Solid Rocket Propellant Production

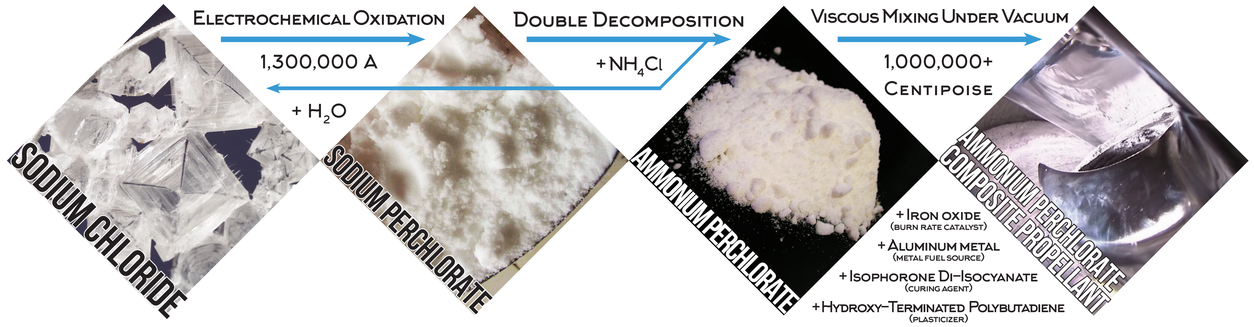
Gunjan Patel – Jobylyn Pineda – Elena Holyakova – Brett Redding

(Project Lead) (Design Lead)

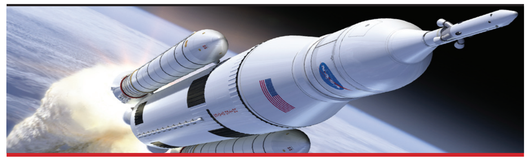
SJSU San José State University

Charles W. Davidson College of Engineering

LOCKHEED MARTIN

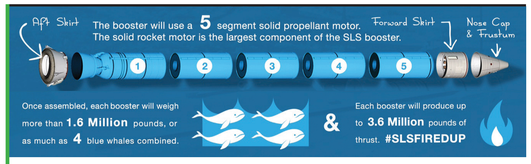


NASA Space Launch System (SLS)



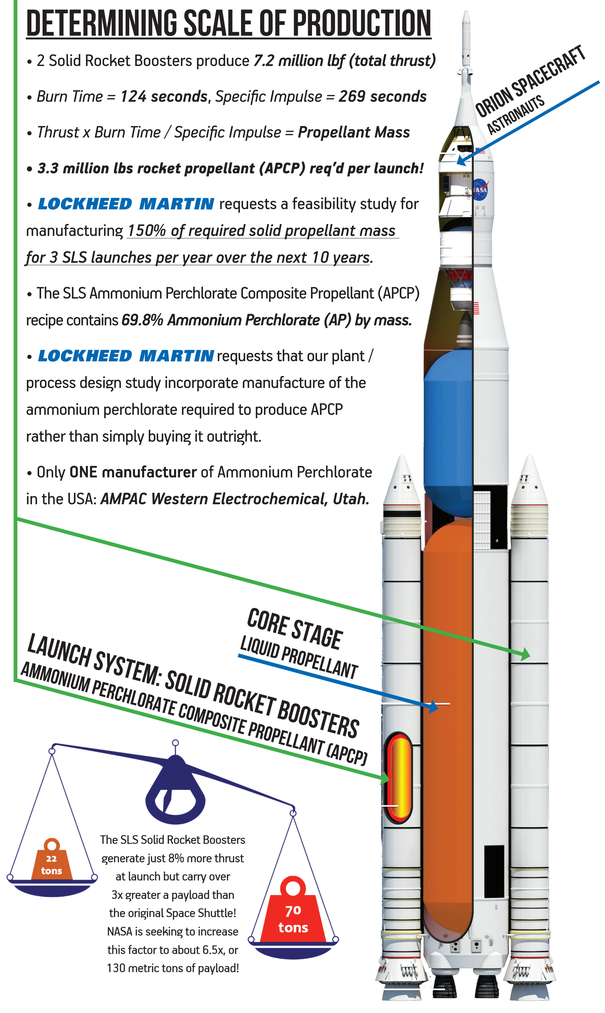
- NASA seeks to carry payloads from 70 up to 130 metric tons. The NASA Space Launch System is the world's most advanced space delivery system.
- It is capable of lifting and transporting payloads and human astronauts much farther into our solar system than any other launch vehicle in history.
- Current goals include landing on asteroids, and a manned mission to Mars.

