LIFE CYCLE IN SEMICONDUCTORS AND SUPPLY CHAIN SYSTEMS

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ENGINEERING DECISION-MAKING CONTEXT FOR LIFE CYCLE EVALUATIONS

- OFTEN DEALING WITH A HIGHLY TECHNICAL AUDIENCE
- INTERTWINED WITH ECONOMICS
- VERY CORPORATE IN DIMENSION

LIFE CYCLE AND TECHNOLOGY SEQUENCES

- SUCCESSION OF TECHNOLOGY ALTERNATIVES
- RANGE OF DESIGN AND INPUT VARIABLES FOR A SINGLE TECHNOLOGY
- METRICS FOR EVALUATING NEW ENGINEERING SOLUTIONS

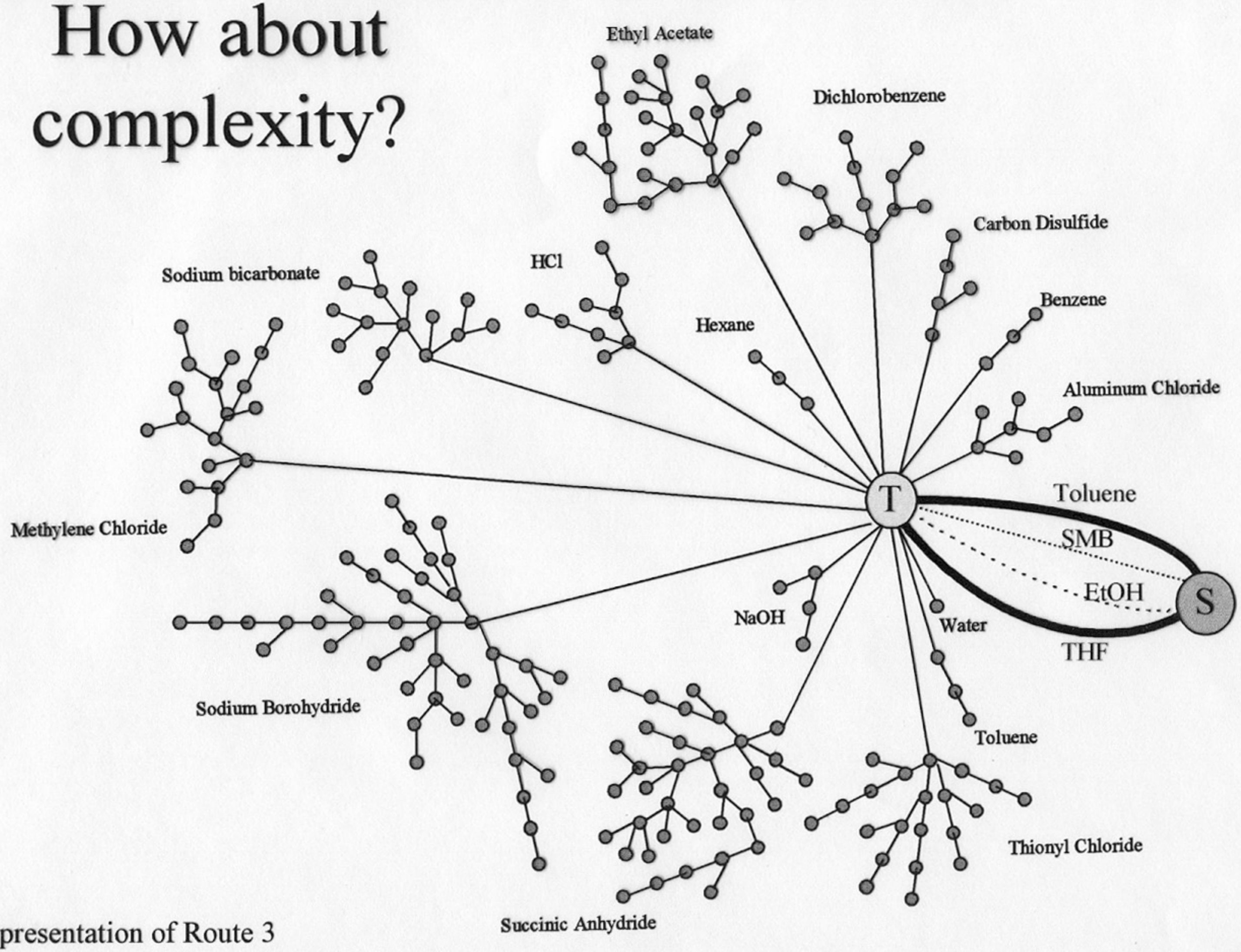
LIFE CYCLE TOOLS

LIFE CYCLE STAGE	DECISIONS
IMPROVEMENT ANALYSIS	
IMPACT ASSESSMENT	**•POLICY ISSUES** **•SUSTAINABILITY** **•MACRO IMPROVEMENTS**
INVENTORY ANALYSIS	**•NEW TECHNOLOGY** **•POLLUTION PREVENTION** **•PROCESS ALTERNATIVES**

Chemical tree for life cycle evaluation of methyl N-methylamidomalonic acid (MMAM)

Primary	2nd	3rd	4th	5th	6th	7th	8th	9th	10th	11th	12th
MMAM	Dimethyl malonate	Chloroacetic acid	Acetic acid	Methanol	Natural gas						
					Hydrogen	Natural gas					
					Carbon monoxide	Natural gas					
				Carbon monoxide	Natural gas						
			Acetic anhydride	Kentene	Acetone	Isopropanol	Propylene	Petroleum extraction /refinery			
								Water			
							Sulphuric acid	Sulphur trioxide	Sulfur Dioxide	Sulfur	Petroleum extraction /refinery
										Oxygen	
									Oxygen		
								Water			
							Water				
						Oxygen					
				Acetic acid	Methanol	Natural gas					
						Hydrogen	Natural gas				
						Carbon monoxide	Natural gas				
					Carbon monoxide	Natural gas					
			Chlorine	Sodium chloride							
				Water							
		Sodium Cyanide	Sodium Hydroxide	Sodium chloride							
				Water							
			Hydrogen cyanide	Ammonia	Natural gas						
					Water						
					Air						
				Natural gas							
				Oxygen							
		Methanol	Natural gas								
			Hydrogen	Natural gas							
			Carbon monoxide	Natural gas							
		Sodium Hydroxide	Sodium chloride								
			Water								
		Sulphuric acid	Sulphur trioxide	Sulfur Dioxide	Sulfur	Petroleum extraction /refinery					
					Oxygen						
				Oxygen							
			Water								
	Methylamine	Methanol	Natural gas								
			Hydrogen	Natural gas							
			Carbon monoxide	Natural gas							
		Ammonia	Natural gas								
			Water								
			Air								

How about complexity?



Representation of Route 3

7th	8th	9th	10th	11th	12th	13th	14th	15th
Nylon6.6 1000kg	Hexamethylenediamine 476kg	Adiponitrile 443kg	Adipic Acid 599kg	Cyclohexanol 223kg	Cyclohexane 196kg	Benzene 182kg	Naptha 2230kg	Oil Refinery
						Hydrogen 14.9kg	Natural Gas 209kg	
							Water 418kg	
							Oxygen 61.1kg	Air 364kg
					Oxygen 22.5kg	Air 134kg		
				Cyclohexanone 223kg	Cyclohexane 265kg	Benzene 246kg	Naptha 3010kg	Oil Refinery
						Hydorgen 20.1kg	Natural Gas 72.4kg	
							Water 145kg	
							Oxygen 82.4kg	Air 489kg
					Oxygen 72.7kg	Air 433kg		
				Nitric Acid 6410kg	Ammonia 1560kg	Air 2800kg		
						Natural Gas 697kg		
						Water 1870kg		
					Water 641kg			
					Air 22000kg			
			Ammonia 140kg	Air 252kg				
				Natural Gas 62.5kg				
				Water 168kg				
		Hydrogen 33.1kg	Natural Gas 119kg					
			Water 283kg					
			Oxygen 136kg	Air 811kg				
	Adipic Acid 645kg	Cyclohexanol 241kg	Cyclohexane 212kg	Benzene 197kg	Naptha 2410kg	Oil Refinery		
				Hydrogen 16.1kg	Natural Gas 58.0kg			
					Water 116kg			
					Oxygen 66.0kg	Air 393kg		
			Oxygen 24.3kg	Air 145kg				
		Cyclohexanone 241kg	Cyclohexane 286kg	Benzene 265kg	Naptha 3250kg	Oil Refinery		
				Hydorgen 21.7kg	Natural Gas 78.1kg			
					Water 156kg			
					Oxygen 89.0kg	Air 531kg		
			Oxygen 78.6kg	Air 469kg				
		Nitric Acid 6902kg	Ammonia 1679kg	Air 3010kg				
				Natural Gas 751kg				
				Water 2010kg				
			Water 690kg					
			Air 23700kg					
Polypropylene 1058kg	Propylene 1058kg	Naptha 6010kg	Oil Refinery					
		Steam 3005kg	Water 3005kg					
Hevea brasileinsis sap	Hevea brasileinsis tree							

