. (1994) *Manufacturing processes reference guide,* Industrial Press, New York.

Products Developed and Technology Transfer

A. Publications (Journals, Conference Proceedings, Abstracts, Presentations, Thesis, Dissertation, Student Projects)

1. J. Twomey and M. Overcash (2009) Critical Information for the Advancement of Wind Energy - Update of DOE Project. Kansas Wind Energy Work Group: Meeting 4, February 20, 2009 Topeka, KS.

2. M. Overcash and J. Twomey (2009), Life cycle conference for wind generation and use, 63p. Wichita State University, March 26, 2009.

3. M. Overcash and J. Twomey (2009), Life cycle and sustainability, two manufacturing firms with potential products for wind generators., March, 2009.

4. J. Twomey, and M. Overcash (2009), Environmental life cycle for manufacturing unit process., invited abstract, IERC 2009 Annual Conference May 30 - June 3, Miami, Fl.

5. Isaacs, J., J. Twomey, M. Overcash, Unit process life cycle inventory: a project in environmentally benign design and manufacturing, MIT Workshop on manufacturing, 31p. Aug. 29, 2009.

6. Isaacs, J., J. Twomey, M. Overcash, Manufacturing Unit Process Life Cycle Inventories: A Project in Environmentally Benign Design and Manufacturing (EBDM), NIST Performance Metrics for Intelligent Systems Workshop, 24p., September 21, 2009

7. Kalla, D., J. Twomey, M. Overcash, Unit Process Life Cycle Inventory For Product Manufacturing Operations, 2009 International Manufacturing Science & Engineering Conference, 18 p., October 4 - 7, 2009.

PI and COPI Project Presentations, Wind Energy Research Symposium, March 26th, 2009, Wichita, KS. 1:00 – 5:00pm Room 307, NIAR (see attached).

B. Web site / Internet sites

The project website is:

www.wichita.edu/sustainability

http://cratel.wichita.edu/uplci

C. Networks or collaborations fostered;

- Northwestern University, Evanston, IL (NU)
- Kansas State University
- Purdue University
- Oregon State University
- St. Thomas University
- Northeastern University
- University of South Florida
- University of Tennessee

- European initiative: Cooperative Effort on (CO2) Process Emissions CO2PE!

- ElectroMech
- Chance Rides
- Enertech Wind, Inc.
- BTI Wind Energy

College of Engineering Wichita State University
Wind Energy Research Symposium

March 26th, 2009
1:00 – 5:00pm Room 307, NIAR

(www.wichita.edu/sustainability)

Supported by the Department of Energy (DOE DE-FG36-08GO88149)

Over the past year the College of Engineering has engaged in research activities that draw from aviation design and manufacturing research to target issues critical to the wide spread deployment of wind energy. This symposium will include presentations and posters summarizing the research and findings of faculty and students supported by a Department of Energy award.

Schedule of Presentations

Time	Topic	Presenter
1:00-1:20	Posters	Students
1:20-1:40	Welcome and Introductions	College of Engineering: Dean Zulma Toro-Ramos Project PI: Dr. Twomey
1:40-2:00	Network Monitoring and Control	Dr. Jewell
2:00-2:20	Wind Turbine Reliability and Maintainability	Dr. Steck
2:20-2:40	Environmental Impacts of Wind Energy Systems using Life Cycle	Dr. Overcash
2:40-3:00	Break/Posters	
3:00-3:20	Fiber-Reinforced Composite Blade UV Degradation Prevention using Nanotechnology	Dr. Asmatulu
3:20-3:40	Intelligent Manufacturing of Hybrid Carbon-Glass Fiber-Reinforced Composite Wind Turbine Blades	Dr. Minaie
4:00-4:20	Wind Energy Supply Chain/ Co-Generation Technologies (PEM Fuel Cells)	Drs. Yildirim and T.S. Ravi
4:20-4:30	Wrap-up	Dr. Twomey
	Posters	Students