APCP Solid Rocket Boosters



Determining Scale of Production

- 2 Solid Rocket Boosters produce ***7.2 million lbf (total thrust)***
- *Burn Time =* ***124 seconds****, Specific Impulse =* ***269 seconds***
- *Thrust x Burn Time / Specific Impulse =* ***Propellant Mass***
- ***3.3 million lbs rocket propellant (APCP) req'd per launch!***
- ***LOCKHEED MARTIN*** requests a feasibility study for manufacturing *150% of required solid propellant mass for 3 SLS launches per year over the next 10 years.*
- The SLS Ammonium Perchlorate Composite Propellant (APCP) recipe contains ***69.8% Ammonium Perchlorate (AP) by mass.***
- ***LOCKHEED MARTIN*** requests that our plant / process design study incorporate manufacture of the ammonium perchlorate required to produce APCP rather than simply buying it outright.
- Only **ONE manufacturer** of Ammonium Perchlorate in the USA: ***AMPAC Western Electrochemical, Utah.***



Area 100: Salt & Water Purification

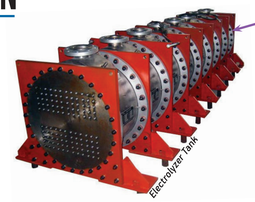
Water & Sodium Chloride sent into the manufacturing process must be as clean as possible in order to produce the desired 99.99% purity for Ammonium Perchlorate required for space grade rocket propellant.

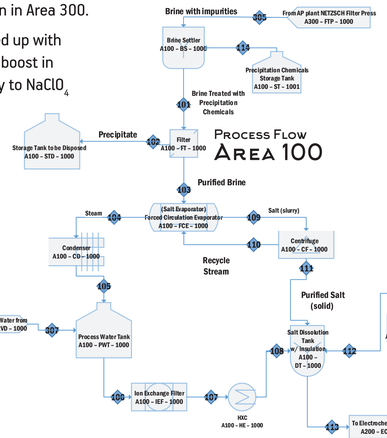
After Sodium Chloride undergoes caustic wash to remove impurities, brine water is filtered and reclaimed via distillation in a salt evaporator. The washed salt is collected, centrifuged, and re-dissolved.

This must occur regardless of whether salt is obtained from a supplier or reclaimed from double decomposition reaction of NH_4Cl and $NaClO_4$ taking place in in Area 300.

Before leaving Area 100, the brine is topped up with 2 g/L of NaF. This provides a much needed boost in current efficiency oxidizing NaCl all the way to $NaClO_4$

Input: ***$NaCl + H_2O$ + Impurities***
Output: ***$NaCl + H_2O$ (clean) + NaF***

