LBNF Target Hall
Hydrogen Control System
Preliminary Design Review

Abhishek Deshpande

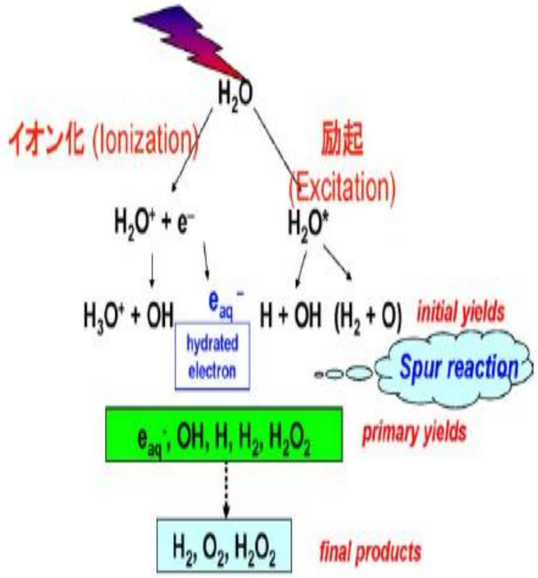
February 19 & 20, 2020

Overview

- Motivation
- NuMI operations background
- Requirements
- Conceptual design of the system
- On-going research, experimental measurements, and design work
- Future work
- Questions and discussion

Motivation

- Water in close proximity to the beam in components such as the horns, disassociates to hydrogen and oxygen (H+O).
- The Lower Explosive Limit (LEL) of H2 in air is ~4%. This is the lowest concentration at which H can become flammable in the presence of an ignition source.
- Need to dilute the H2 in the systems to keep it below 4%.
- Argon (Ar) gas may be pumped into the beam components to reduce the H2 percentage.
- However, argon gas becomes radioactive, Ar41, which cannot be vented readily into the Target Hall air.
- Other inert gases such as Helium are expensive and have other limitations.
- Thus, a system is required to:
  - Control the H2 percentage in all the RAW systems.
  - Prevent the out-flow of Ar41 to Target Hall air.



G-value; number of molecules formed per 100 eV radiation energy absorbed

図2　水の放射線分解スキーム

Y. Katsumura, Radiation Chemistry, No.81, 2-7 (2006)

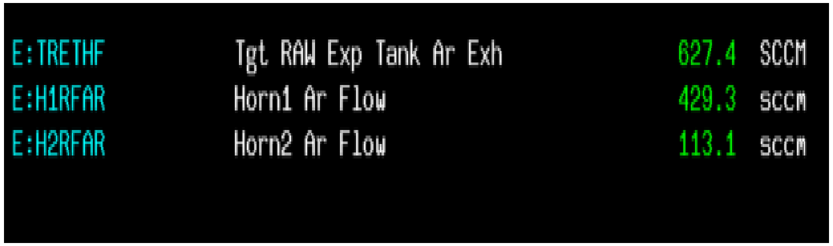
NuMI Operations Background

- In NuMI, fresh Argon is pumped into the head spaces of the Horn 1, Horn 2, and TGT RAW systems and is vented into the Target Hall atmosphere. This is done to dilute produced H2.
- Fresh Ar is also pumped into Horn 1 and Horn 2 water spray nozzles.
- The amount of Ar is determined by theoretical estimations on H2 production in above systems at different beam powers.

Current requirement at 700 kW

	(I)	(II)	(III)
	Hydrogen Gas Produced (gal/day)	Required Argon Purge (sccm) Measured by Mass Flow Meter	Required Argon Purge (cfh) Equivalent to Column II.
NOvA ME Target	4.75	625	1.32
Horn 1	3.3	435	0.92
Horn 2	0.65	85	0.21

Current operations (measured) at ~700 kW



```
E:TRETHF        Tgt RAW Exp Tank Ar Exh     627.4  SCCM
E:H1RFAR        Horn1 Ar Flow               429.3  sccm
E:H2RFAR        Horn2 Ar Flow               113.1  sccm
```