Table 1.1 Life Cycle Diagram of Nylon 66 Carpet

P11	P10	P9	P8	P7	P6	P5	P4	P3	P2	P1	Primary	2nd	3rd	4th	5th	6th
			Cogeneration Plant	Non-polyamid 66	Separation	Size Reduction	Automatic Sorting	Carpet Waste	Steam Cleaning	Vacuuming 900MJ	Carpet Ready For Sale 1029m^2 2058kg	Dyeing 36400MJ	Carpet 1029m^2 2058kg	Tufting 14.03MJ	Nylon Yarn 1000kg	Spinning 2909MJ
				Chalk from Backing												
Reuse	Nylon 6,6	Virgin + Recycled Nylon	Melting	Polyamide 66												
															Carpet Backing 1058kg	Forming/Molding
															Adhesive	Latex

LIFE CYCLE OF MANUFACTURE PUMP

ENERGY OR CHEMICAL LOSS	AMOUNT	UNITS
PRODUCTION ENERGY	930	MJ/PUMP
TRANSPORT ENERGY	36	MJ/PUMP
AIR EMISSIONS	58	KG/PUMP
WATER EMISSIONS	0.01	KG/PUMP
SOLID WASTES	9.3	KG/PUMP
TOTAL CHEMICAL LOSSES	67	KG/PUMP

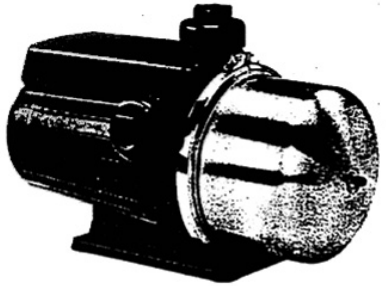
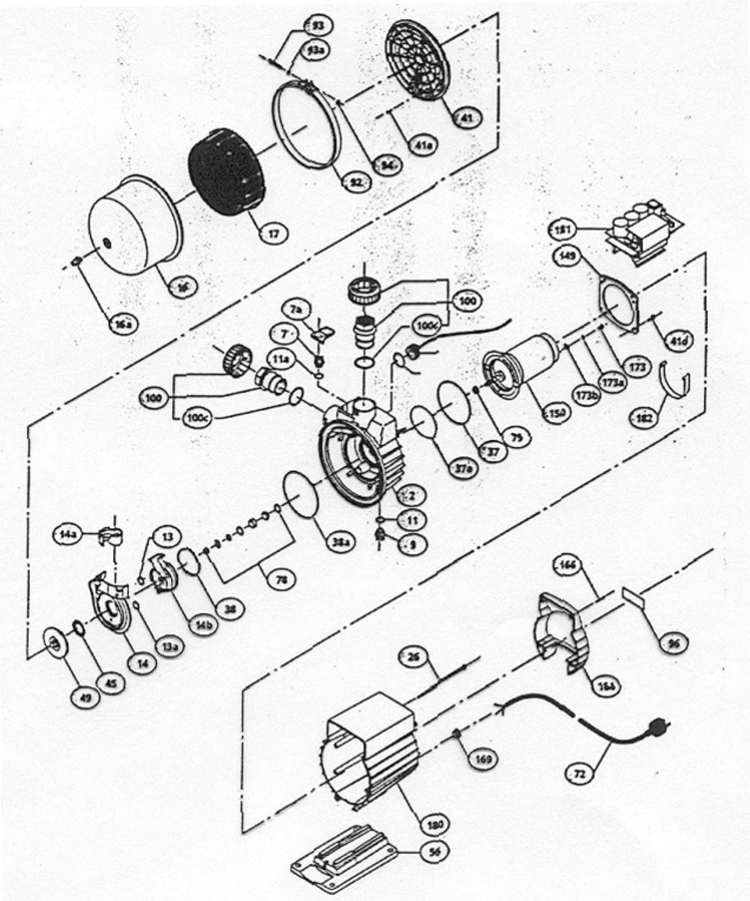


Figure 29.1. The reference product, the JetpaQ



LIFE CYCLE IS A TOOL

- DEVELOPED TO DEAL WITH COMPLEXITY OF ENVIRONMENT AND PRODUCTS
- HELPS US QUANTIFY, UNDERSTAND, AND SEEK IMPROVEMENT
  - IMPROVE ENVIRONMENT
  - IMPROVE ECONOMICS

IMPROVED LCI CLASSIFICATION SYSTEM

LOW COMPLEXITY	PACKAGING, BASIC MATERIALS
MODERATE COMPLEXITY	SEMICONDUCTORS, PHARMACEUTICAL PRODUCTS, MANY CONSUMER PRODUCTS
HIGH COMPLEXITY	AUTOMOBILE, FIGHTER AIRCRAFT

LIFE CYCLE EFFORTS AT NCSU

- RESEARCH TO DEVELOP RAPID LCI TECHNIQUES
- DEVELOPMENT OF GENERIC TOOLS FOR LCI
- CREATION OF LCI LIBRARY
- RESEARCH TO INTEGRATE LCI WITH ENVIRONMENTAL DECISION-MAKING

ORDER OF MAGNITUDE OF THE UNIVERSE FOR LIFE CYCLE INVENTORIES

- 100,000 CHEMICALS IN COMMERCE

- 10,000 PRODUCTS AT THE 4 DIGIT UNSPSC LEVEL

A LIFE CYCLE INVENTORY (LCI) IS A COMPLETE MASS AND ENERGY BALANCE TO DETERMINE

- INPUTS
- CHEMICAL EMISSIONS
- ENERGY NEEDS

SOME BOUNDARY MUST BE SPECIFIED

FOUR GENERAL METHODS FOR LIFE CYCLE INVENTORY DATA

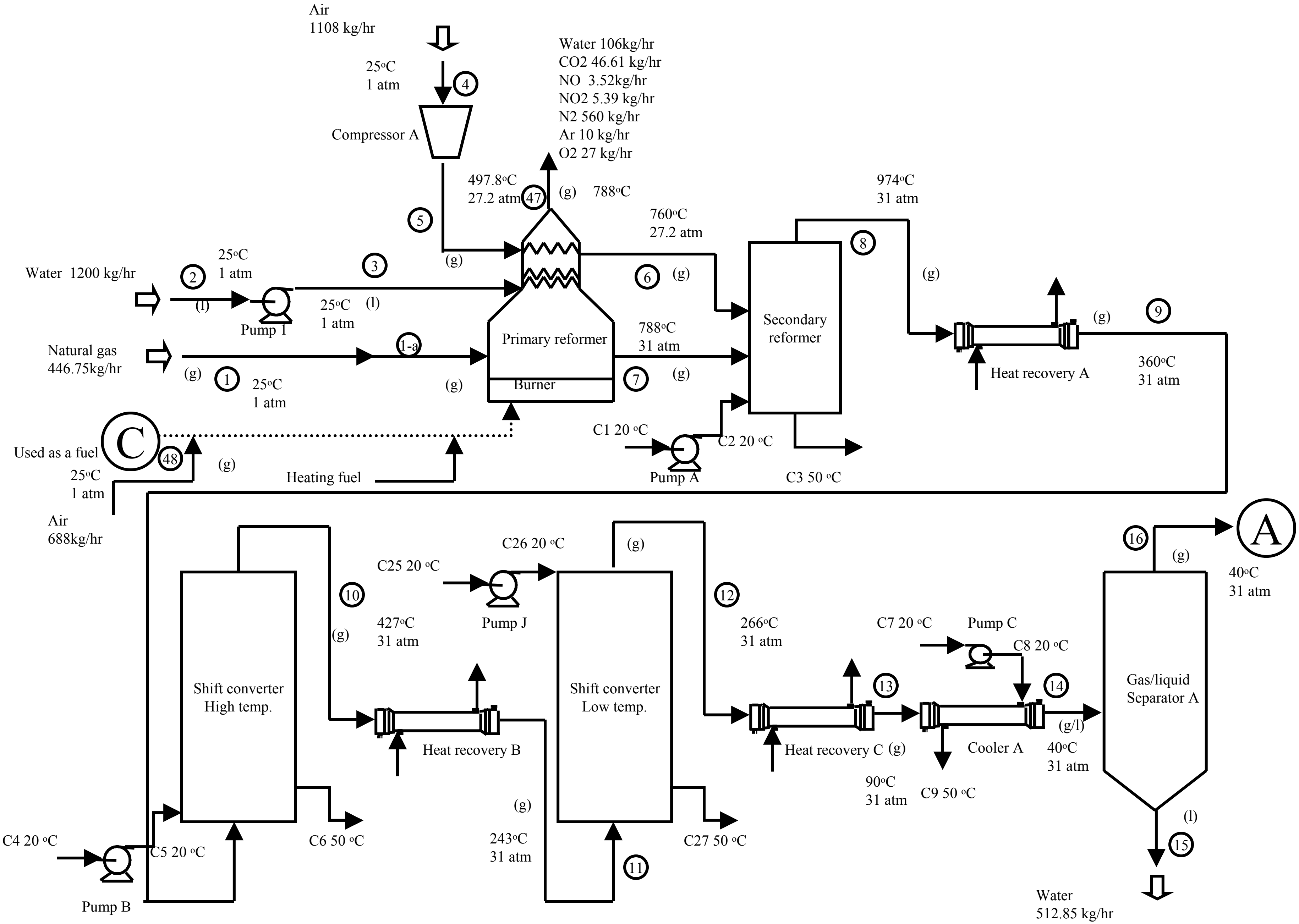
1. DIRECT MEASUREMENT FROM FACILITIES
2. CONSORTIA OF STAKEHOLDERS
3. ECONOMIC INPUT/OUTPUT
4. CHEMICAL ENGINEERING DESIGN METHOD