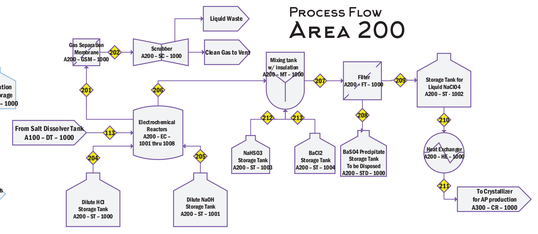




Area 200: Electrochemical Oxidation

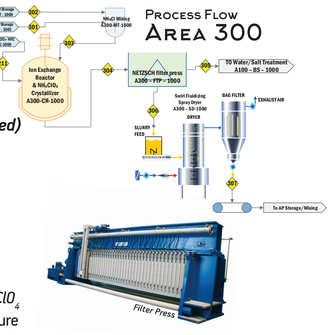
Feed:	***Sodium Chloride (NaCl) + H_2O***
Product:	***Sodium Perchlorate ($NaClO_4$) + Intermediates***
Reactors:	***8 Electrolyzer Tanks, Two Sets of 4 in Parallel***
Electrolysis:	***2 Electrochemical Cells per Reactor***
Anodes:	***Graphite Lead Dioxide, 36 per E.C. Cell, 7.84 sq. ft each***
Cathodes:	***Stainless Steel, 12 per E.C. Cell, 7.84 sq. ft each***
Current:	***1,300,000 Amps, 288 A / ft² current density***
Time:	***24-hr Batch Electrolysis Run Time per Reactor***
	3-hr charge / discharge offset per reactor
Batch Vol:	***1278 gallons (water + feed + product)***
Reactant In:	***1880 lb NaCl (aq) + 278 gal H_2O (l)***
Product Out:	***3940 lb $NaClO_4$ (s) + 260 lb H_2 (g)***
Gas Effluent:	***$H_2O + H_2$ + Trace Cl_2***

When operating at high currents, using multiple reactors in parallel with longer 24-hour runs maximizes current efficiency. This also doubles as a robust system redundancy in case there is a problem with any given reactor.



Area 300: Crystallization

Feed:	***Sodium Perchlorate ($NaClO_4$)***
	6M Ammonia** (NH_3)
	6M Hydrochloric Acid** (HCl)
Product:	***Ammonium Perchlorate (NH_4ClO_4)***
	Sodium Chloride (NaCl)
Reactors:	***2 Crystallization Reactors (Jacketed)***
Separation:	***Filter Press***
Drying:	***Fluidizing Spray Dryer***
Reactant In:	***~3750 lb $NaClO_4$ + 1640 lb NH_4Cl***
Product Out:	***~3600 lb NH_4ClO_4 + 1790 lb NaCl***
Req'd PSD:	***~50 - 400 µm diameter***
	class 1.3 explosive



***Mixture of NH_3 + HCl prior to combining with $NaClO_4$ generates heat.** Once combined, our reaction mixture gets close to the ideal start temperature of 80 - 82°C.

Our process requires tight cooling and mixing control. Reactor hydrodynamics and rate of temperature drop are absolutely crucial to selectively crystallizing NH_4ClO_4.

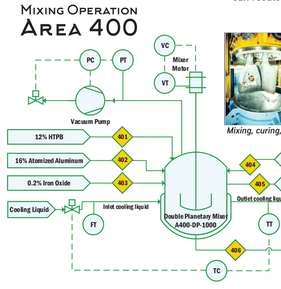
The required rate of cooling increases as reaction temperature drops. Also, the cooling occurs in two stages, with two different cooling fluids;
80 - 40°C : (cooling water only)
40 - 10°C : (ethylene glycol + water)

The filter press cake is washed with water to displace residual brine. Excessive presence of sodium chloride (>100ppm) in Area 400's mixing operation can make a batch of solid rocket fuel unfit for a NASA SLS Launch

Area 400: Propellant Mixing & Compositing

Feed:	69.8% *Ammonium Perchlorate ($NaClO_4$)*
	16.0% Atomized Aluminum (Al)
	12.0% Hydroxyl-Terminated Polybutadiene (HTPB)
	2.0% Isophorone Di-Isocyanate (IPDI)
	0.2% Iron Oxide (Fe_2O_3)
Product:	*Ammonium Perchlorate Composite Propellant (APCP)*
Output:	*600 Gal APCP / batch*
Reactors:	*4 Double Planetary Polymerization Mixers (vacuum)*
Pressure:	*0 - 2 psia*
Viscosity:	*1,000,000+ cP**

**Note: Viscous Mixing generates a LOT of heat! Cooling control is EXTREMELY important to safety of the process. Also, mixing is done under vacuum because bubbles/voids inside the propellant can result in inconsistent burn patterns and even a faulty launch.*





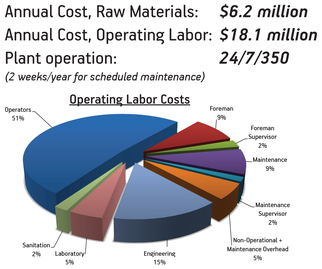
Mixing, curing, and solid casting for solid rocket motors.