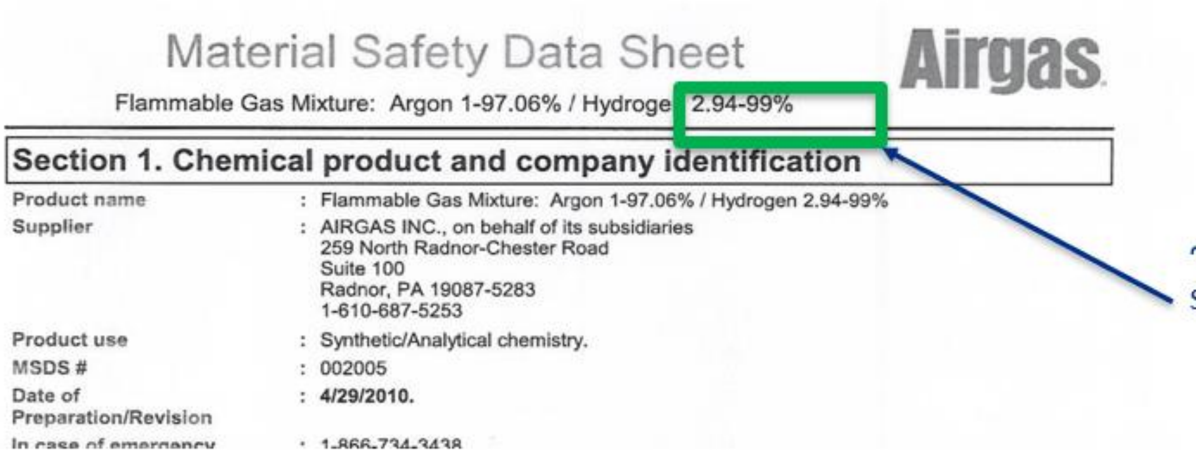
System Requirements

- Maintain H2 levels in the RAW system expansion tanks below << 4%.

- If Argon is selected as the purge gas, allow Argon-41 that is produced sufficient time to decay before venting the gas to Target Hall atmosphere or other atmospheres.

Conceptual Design of the System: LEL

- Is the LEL really 4% in Argon atmosphere? It is a little lower:



Material Safety Data Sheet

Airgas

Flammable Gas Mixture: Argon 1-97.06% / Hydroge 2.94-99%

Section 1. Chemical product and company identification

Product name	: Flammable Gas Mixture: Argon 1-97.06% / Hydrogen 2.94-99%
Supplier	: AIRGAS INC., on behalf of its subsidiaries 259 North Radnor-Chester Road Suite 100 Radnor, PA 19087-5283 1-610-687-5253
Product use	: Synthetic/Analytical chemistry.
MSDS #	: 002005
Date of Preparation/Revision	: **4/29/2010.**
In case of emergency	: 1-866-734-3438

~2.94%

Source: Airgas MSDS

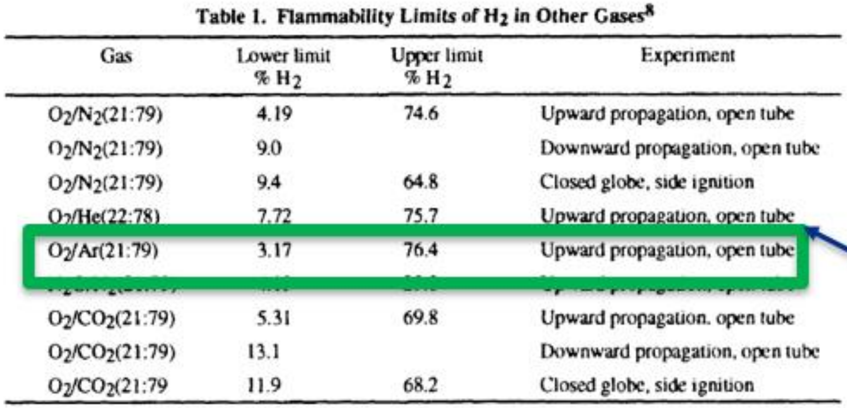


Table 1. Flammability Limits of H_2 in Other Gases[8]

Gas	Lower limit % H_2	Upper limit % H_2	Experiment
O_2/N_2(21:79)	4.19	74.6	Upward propagation, open tube
O_2/N_2(21:79)	9.0		Downward propagation, open tube
O_2/N_2(21:79)	9.4	64.8	Closed globe, side ignition
O_2/He(22:78)	7.72	75.7	Upward propagation, open tube
O_2/Ar(21:79)	3.17	76.4	Upward propagation, open tube
[illegible]	[illegible]	[illegible]	[illegible]
O_2/CO_2(21:79)	5.31	69.8	Upward propagation, open tube
O_2/CO_2(21:79)	13.1		Downward propagation, open tube
O_2/CO_2(21:79	11.9	68.2	Closed globe, side ignition