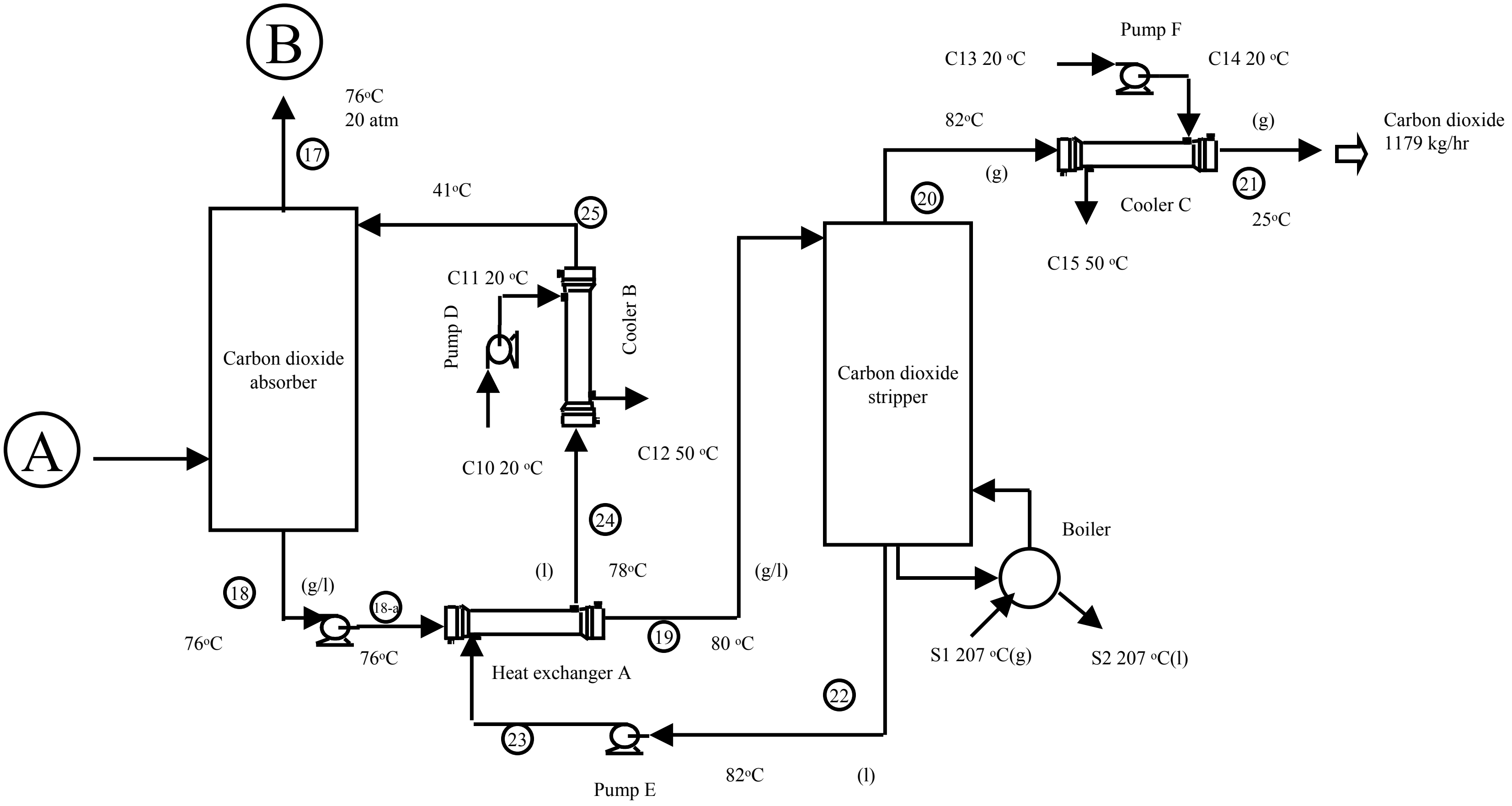
LIFE CYCLE INVENTORY QUALITY

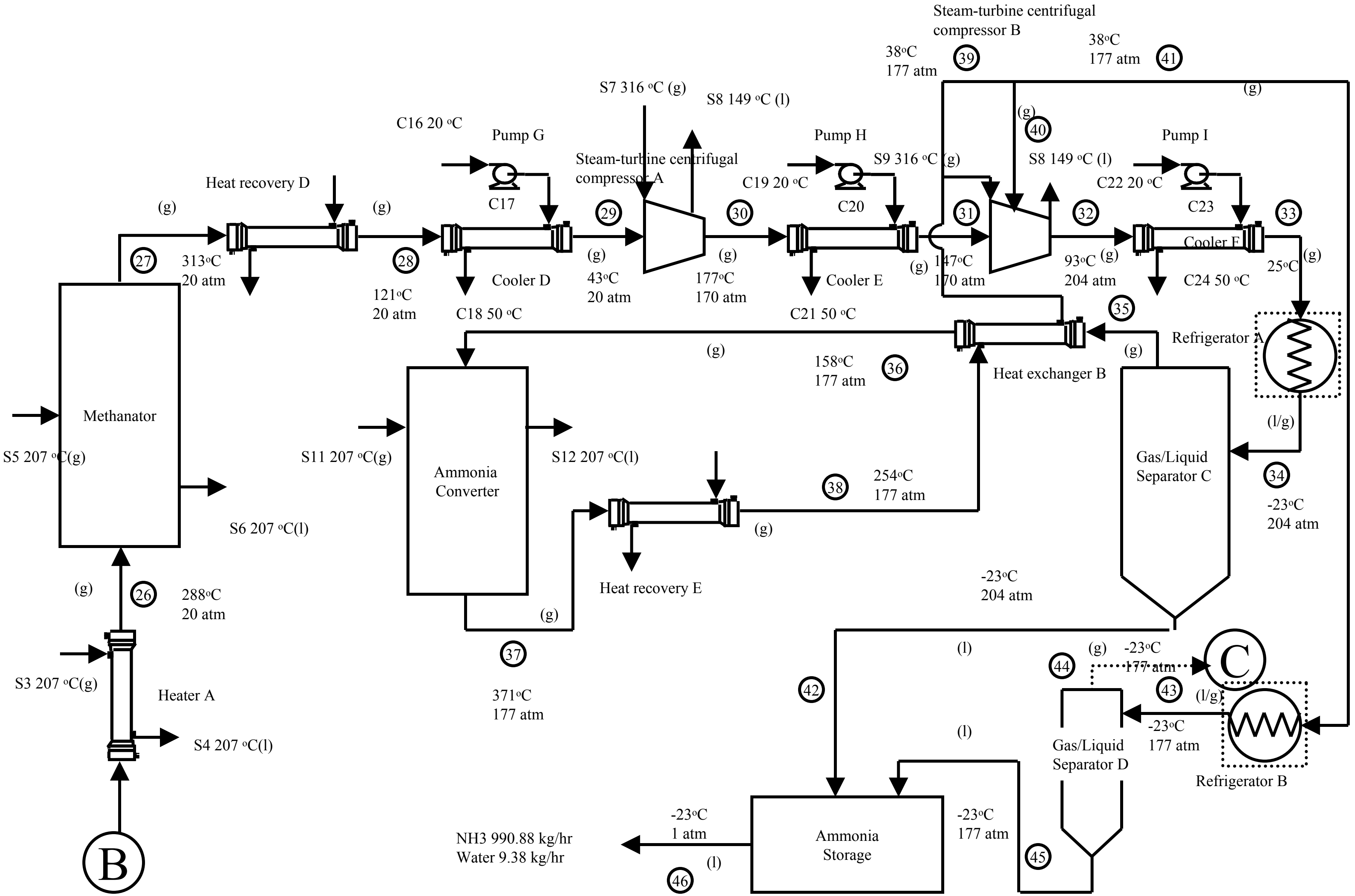
- TRANSPARENCY
- ENGINEERING PRINCIPLES OF MASS & ENERGY
- MULTIPLE VIEWS
- LOGICAL MECHANISM TO CHANGE
- EXPECTATIONS OF DECISION-MAKERS
- CRITICAL RELATION OF SYSTEM TO SUSTAINABILITY FACTORS

LIFE CYCLE INVENTORY METHODOLOGY GATE-TO-GATE

- SEARCH FOR PROCESSES
- PROCESS DIAGRAM AND PHYSICAL PROPERTIES
- MASS BALANCE – BY STREAM
- IDENTIFICATION OF PROCESS WASTES (g,l,s)
- ENERGY BALANCE – BY UNIT PROCESS
- SUMMARY


Air
1108 kg/hr
25°C
1 atm
4
Compressor A
5
(g)
Water 106kg/hr
CO2 46.61 kg/hr
NO 3.52kg/hr
NO2 5.39 kg/hr
N2 560 kg/hr
Ar 10 kg/hr
O2 27 kg/hr
497.8°C
27.2 atm
47
(g)
788°C
760°C
27.2 atm
974°C
31 atm
8
(g)
Water 1200 kg/hr
2
(l)
25°C
1 atm
Pump 1
3
25°C
1 atm
(l)
6
(g)
Secondary reformer
Heat recovery A
(g)
9
360°C
31 atm
Natural gas
446.75kg/hr
(g)
1
25°C
1 atm
1-a
(g)
Primary reformer
Burner
788°C
31 atm
7
(g)
C1 20 °C
Pump A
C2 20 °C
C3 50 °C
Used as a fuel
C
48
25°C
1 atm
(g)
Heating fuel
Air
688kg/hr
Shift converter High temp.
10
(g)
427°C
31 atm
C25 20 °C
C26 20 °C
Pump J
Heat recovery B
Shift converter Low temp.
(g)
12
266°C
31 atm
C7 20 °C
Pump C
C8 20 °C
13
14
Heat recovery C
(g)
Cooler A
(g/l)
40°C
31 atm
90°C
31 atm
C9 50 °C
16
(g)
A
40°C
31 atm
Gas/liquid Separator A
(l)
15
Water
512.85 kg/hr
C4 20 °C
C5 20 °C
Pump B
C6 50 °C
(g)
243°C
31 atm
11
C27 50 °C