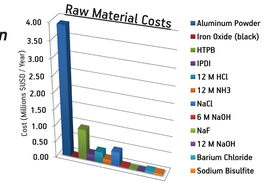


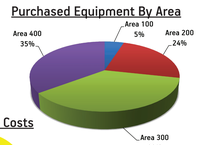
Double Planetary Mixer

Economics / Cost Analyses / Profitability

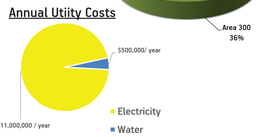
Annual Cost, Raw Materials:	*$6.2 million*
Annual Cost, Operating Labor:	*$18.1 million*
Plant operation:	*24/7/350*
	(2 weeks/year for scheduled maintenance)

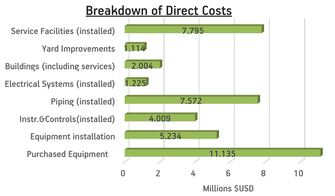


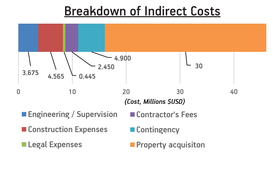




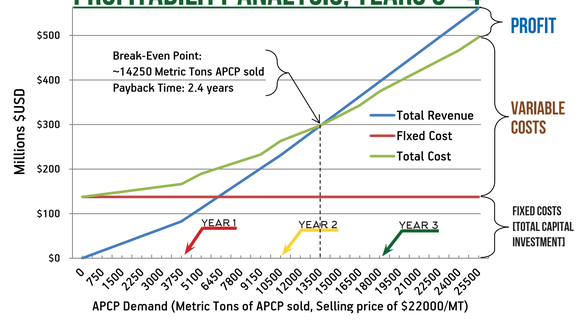
Direct Costs:	*$ 40 million*
Indirect Costs:	*$ 46 million*
Working Capital Cost:	*$ 10 million*
Land Acquisition:	*$ 30 million*
Start-Up Costs:	*$ 9 million*
Total Initial Investment:	***$135 million***
(@ Time = Year Zero)	







Profitability Analysis, Years 0 - 4



Preliminary Scope of Potential for Investment

Total Initial Investment:		***$ 135 million***
[@ Time = Year Zero, incl. startup cost]		
Total Profit:	[After 3 Years]	***$ 22 million***
[@ 35% Tax Rate]	[After 5 Years]	***$ 151 million***
	[Plant Lifetime]	***$ 350 million***

Note: Project financials were calculated from mostly conservative estimates.

Costs were generally overestimated and revenues underestimated as a precaution.

This project has ample room for process optimization and profitability improvement!

References

1) Mr. Živko Andrić. "Crystallization of Ammonium-Perchlorate from Solution of Electrolytically Produced Sodium-Perchlorate in a Pilot-Scale Plant." Chemical Process and Product R&D Department, 81 000 Podgorica, Montenegro. 19 December 2007.

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7) Wiheeb, Ahmed. et al. "The Manufacture of Perchlorate by Direct Method Using Graphite Substrate Lead Dioxide (GSLD) Anode" Chem. Eng. Dept, University of Tikrit, Iraq. Received 16 March 1971.