~3.17%

Source: Coward and Jones (1952), Bureau of Mines Bulletin 503

Conceptual Design of the System: LEL

- What is the effect of pressure on LEL; we have conflicting evidence in literature:

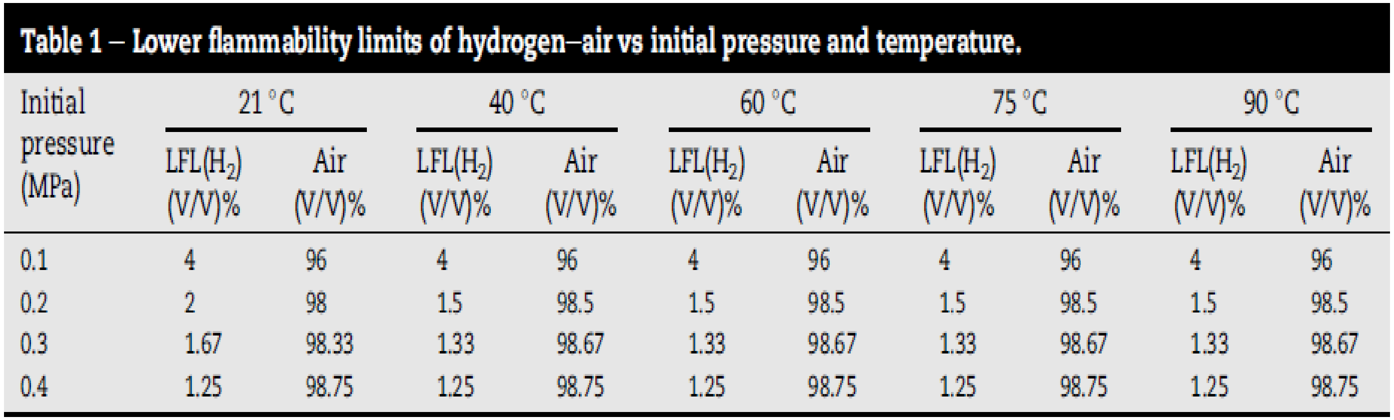
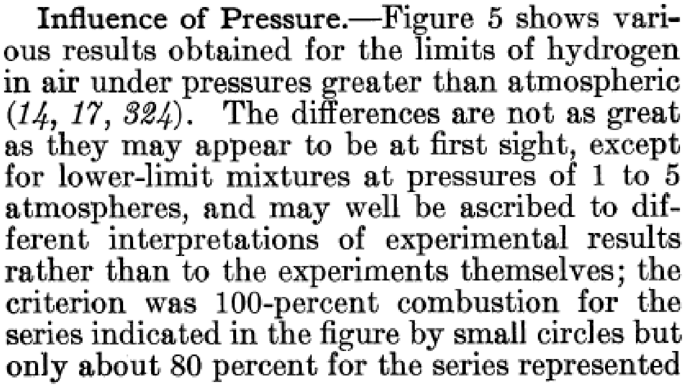


Table 1 – Lower flammability limits of hydrogen–air vs initial pressure and temperature.

Initial pressure (MPa)	21 °C		40 °C		60 °C		75 °C		90 °C	
	LFL(H_2) (V/V)%	Air (V/V)%	LFL(H_2) (V/V)%	Air (V/V)%	LFL(H_2) (V/V)%	Air (V/V)%	LFL(H_2) (V/V)%	Air (V/V)%	LFL(H_2) (V/V)%	Air (V/V)%
0.1	4	96	4	96	4	96	4	96	4	96
0.2	2	98	1.5	98.5	1.5	98.5	1.5	98.5	1.5	98.5
0.3	1.67	98.33	1.33	98.67	1.33	98.67	1.33	98.67	1.33	98.67
0.4	1.25	98.75	1.25	98.75	1.25	98.75	1.25	98.75	1.25	98.75