B
76°C
20 atm
17
Pump F
C13 20 °C
C14 20 °C
82°C
(g)
Carbon dioxide
1179 kg/hr
(g)
20
21
Cooler C
25°C
41°C
25
C15 50 °C
C11 20 °C
Pump D
Cooler B
Carbon dioxide absorber
Carbon dioxide stripper
A
C12 50 °C
C10 20 °C
24
Boiler
18
(g/l)
(l)
78°C
(g/l)
18-a
76°C
76°C
19
80 °C
Heat exchanger A
S1 207 °C(g)
S2 207 °C(l)
22
23
Pump E
82°C
(l)


Steam-turbine centrifugal compressor B
38°C 177 atm
39
38°C 177 atm
41
(g)
S7 316 °C (g)
S8 149 °C (l)
(g)
40
C16 20 °C
Pump G
Steam-turbine centrifugal compressor A
Pump H
S9 316 °C (g)
S8 149 °C (l)
Pump I
Heat recovery D
C17
C19 20 °C
C20
C22 20 °C
C23
(g)
(g)
29
30
31
32
33
Cooler F
27
313°C 20 atm
28
(g)
43°C 20 atm
(g)
177°C 170 atm
(g)
147°C 170 atm
93°C 204 atm
(g)
25°C
(g)
Cooler D
Cooler E
C24 50 °C
121°C 20 atm
C18 50 °C
C21 50 °C
35
Refrigerator A
(g)
(g)
158°C 177 atm
36
Heat exchanger B
Methanator
Ammonia Converter
Gas/Liquid Separator C
(l/g)
S5 207 °C(g)
S11 207 °C(g)
S12 207 °C(l)
34
254°C 177 atm
38
-23°C 204 atm
S6 207 °C(l)
(g)
Heat recovery E
(g)
26
288°C 20 atm
(g)
-23°C 204 atm
37
(l)
(g)
-23°C 177 atm
C
44
43
(l/g)
S3 207 °C(g)
Heater A
42
371°C 177 atm
-23°C 177 atm
S4 207 °C(l)
(l)
Gas/Liquid Separator D
Refrigerator B
-23°C 1 atm
-23°C 177 atm
NH3 990.88 kg/hr
Water 9.38 kg/hr
Ammonia Storage
(l)
46
45
B

Ammonia Process
CONTENTS OF FACTORY GATE TO FACTORY GATE LIFE CYCLE INVENTORY SUMMARY (Byproduct allocation not included)

- Chemistry
- Process Summary
- Summary of LCI Information
- Process Diagram Interpretation Sheet
- Process Diagram or Boundary of LCI
- Mass Balance of Chemicals in each Process Stream (Highlighting Chemicals that are Wastes and the Physical State when Lost)
- Graph of Cumulative Chemical Losses through Manufacturing Process
- Graph of Cumulative Non-Contaminated Water Use/Emission through Manufacturing Process (Not applicable)
- Graph of Cumulative Non-Contaminated Water Use/Emission through Manufacturing Process
- Energy Input for each Unit Process, Cumulative Energy Requirements, Cooling Requirements (exotherms), and Assumed Heat Recovery from Hot Streams Receiving Cooling
- Graph of Cumulative Energy Requirements
- Conversion of Chemical Losses and Energy Requirements into Environmental Parameters, Prior to any Treatment or Discharge to the Environment
- Waste Management Summary

CHEMISTRY:

$$N_2 + 3H_2 \rightarrow 2NH_3$$

Nitrogen Hydrogen Ammonia

$$CH_4 + 2H_2O \rightarrow CO_2 + 4H_2$$

Methane Water Carbon dioxide Hydrogen

PROCESS:

Ammonia is produced by the reaction of nitrogen and hydrogen, The source of hydrogen is natural gas, and nitrogen is air. Carbon dioxide is also produced in the ammonia plant. This is regarded as a by-product. Ammonia is purified by refrigeration

SUMMARY OF LCI INFORMATION

Product:	Ammonia
Basis:	1,000 kg/hr ammonia
Reference:	Slack, V. and James R.G., Ammonia, Marcel Dekker, inc., 1973. Brykowski F.J. Ammonia and synthesis gas, Noyes Data Corporation, 1981.
Plant Location:	
Comments:	All mass and energy units per hour are equivalent to per 1,000 kg of ammonia

Inputs

Chemical	Amount	Units	Comments
Air	1,796.85	kg/hr	688.6 kg of air is used in burning flue gas.
Natural gas	446.75		
Water	1,200		
Total	3,443.6		

Product

Chemical	Amount	Units	Comments
Ammonia	1,000	kg/hr	99 % purity (9.4 kg/hr water)
Carbon dioxide	1,179		100% purity

Process emissions*

Chemical	Amount				Units	Comments
	Air	Liquid	Solid	Solvent		
Ar	13.29				kg/hr	
CH4	2.23					
CO	2.9					
CO2	52.54					
H2	3.07					
NH3	6.42					
NO	3.52					
NO2	5.39					
Mass balance difference	-30.72					

Water (513 kg), oxygen (27kg) and nitrogen (560 kg) are not included.

Energy Requirements

Source	Amount	Units	Comments
Electricity	7.00E+02	MJ/hr	
Heating – Steam	9.00E+03		Consider the heat transfer efficiency
Heating fuel	9.86E+03		Consider the heat transfer efficiency
Cooling refrigeration			
Cooling water	-1.71E+04		
Potential Heat Recovery	-9.15E+03		
Net Energy**	1.04E+04		

* Oxygen and nitrogen are not included;
** Energy requirement minus potential heat recovery from cooling systems
N/A not applicable for this chemical process

Mass Balance of Chemicals in each Process Stream

Mass Flow (kg/1000kg product)

Physical State of Chemical Losses

Gas

Liquid

Solid

Stream	Total flow	methane	nitrogen	hydrogen	ammonia	carbon dioxide	carbon monoxide	Argon	oxygen	Monoethanol amine	NO	NO2	Water
1	446.75	446.75											
1-a	446.75	446.75											
2	1200.00												1200.00
3	1200.00												1200.00
4	1108.24		850.08						258.16				
5	1108.24		850.08						258.16				
6	1108.24		850.08						258.16				
7	1646.96	102.75		146.21		353.94	375.44						668.62
8	2755.26	8.64	850.08	146.21		289.39	580.87						880.08
9	2755.26	8.64	850.08	146.21		289.39	580.87						880.08
10	2755.13	8.64	850.08	180.85		1044.00	100.51						571.04
11	2755.13	8.64	850.08	180.85		1044.00	100.51						571.04
12	2755.00	8.64	850.08	187.37		1186.00	10.05						512.85
13	2755.00	8.64	850.08	187.37		1186.00	10.05						512.85
14	2755.00	8.64	850.08	187.37		1186.00	10.05						512.85
15	-512.85												-512.85
16	2242.15	8.64	850.08	187.37		1186.00	10.05						
17	1063.27	8.64	850.08	187.37		7.12	10.05						
18	16404.88					1178.88				3046.00			12180.00
18-a	16404.88					1178.88				3046.00			12180.00
19	16404.88					1178.88				3046.00			12180.00

Stream	Total flow	methane	nitrogen	hydrogen	ammonia	carbon dioxide	carbon monoxide	Argon	oxygen	Monoethanolamine	NO	NO2	Water
20	1178.88					1178.88							
21	-1178.88					-1178.88							
22	15226.00									3046.00			12180.00
23	15226.00									3046.00			12180.00
24	15226.00									3046.00			12180.00
25	15226.00									3046.00			12180.00
26	1063.27	8.64	850.08	187.37		7.12	10.05						
27	1060.35	16.99	850.08	183.89									9.38
28	1060.35	16.99	850.08	183.89									9.38
29	1060.35	16.99	850.08	183.89									9.38
30	1060.35	16.99	850.08	183.89									9.38
31	1060.35	16.99	850.08	183.89									9.38
32	5600.96	374.79	2727.00	613.18	1266.00			610.61					9.38
33	5600.96	374.79	2727.00	613.18	1266.00			610.61					9.38
34	5600.96	374.79	2727.00	613.18	1266.00			610.61					9.38
35	4614.21	374.79	2727.00	613.18	288.63			610.61					
36	4614.21	374.79	2727.00	613.18	288.63			610.61					
37	4613.58	374.79	1909.00	436.19	1283.00			610.61					
38	4613.58	374.79	1909.00	436.19	1283.00			610.61					
39	4613.58	374.79	1909.00	436.19	1283.00			610.61					
40	4529.46	357.80	1877.00	429.29	1265.00			600.37					
41	84.13	16.99	32.00	6.90	18.00			10.23					
42	986.75				977.37								9.38
43	84.13	16.99	32.00	6.90	18.00			10.23					
44	70.62	16.99	32.00	6.90	4.49			10.23					
45	13.51				13.51								
46	-1000.26				-990.88								-9.38
47	-758.72		-560.19			-46.61		-10.23	-26.73		-3.52	-5.39	-106.05
48	688.60		528.19						160.41				
Fugitive loss	-23.60	-2.23		-3.07	-6.42	-5.93	-2.90	-3.05					