Acknowledgements

Dr. Michael Jennings
(Professor, Benevolent Dictator, People's Republic of Jenningston)

Dr. Gregory Young
(BCME Department Chair, Champion Table Flipper, Blank Stare Hall-of-Fame)

Felino Berdan
(Industry Advisor, Grandmaster of Non-Disclosure, Lockheed Martin)

Mr Živko Andrić
(Montenegro's 2013 Scientist of the Year, Electrochemistry Expert, POLIEX Corporation)

STREAM #	101	102	103	104	105	106	107
Description	process reclaiimed brine solution	removal of impurities(s)	Brine solution from filter	steam from salt evaporator	reclaimed water from condensor	Process water from storage tank	Process water from ion exchange filter
Temperature (oF)	55		55	250	60	50	50
Pressure	14.7		14.7	15.1	14.7	17.7	17.7
H2O	4029.6		3995.6	2000	2000	2303.7	2303.7
NaF	0		0	0	0	0	0
NaCl	584.3		584.3	0	0	0	0
NaOH	8.15		0	0	0	0	0
NH4Cl	10.9		0	0	0	0	0
NH4OH	0		0	0	0	0	0
Total Mass Flow	4633.0		4579.9	2000	2000	2303.7	2303.7
Total Volumetric Flow (GPM/CFM)	9.3		9.1	2.4	4.0	4.6	4.6
STREAM #	**108**	**109**	**110**	**111**	**112**	**113**	**114**
Description	process water from heat exchanger	Brine into Centrifuge	water reclaimed from centrifuge	NaCl(s) to be added to Brine mixing tank (variable, unresolved)	NaF feed (s) (variable, unresolved)	Brine solution to Electolytic cell	6M NaOH feed to Brine Settler
Temperature (oF)	~113	250	110			~113	~55
Pressure	17.7	14.7	14.7			14.7	14.7
H2O	2303.7	1995.6	400			2303.7	34
NaF	0	0	0			4.6	0
NaCl	0	584.3	0			627.7	0
NaOH	0	0	0			0	8.15
NH4Cl	0	0	0			0	0
NH4ClO4-	0	0	0			0	0
Total Mass Flow	2303.7	2579.9	400			2936.0	42.2
Total Volumetric Flow	4.6	5.2	0.8			5.9	0.1
STREAM #	**113**	**201**	**202**	**203**	**204**	**205**	**206**
Description	Purified Sodium Chloride Solution FEED from AREA 100	GAS evolved from ELECTROCHEMICAL CELL	H2 GAS and Trace Cl2 gas	*Null (Removed)*	Electrochemical Cell pH Control 1, Dilute HCl	Electrochemical Cell pH Control 2, Dilute NaOH	Electrochemical Oxidation Product Solution TO MIXING TANK
Temperature (oF)	~113	~113	~113		~68	~68	~113
Pressure (psia)	14.7	14.7	14.7		14.7	14.7	14.7
H2 (lb/hr)	0	81.62	81.62		0	0	0
H2O (lb/hr)	2303.7	54.36	0		0	0	1569.11
NaCl (lb/hr)	627.65	0	0		0	0	0
NaClO3- (lb/hr)							6.1
NaClO4- (lb/hr)	0	0	0		0	0	1248.85
Cl_2 (lb/hr)	0	0.24	0.24		0	0	0
HCl (lb/hr)	0	0	0		As needed	0	0
NaOH (lb/hr)	0	0	0		0	As needed	0
Total Mass Flow (lb/hr)	**2931.4**	**136.2**	**81.9**		**0.0**	**0.0**	**2824.1**
Total Volumetric Flow (GPM), (CFM for gas)	5.85	405.43	243.63		0.00	0.00	5.64
STREAM #	**207**	**208**	**209**	**210**	**211**	**212**	**213**
Description	Sodium Perchlorate Slurry FEED TO FILTRATION	Precipitated Solids Disposal	Aqueous NaClO4 Solution TO STORAGE TANK	Aqueous NaClO4 Solution TO HEAT EXCHANGER	HEATED NaClO4 Solution TO AREA 300	Sodium Bisulfite Precipitation Chemical TO MIXING TANK	Barium Chloride Precipitation Chemical TO MIXING TANK
Temperature (oF)	~110	~100	~100	~68	179.6	~68	~68
Pressure	14.7	14.7	14.7	14.7	14.7	14.7	14.7
H2 (lb/hr)	0	0	0	0		0	0
H2O (lb/hr)	1677.11	108	1569.11	1569.11	1569.11	36	72
NaCl (lb/hr)	10.06	0	10.06	10.06	10.06	0	0
NaClO4- (lb/hr)	1248.85	0	1248.9	1248.9	1248.9	0	0
NaClO3- (lb/hr)	0	0	0	0	0	0	0
NH4Cl (lb/hr)	0	0	0	0	0	0	0
NH4ClO4- (lb/hr)	0	0	0	0	0	0	0
NaHSO3 (lb/hr)	0	0	0	0	0	17.92	0
BaCl2 (lb/hr)	0	0	0	0	0	0	35.86
BaSO4 (lb/hr)	40.19	40.19	0	0	0	0	0
Total Mass Flow (lb/hr)	2976.21	148.19	2828.07	2828.07	2828.07	53.92	107.86
Total Volumetric Flow (GPM), (CFM for gas)	5.94	0.30	5.65	5.65	5.65	0.11	0.22