This says as pressure increases, LEL decreases

Source: Liu and Zhang (2014), International Journal of Hydrogen Energy



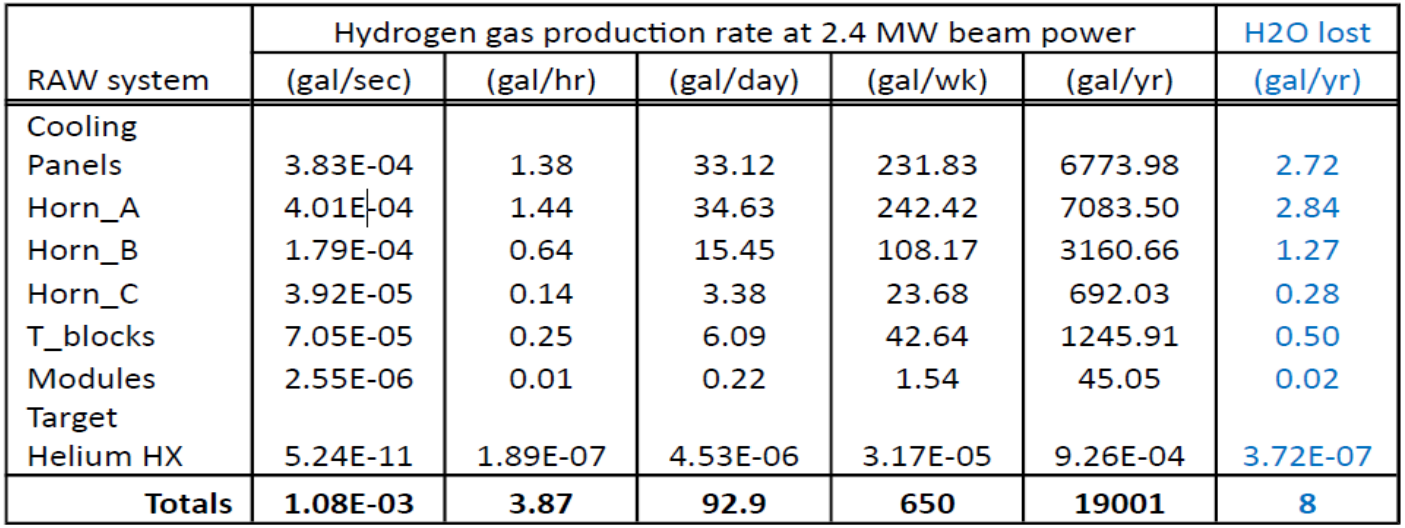
Influence of Pressure.—Figure 5 shows various results obtained for the limits of hydrogen in air under pressures greater than atmospheric (*14*, *17*, *324*). The differences are not as great as they may appear to be at first sight, except for lower-limit mixtures at pressures of 1 to 5 atmospheres, and may well be ascribed to different interpretations of experimental results rather than to the experiments themselves; the criterion was 100-percent combustion for the series indicated in the figure by small circles but only about 80 percent for the series represented

This says between 1-5 atms, the LEL is no affected. This is confirmed by other studies, however, the above study, Liu and Zhang (2014), has not been repeated

Source: Coward and Jones (1952), Bureau of Mines Bulletin 503

Conceptual Design of the System: Hydrogen production

- H2 production in RAW systems for LBNF 2.4 MW operations:



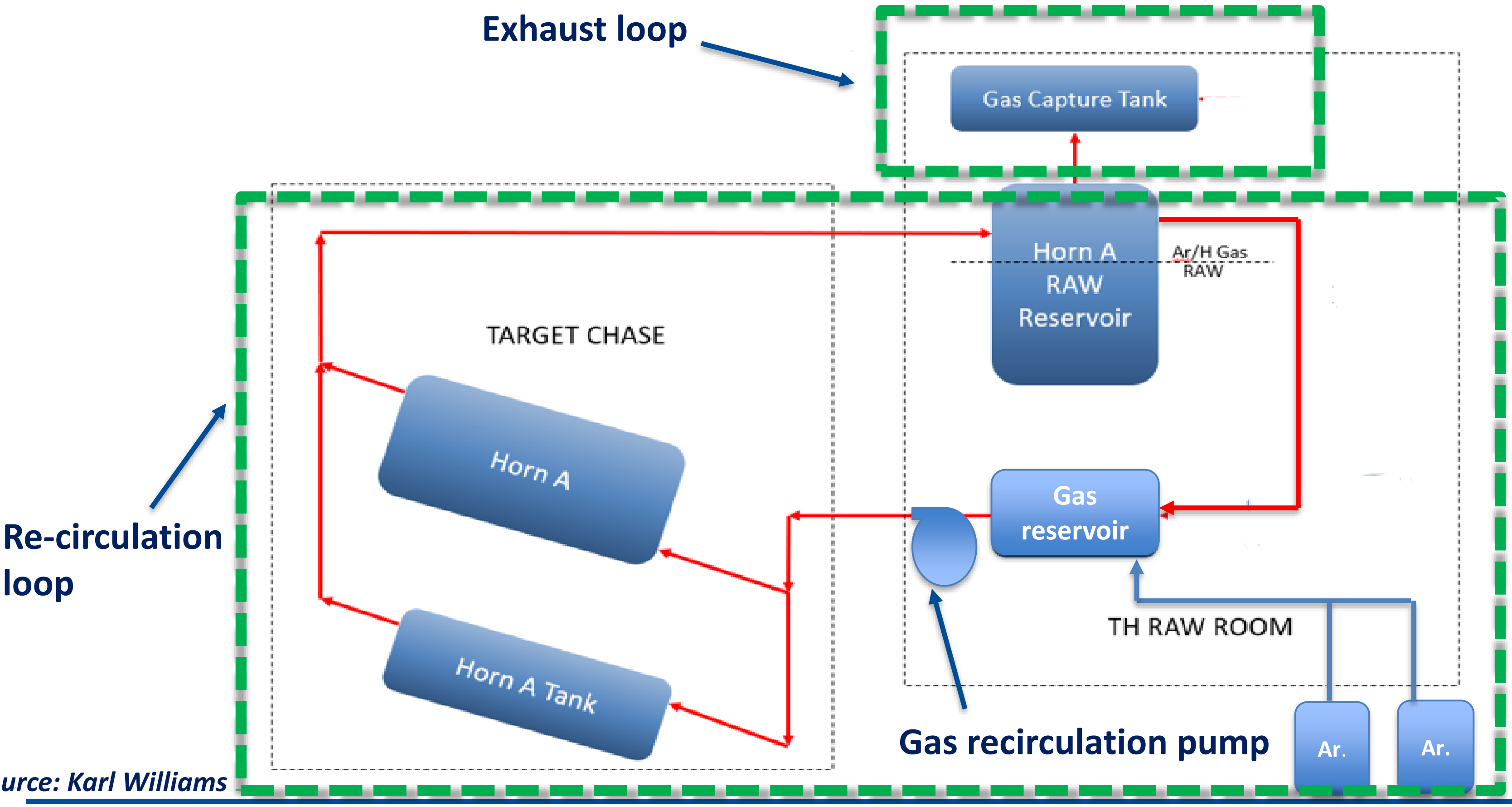
RAW system	Hydrogen gas production rate at 2.4 MW beam power					H2O lost
	(gal/sec)	(gal/hr)	(gal/day)	(gal/wk)	(gal/yr)	(gal/yr)
Cooling Panels	3.83E-04	1.38	33.12	231.83	6773.98	2.72
Horn_A	4.01E-04	1.44	34.63	242.42	7083.50	2.84
Horn_B	1.79E-04	0.64	15.45	108.17	3160.66	1.27
Horn_C	3.92E-05	0.14	3.38	23.68	692.03	0.28
T_blocks	7.05E-05	0.25	6.09	42.64	1245.91	0.50
Modules	2.55E-06	0.01	0.22	1.54	45.05	0.02
Target Helium HX	5.24E-11	1.89E-07	4.53E-06	3.17E-05	9.26E-04	3.72E-07
Totals	**1.08E-03**	**3.87**	**92.9**	**650**	**19001**	**8**

Source: Kamran Vaziri

System	H2 prod, Gal/Hr.	H2 prod, cc/min.	Flush rate, cc/min[1]
Target Shield Pile RAW	**1.38**	**87.06**	**4353**
Horn A RAW	**1.44**	**90.85**	**4542**
Horn B RAW	**0.64**	**40.38**	**2019**
Horn C RAW	**0.14**	**8.83**	**442**
Total flush rate from RAW systems-->[2]			**11356**
Notes:			
1). Flush rate to keep H2 below 2%.			
2). Total flush rate if no re-combination is used.			