Stream	Total flow	methane	nitrogen	hydrogen	ammonia	carbon dioxide	carbon monoxide	Argon	oxygen	Monoethanolamine	NO	NO2	Water
C1	14590.00												14590.00
C2	14590.00												14590.00
C3	-14590.00												-14590.00
C4	3148.00												3148.00
C5	3148.00												3148.00
C6	-3148.00												-3148.00
C7	16360.00												16360.00
C8	16360.00												16360.00
C9	-16360.00												-16360.00
C10	20290.00												20290.00
C11	20290.00												20290.00
C12	-20290.00												-20290.00
C13	532.36												532.36
C14	532.36												532.36
C15	-532.36												-532.36
C16	2826.00												2826.00
C17	2826.00												2826.00
C18	-2826.00												-2826.00
C19	1000.00												1000.00
C20	1000.00												1000.00
C21	1000.00												1000.00
C22	9816.00												9816.00
C23	9816.00												9816.00
C24	-9816.00												-9816.00
C25	16.27												16.27
C26	16.27												16.27
C27	-16.27												-16.27
S1	1461.00												1461.00
S2	-1461.00												-1461.00
S3	466.86												466.86
S4	-466.86												-466.86

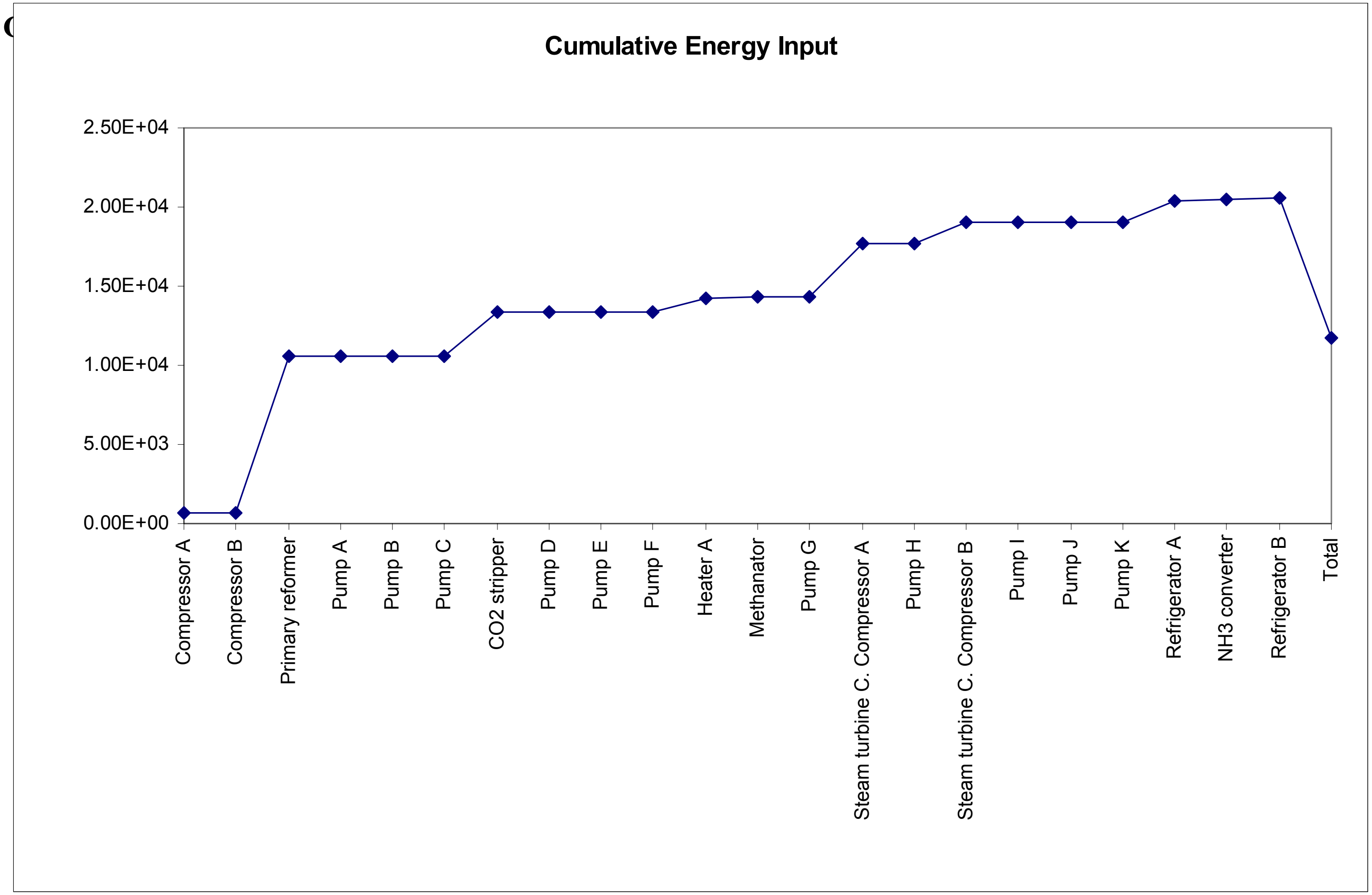
Stream	Total flow	methane	nitrogen	hydrogen	ammonia	carbon dioxide	carbon monoxide	Argon	oxygen	Monoethanolamine	NO	NO2	Water
S5	17.52												17.52
S6	-17.52												-17.52
S7	11400.00												11400.00
S8	-11400.00												-11400.00
S9	4665.00												4665.00
S10	-4665.00												-4665.00
S11	93.81												93.81
S12	-93.81												-93.81

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

	Energy Input (MJ/1000 kg product)			Cooling Requirements (MJ/1000kg product)				
	Unit Operation	Energy Input	Cumulative Energy Input	Unit Operation	Energy Loss*	Cumulative	Temperature (°C)	Heat Recovered**
E	Pump 1	3.46E-03	3.46E-03	Secondary reformer	-1.27E+03	-1.27E+03	974	-9.50E+02
E	Compressor A	7.00E+02	7.00E+02	Heat recovery A	-3.52E+03	-4.78E+03	974	-3.52E+03
E	Compressor B		7.00E+02	HT shift		-4.78E+03	427	
HF	Primary reformer	8.38E+03	9.08E+03	Heat recovery B	-1.38E+03	-6.16E+03	427	-1.38E+03
E	Pump A	3.42E-02	9.08E+03	LT shift		-6.16E+03	243	0.00E+00
E	Pump B		9.08E+03	Heat recovery C	-2.27E+03	-8.43E+03	266	-1.02E+03
E	Pump C	4.71E-02	9.08E+03	Cooler A	-3.37E+02	-8.77E+03	116	-8.41E+01
S	CO2 stripper	2.38E+03	1.15E+04	Cooler B	-2.17E+03	-1.09E+04	81	-5.42E+02
E	Pump D	5.85E-02	1.15E+04	Cooler C	-5.68E+01	-1.10E+04	82	-1.42E+01
E	Pump E	4.39E-02	1.15E+04	Cooler D	-3.02E+02	-1.13E+04	121	-7.54E+01
E	Pump F	1.53E-03	1.15E+04	Cooler E	-1.07E+02	-1.14E+04	177	-4.81E+01
S	Heater A	7.61E+02	1.22E+04	Cooler F	-1.05E+03	-1.24E+04	93	-2.62E+02
S	Methanator	2.86E+01	1.23E+04	Heat recovery D	-6.84E+02	-1.31E+04	313	-4.10E+02
E	Pump G	8.14E-03	1.23E+04	Heat recovery E	-1.41E+03	-1.45E+04	371	-8.45E+02
S	Steam turbine C. Compressor A	3.37E+03	1.56E+04	Refrigerator A	-3.38E+03	-1.79E+04	-23	0.00E+00
E	Pump H	2.88E-03	1.56E+04	Refrigerator B	-4.95E+01	-1.80E+04	-23	0.00E+00

S	Steam turbine C. Compressor B	1.38E+03	1.70E+04					
E	Pump I	2.83E-02	1.70E+04					
E	Pump J		1.70E+04					
E	Pump K	4.73E-02	1.70E+04					
E	Refrigerator A	3.32E+02	1.73E+04					
S	NH3 converter	1.53E+02	1.75E+04					
E	Refrigerator B	4.85E+00	1.75E+04					
	Total net energy		8.35E+03					-9.15E+03

*Energy Loss to Cooling Streams
**Energy that can be Gained from HX with Cooling Water Streams.
Based on 85% Efficiency for all HX, Coolers, and Condensers.