STREAM #	211	301	302	303	304	305	306	307
Description	Sodium Perchlorate Feed from AREA 200	12M Ammonia Feed	12M Hydrochloric Acid Feed	Ammonium Chloride Feed to ION EXCHANGE & CRYSTALLIZATION	Ammonium Perchlorate Slurry FEED TO FILTER PRESS	NaCl Brine Filter Press PERMEATE TO AREA 100	Ammonium Perchlorate Wet Solids FEED TO SPRAY DRYER	Ammonium Perchlorate Dry Crystals TO AREA 400 / STORAGE / MIXING
Temperature (oF)	176-180	71	71	275	50	55	50	60
Pressure (psia)	14.7	14.7	14.7	14.7	14.7	14.7	14.7	14.7
H2O (lb/hr)	1569.11	1254.0	1254.0	2508.0	4077.1	3995.6	81.5	0.0
NaCl (lb/hr)	10.06	0.0	0.0	0.0	596.3	584.3	11.9	0.0
NaClO4- (lb/hr)	1248.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0
NH4Cl (lb/hr)	0	0.0	0.0	546.2	10.9	10.9	0.0	0.0
NH4ClO4- (lb/hr)	0	0.0	0.0	0.0	1198.8	0.0	1198.8	1198.8
HCl (lb/hr)	0	0.0	372.4	0.0	0.0	0.0	0.0	0.0
NH3 (lb/hr)	0	173.8	0.0	0.0	0.0	0.0	0.0	0.0
Total Mass Flow (lb/hr)	**2828.07**	**1427.8**	**1626.4**	**3054.2**	**5883.0**	**4590.8**	**1292.2**	**1198.8**
Total Volumetric Flow (GPM)	5.65	2.85	3.25	6.10	11.75	9.17	1.03	0.96