Conceptual Design of the System: Hydrogen control

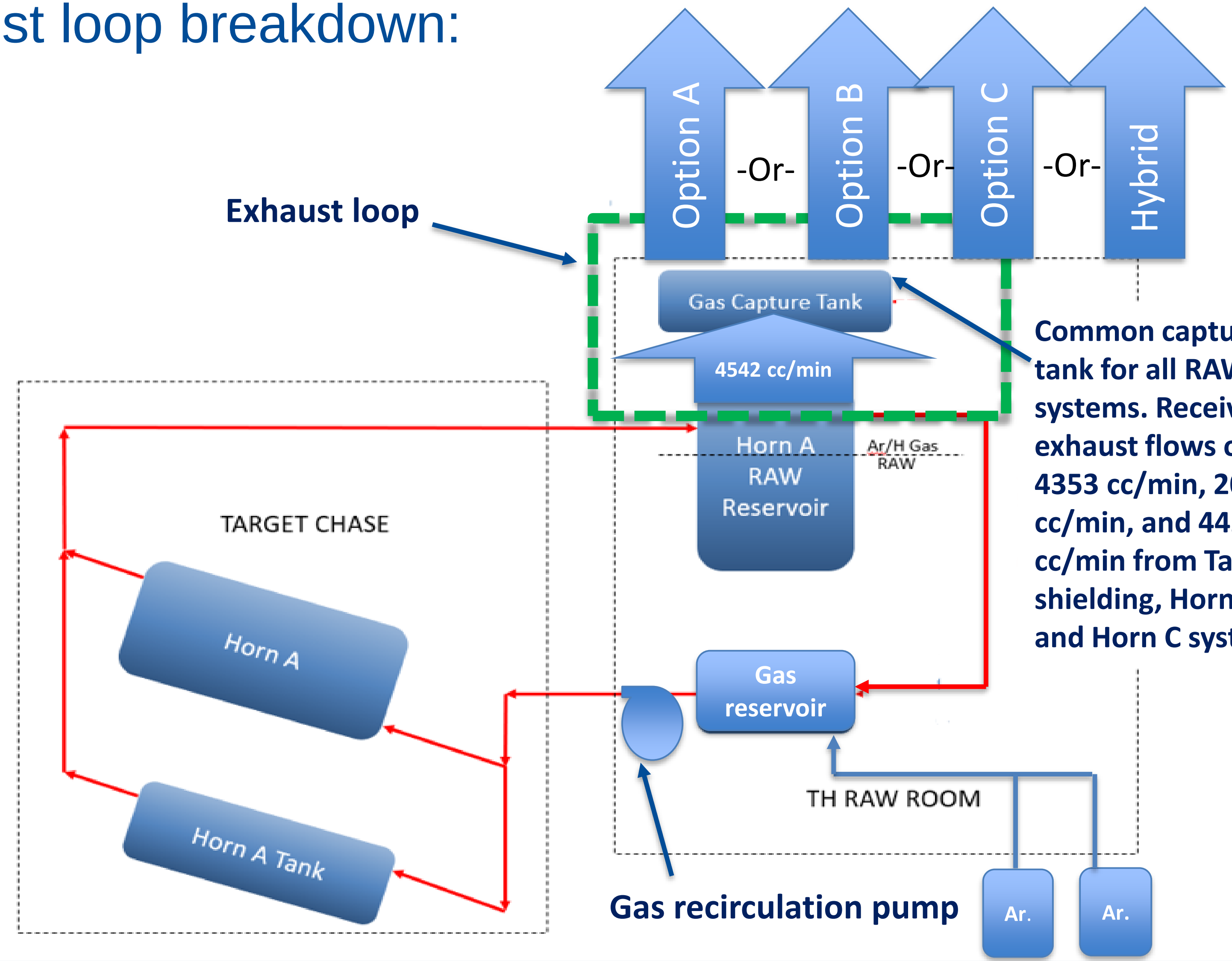
- Below schematic shows a scheme to control H2 levels in Horn A, B, C, and Target shield pile RAW systems:



Source: Karl Williams

Conceptual Design of the System: Hydrogen control

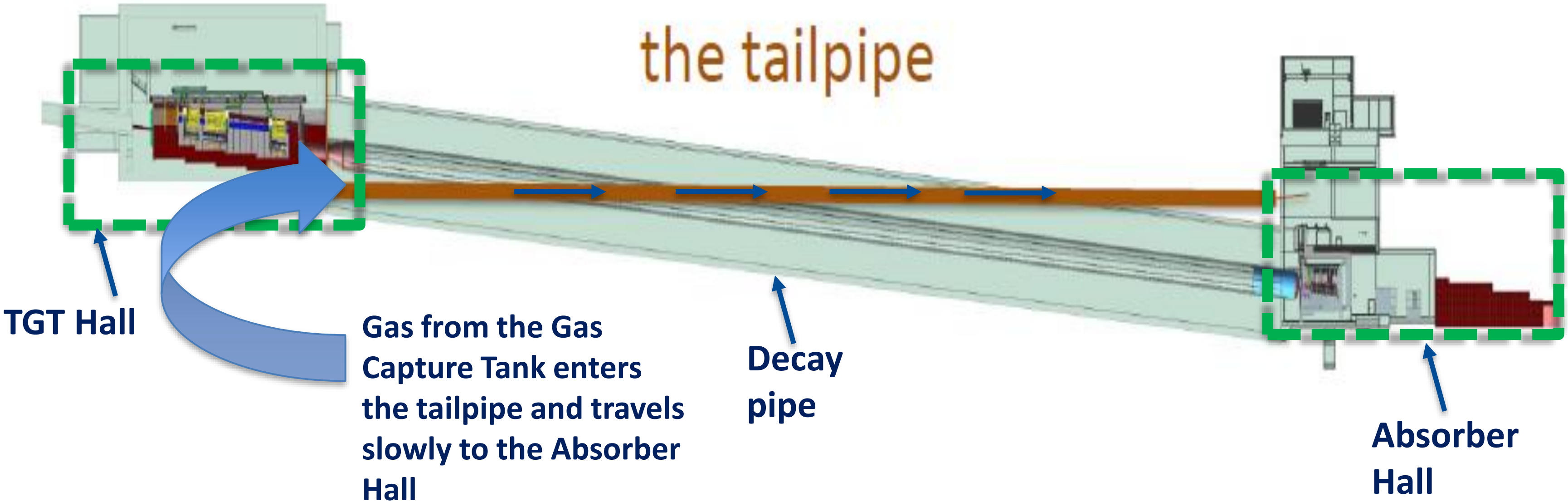
- Exhaust loop breakdown:



Common capture tank for all RAW systems. Receives exhaust flows of 4353 cc/min, 2019 cc/min, and 442 cc/min from Target shielding, Horn B and Horn C systems

Conceptual Design of the System: Hydrogen control

- Option A: The tailpipe



TGT Hall

Gas from the Gas Capture Tank enters the tailpipe and travels slowly to the Absorber Hall

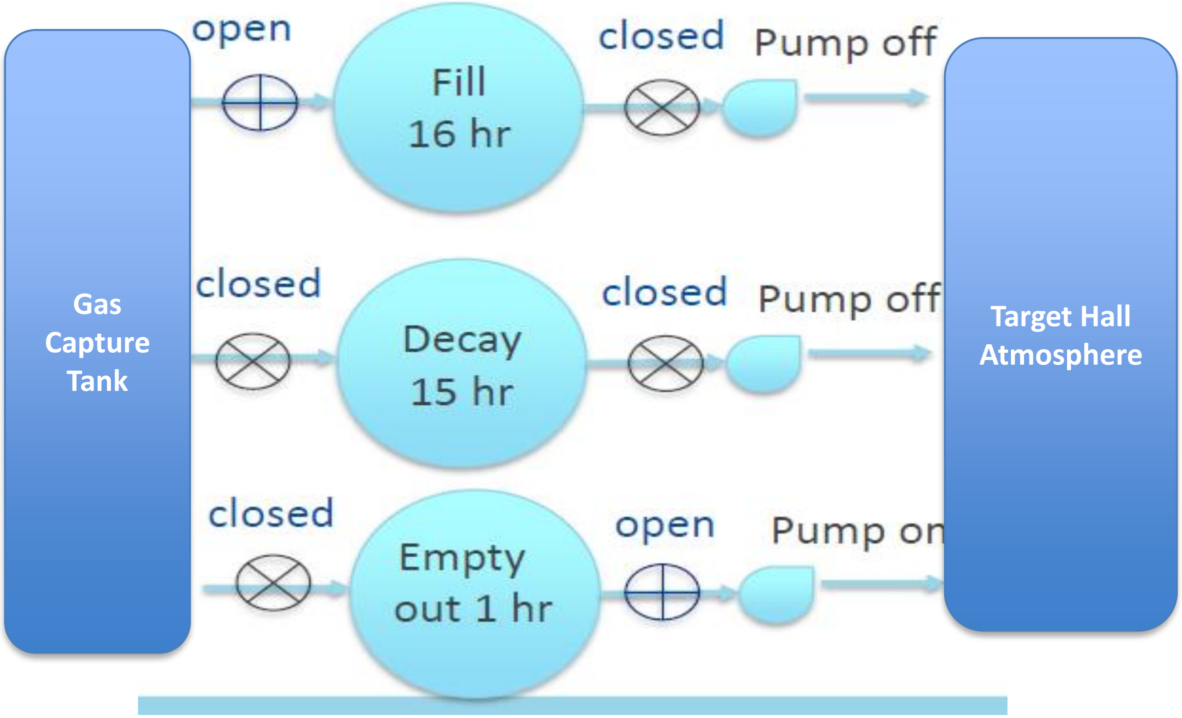
Decay pipe

Absorber Hall

- This pipe needs to be looped back and forth to and from the Abs hall (3-times) to give the Ar41 enough time to decay before it is exhausted to Absorber Hall atmosphere.
- First order estimates are of a 12” IPS pipe that has an overall length of ~580 m.