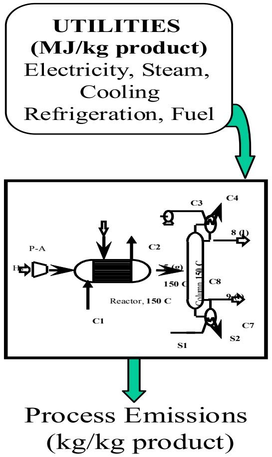

Cumulative Energy Input
2.50E+04
2.00E+04
1.50E+04
1.00E+04
5.00E+03
0.00E+00
Compressor A
Compressor B
Primary reformer
Pump A
Pump B
Pump C
CO2 stripper
Pump D
Pump E
Pump F
Heater A
Methanator
Pump G
Steam turbine C. Compressor A
Pump H
Steam turbine C. Compressor B
Pump I
Pump J
Pump K
Refrigerator A
NH3 converter
Refrigerator B
Total

CRADLE-TO-GATE MODULES

- **UTILITIES**
  - **ELECTRICITY**
  - **COOLING WATER**
  - **REFRIGERATION**
  - **HEATING FUEL – FURNACE**
  - **STEAM**
  - **DOWTHERM**

- **WASTE MANAGEMENT**
  - **SOLVENT DISTILLATION RECOVERY**
  - **BIOLOGICAL WASTEWATER TREATMENT**
  - **THERMAL OXIDIZER OR INCINERATION**
  - **LANDFILL**

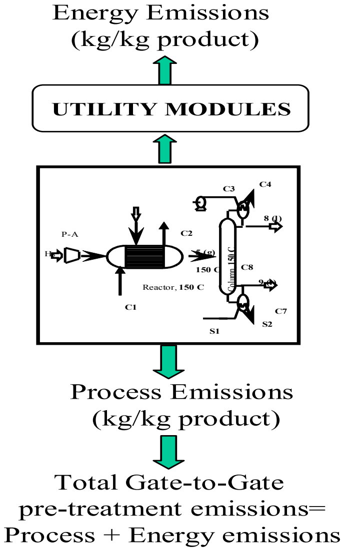
Level 1



UTILITIES
(MJ/kg product)
Electricity, Steam,
Cooling
Refrigeration, Fuel

Process Emissions
(kg/kg product)

Level 2



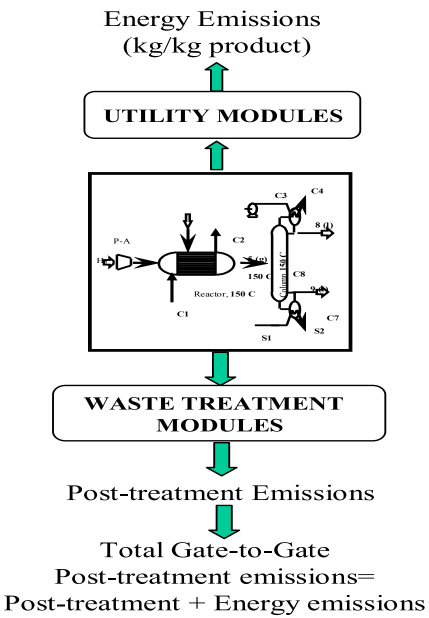
Energy Emissions
(kg/kg product)

UTILITY MODULES

Process Emissions
(kg/kg product)

Total Gate-to-Gate
pre-treatment emissions=
Process + Energy emissions

Level 3



Energy Emissions
(kg/kg product)

UTILITY MODULES

WASTE TREATMENT MODULES

Post-treatment Emissions

Total Gate-to-Gate
Post-treatment emissions=
Post-treatment + Energy emissions

Chemical Tree

Hydrochloric acid, HCl			
Chlorine, Cl_2		Ethylene, C_2H_6	Water, H_2O
Water, H_2O	Sodium Chloride, NaCl	Naphtha Refinery	
	Salt Rock	Petroleum Reserve	

Chemical Tree

Hydrochloric acid, HCl			
Chlorine, Cl_2		Ethylene, C_2H_6	Water, H_2O
Water, H_2O	Sodium Chloride, NaCl	Naphtha Refinery	
	Salt Rock	Petroleum Reserve	

Level 4

Cradle to Gate (Chemical tree):

- Energy emissions (level 2)
- Process emissions (level 2)
- Total Cradle-to-Gate emissions:

$$= \sum_{\substack{\text{Chemical}\\\text{Tree}}} \text{Process} + \sum_{\substack{\text{Chemical}\\\text{Tree}}} \text{Energy}$$

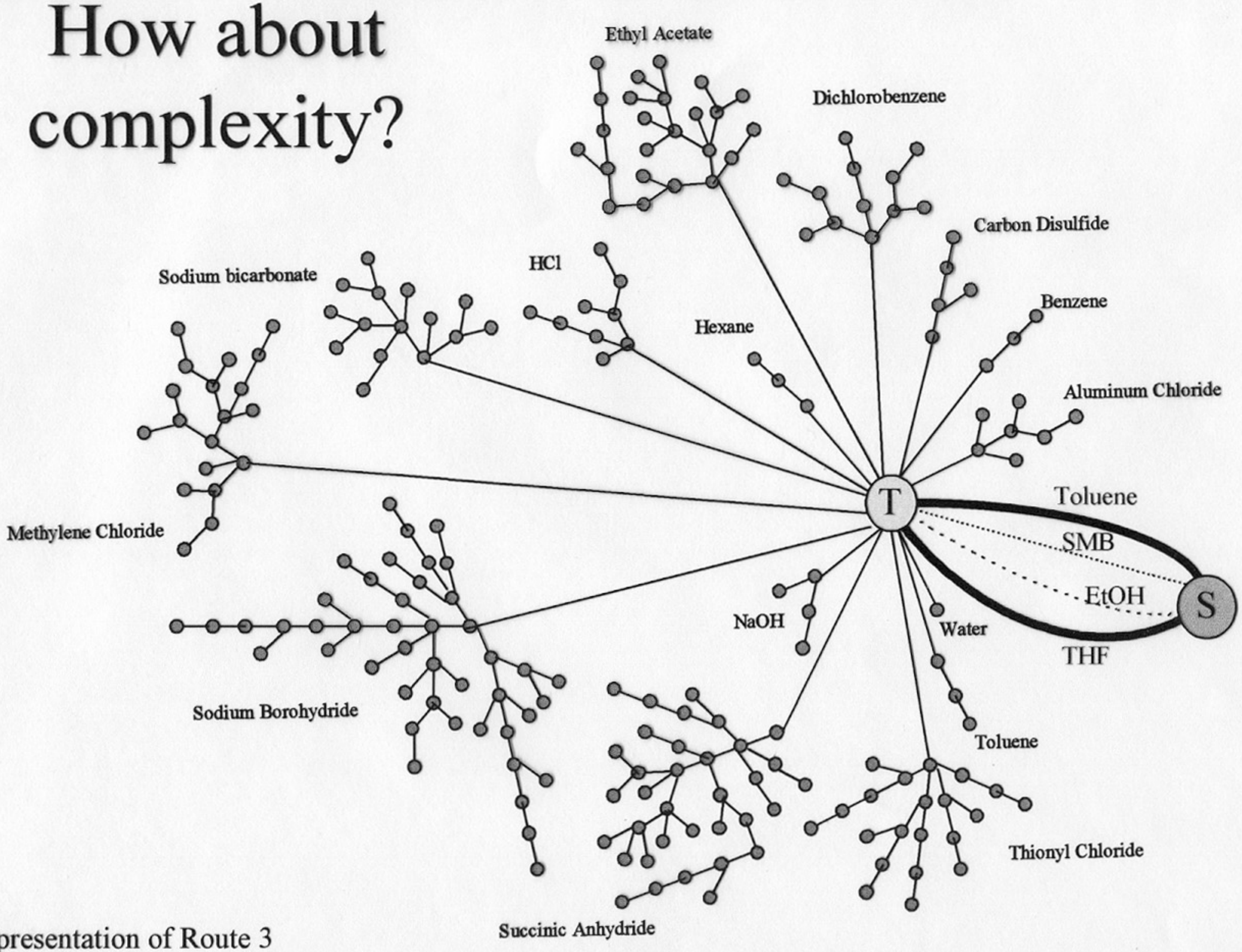
Level 5

Cradle to Gate (Chemical tree):

- Energy emissions (level 3)
- Post-treatment emissions (level 3)
- Total Cradle-to-Gate emissions:

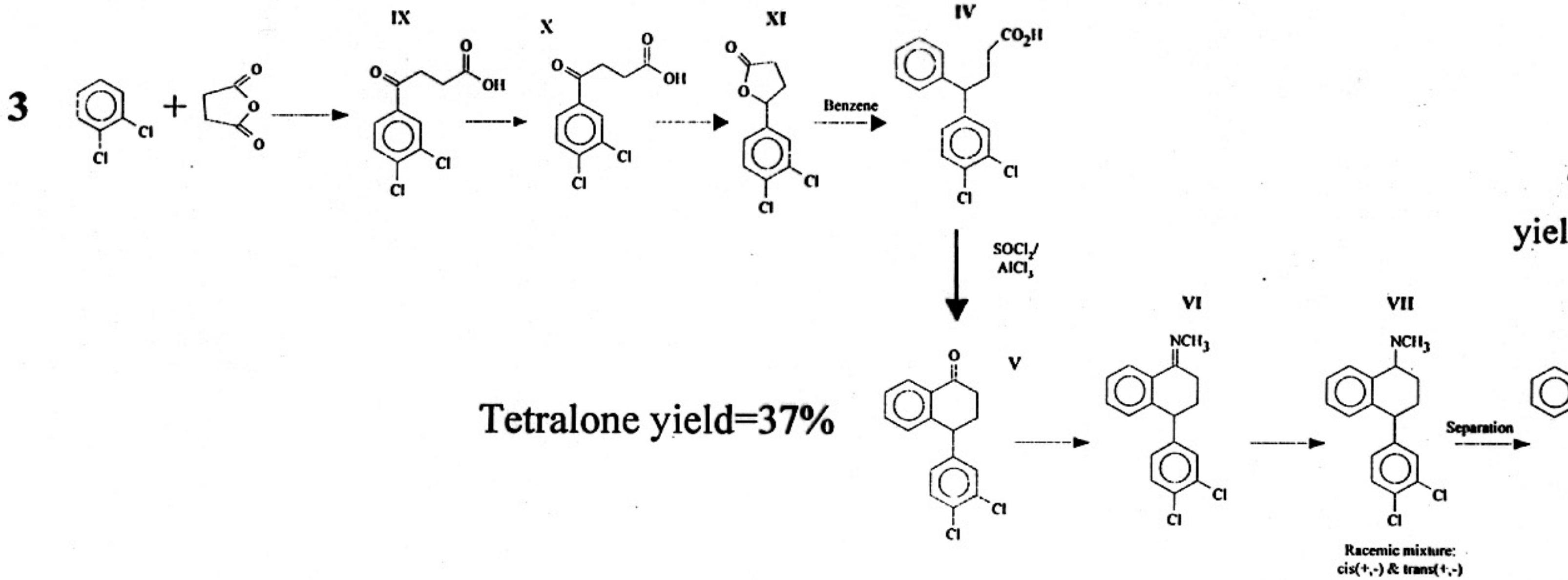
$$= \sum_{\substack{\text{Chemical}\\\text{Tree}}} \text{Post - treatment} + \sum_{\substack{\text{Chemical}\\\text{Tree}}} \text{Energy}$$

How about complexity?