Gunjan Patel
Elena Holyakova
Brett Redding
Jobylyn Pineda

Lockheed Martin ChE165 Plant Design Team

MASS & ENERGY BALANCE

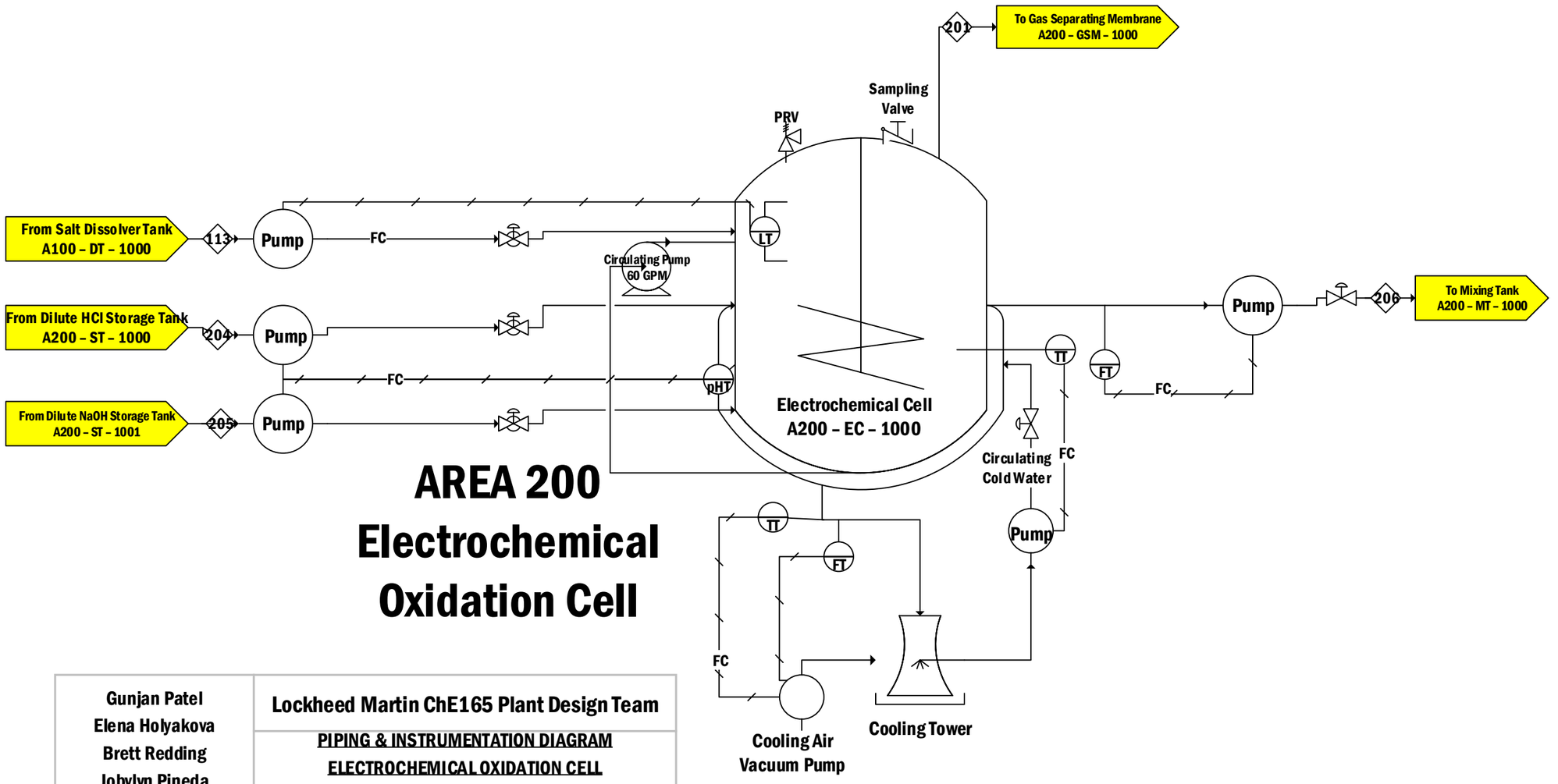
SOLID ROCKET PROPELLANT PRODUCTION

REV F

03/30/2015

ATTN: Felino Berdan
Michael Jennings

ENTIRE PLANT

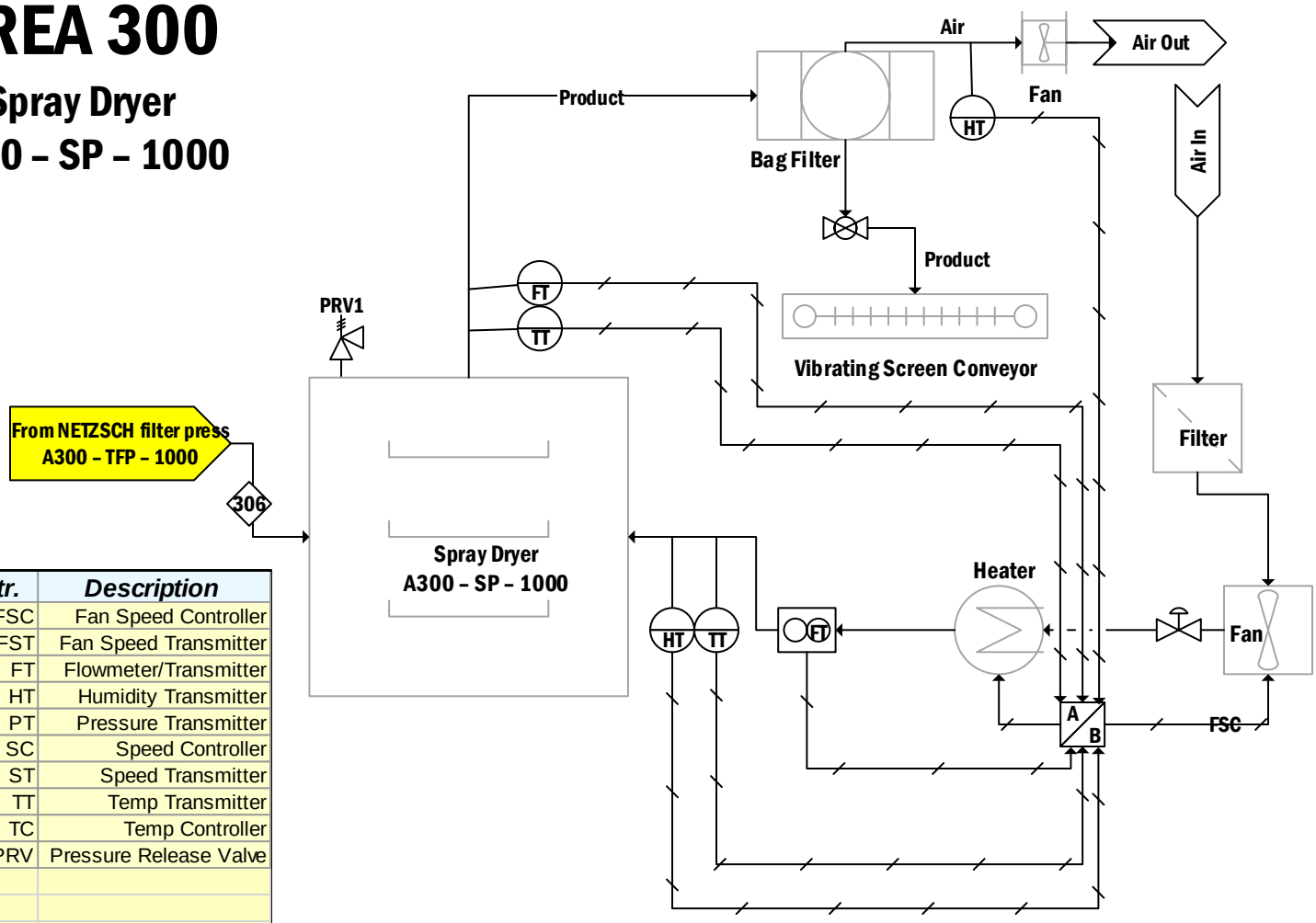


AREA 200
Electrochemical Oxidation Cell

Gunjan Patel Elena Holyakova Brett Redding Jobylyn Pineda	Lockheed Martin ChE165 Plant Design Team		
	PIPING & INSTRUMENTATION DIAGRAM ELECTROCHEMICAL OXIDATION CELL MANUFACTURE OF SOLID ROCKET PROPELLANT		
REV C	03/16/2015	ATTN: Felino Berdan Michael Jennings	
AREA 200			

AREA 300

Spray Dryer
A300 – SP – 1000



Instr.	Description
FSC	Fan Speed Controller
FST	Fan Speed Transmitter
FT	Flowmeter/Transmitter
HT	Humidity Transmitter
PT	Pressure Transmitter
SC	Speed Controller
ST	Speed Transmitter
TT	Temp Transmitter
TC	Temp Controller
PRV	Pressure Release Valve