Representation of Route 3

“Carbon frame” efficiency



T-S
yield=33%

Tetralone yield=37%

Total yield=12.2%

Scenario A: 10% improvement in Carbon Efficiency

Within Pfizer (kg/kg sertraline):

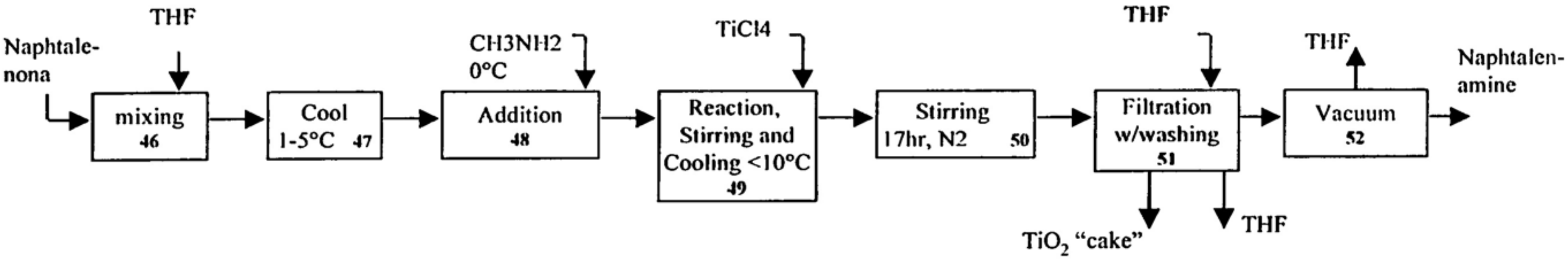
97 → 96 => 1 (most waste is solvent)

Throughout the Pharmaceutical complex (kg/kg sertraline):

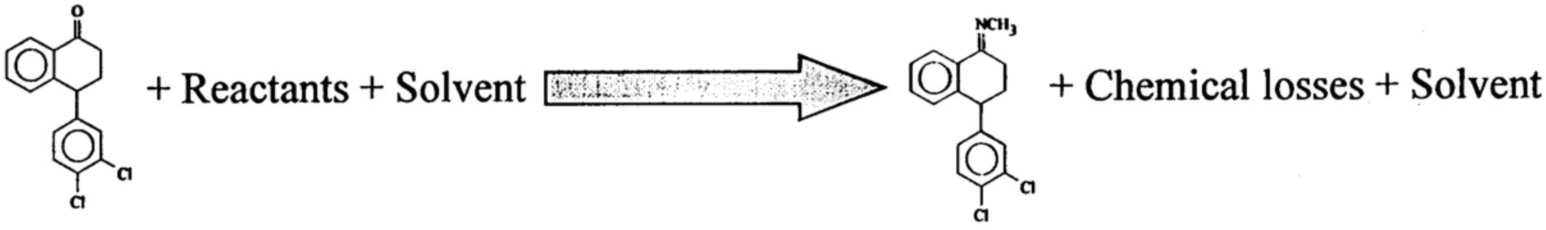
39,098 → 35,794 => 3,304

Over 3,000-fold greater impact!

Solvent usage efficiency



Naphtalenona
THF
mixing 46
Cool 1-5°C 47
CH3NH2 0°C
Addition 48
TiCl4
Reaction, Stirring and Cooling <10°C 49
Stirring 17hr, N2 50
THF
Filtration w/washing 51
TiO_2 "cake"
THF
THF
Vacuum 52
Naphtalen-amine



+ Reactants + Solvent → + Chemical losses + Solvent

Scenario B: 10% improvement in Solvent Usage

Within Pfizer (kg/kg sertraline):

97 → 89 => 8

Throughout the Pharmaceutical complex (kg/kg sertraline):

39,098 → 38,493 => 605

Greatest % effect is within Pfizer, while the greatest amount of reduction is outside Pfizer

In overall, environmental impact Carbon efficiency is better than solvent improvement… for most of the routes.

Semiconductor Effort (in conjunction with ERC-Univ. Az)

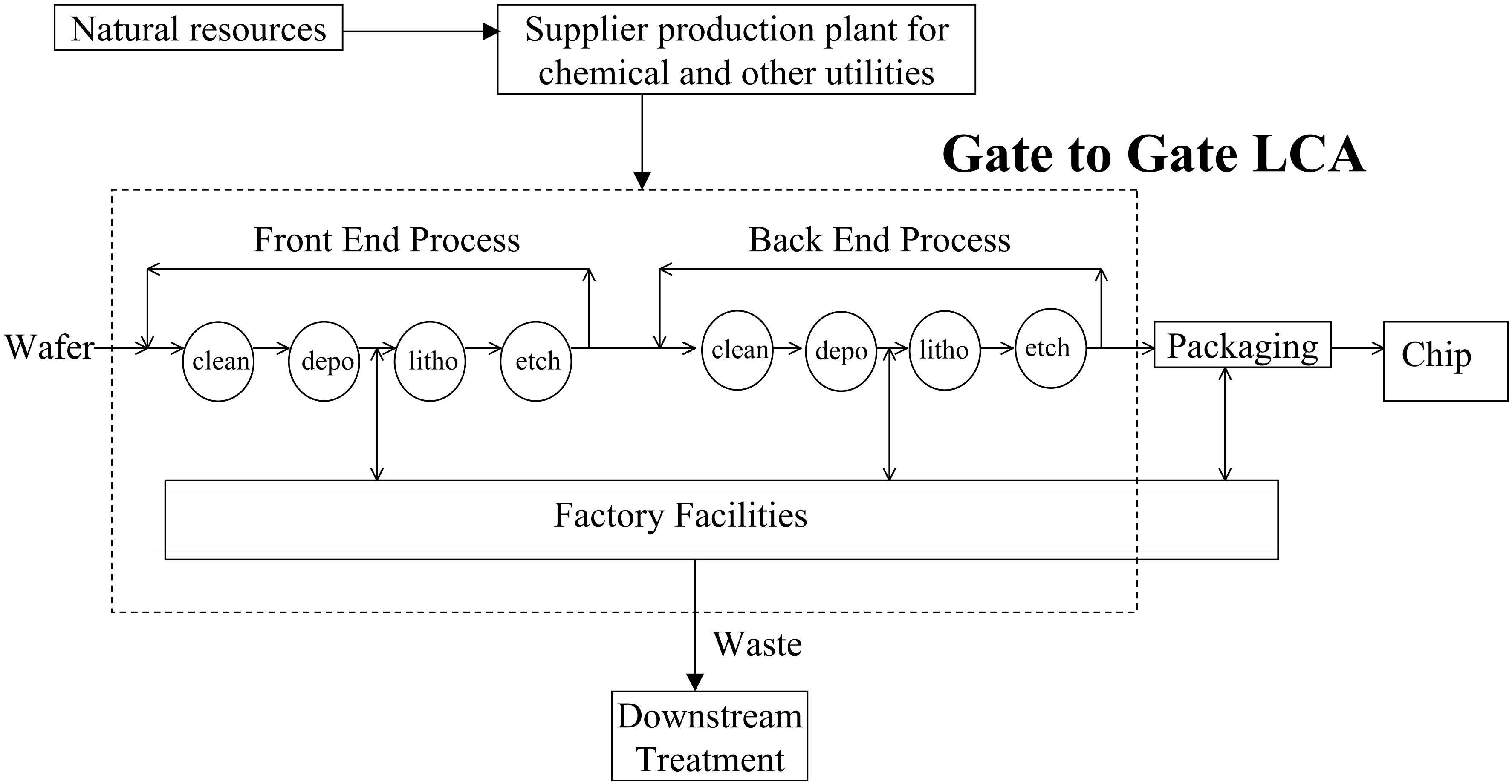
GOALS:

- Research on process steps to create a representative lci of chip manufacturing system
- Research on methods for lci in semiconductor supply chain – design based approach
- Methods that link lci model to significant ERC research and identify life cycle improvements
- Transfer lci tool to user community.

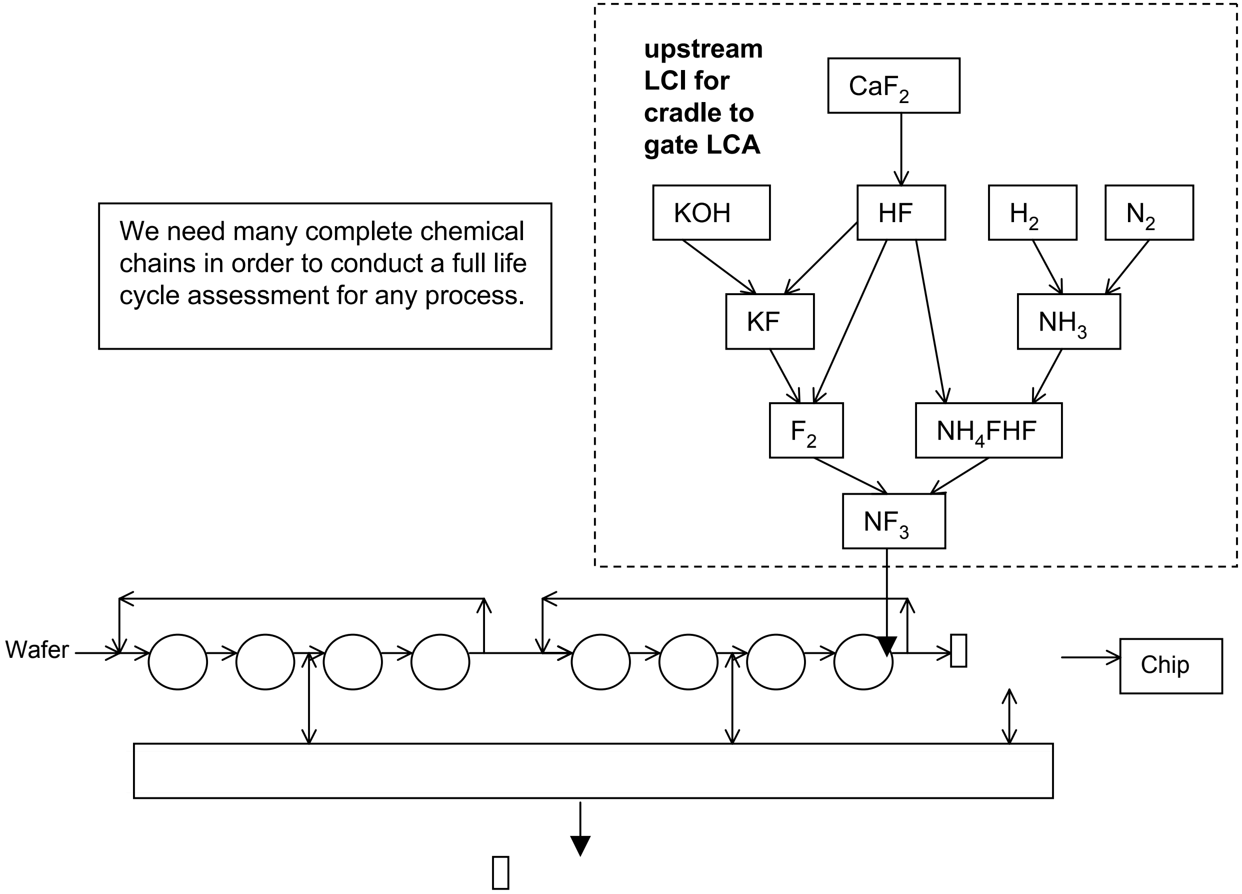
CURRENT WORK

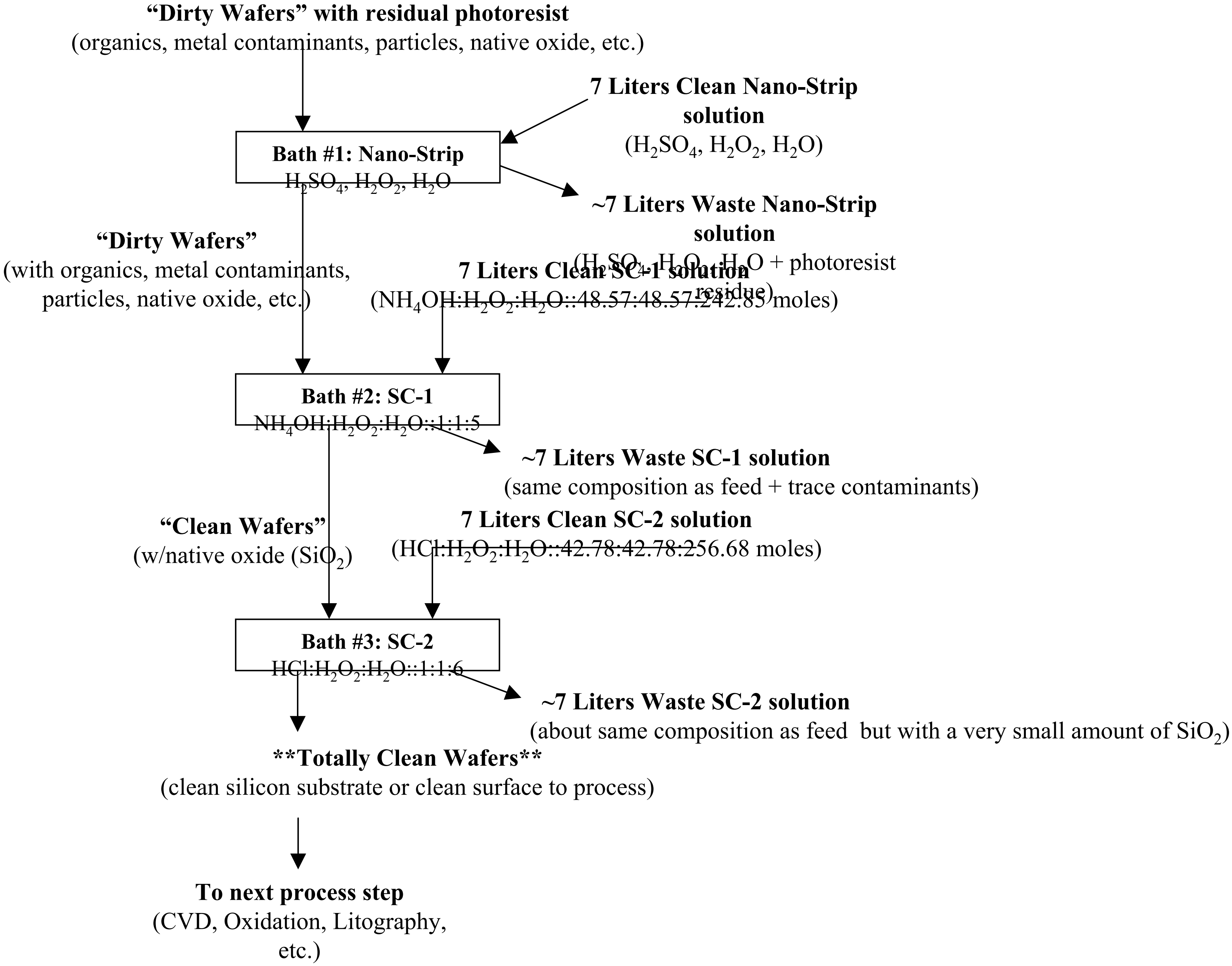
- Conducted trials and completed about 20 semiconductor chemical lci (including arsine, disilane)
- Developed four unit process lci as building blocks in semiconductor manufacturing (synergy with related module at Univ. of Arizona)
- Focus on CMOS product

Life Cycle Assessment View of Semiconductor Fab



We need many complete chemical chains in order to conduct a full life cycle assessment for any process.





"Dirty Wafers" with residual photoresist
(organics, metal contaminants, particles, native oxide, etc.)

7 Liters Clean Nano-Strip solution
(H_2SO_4, H_2O_2, H_2O)

Bath #1: Nano-Strip
H_2SO_4, H_2O_2, H_2O

~7 Liters Waste Nano-Strip solution
(H_2SO_4, H_2O_2, H_2O + photoresist residue)

"Dirty Wafers"
(with organics, metal contaminants, particles, native oxide, etc.)

7 Liters Clean SC-1 solution
($NH_4OH:H_2O_2:H_2O::48.57:48.57:242.85$ moles)

Bath #2: SC-1
$NH_4OH:H_2O_2:H_2O::1:1:5$

~7 Liters Waste SC-1 solution
(same composition as feed + trace contaminants)

"Clean Wafers"
(w/native oxide (SiO_2)

7 Liters Clean SC-2 solution
($HCl:H_2O_2:H_2O::42.78:42.78:256.68$ moles)

Bath #3: SC-2
$HCl:H_2O_2:H_2O::1:1:6$

~7 Liters Waste SC-2 solution
(about same composition as feed but with a very small amount of SiO_2)

****Totally Clean Wafers****
(clean silicon substrate or clean surface to process)

To next process step
(CVD, Oxidation, Litography, etc.)

CONCLUSIONS

1. LCI DATA ARE VITAL TO DEVELOPMENT OF MANUFACTURING IMPROVEMENTS FOR ENVIRONMENTAL QUALITY
2. NEW ISSUES OF SUSTAINABILITY, INDUSTRIAL ECOLOGY, AND CORPORATE POLICY ARE BUILT ON LIFE CYCLE APPROACHES
3. DEVELOPMENTS FOR RAPID, TRANSPARENT LCI ARE BEING MADE
4. A COLLABORATIVE LIFE CYCLE APPROACH FOR SEMICONDUCTOR MANUFACTURING MAY BE OF BENEFIT TO THE ERC.