Conceptual Design of the System: Hydrogen control

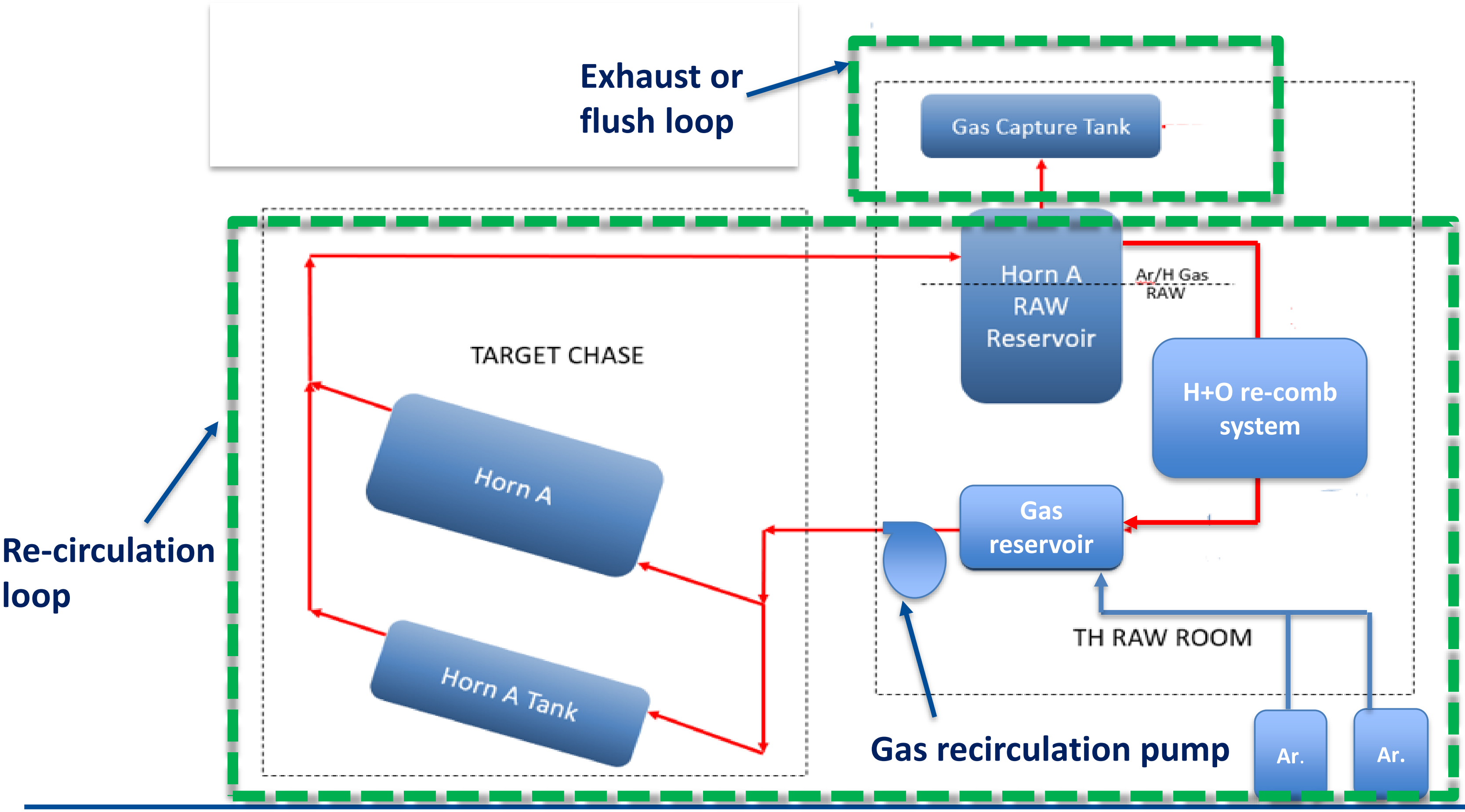
- Option B: Dual tank system



- The actual decay time depends on how much Ar41 is produced (must be calculated using MARS).
- The amount of Ar41 produced depends on how much pure Ar we use for flushing and the amount dissolved in the RAW system water.

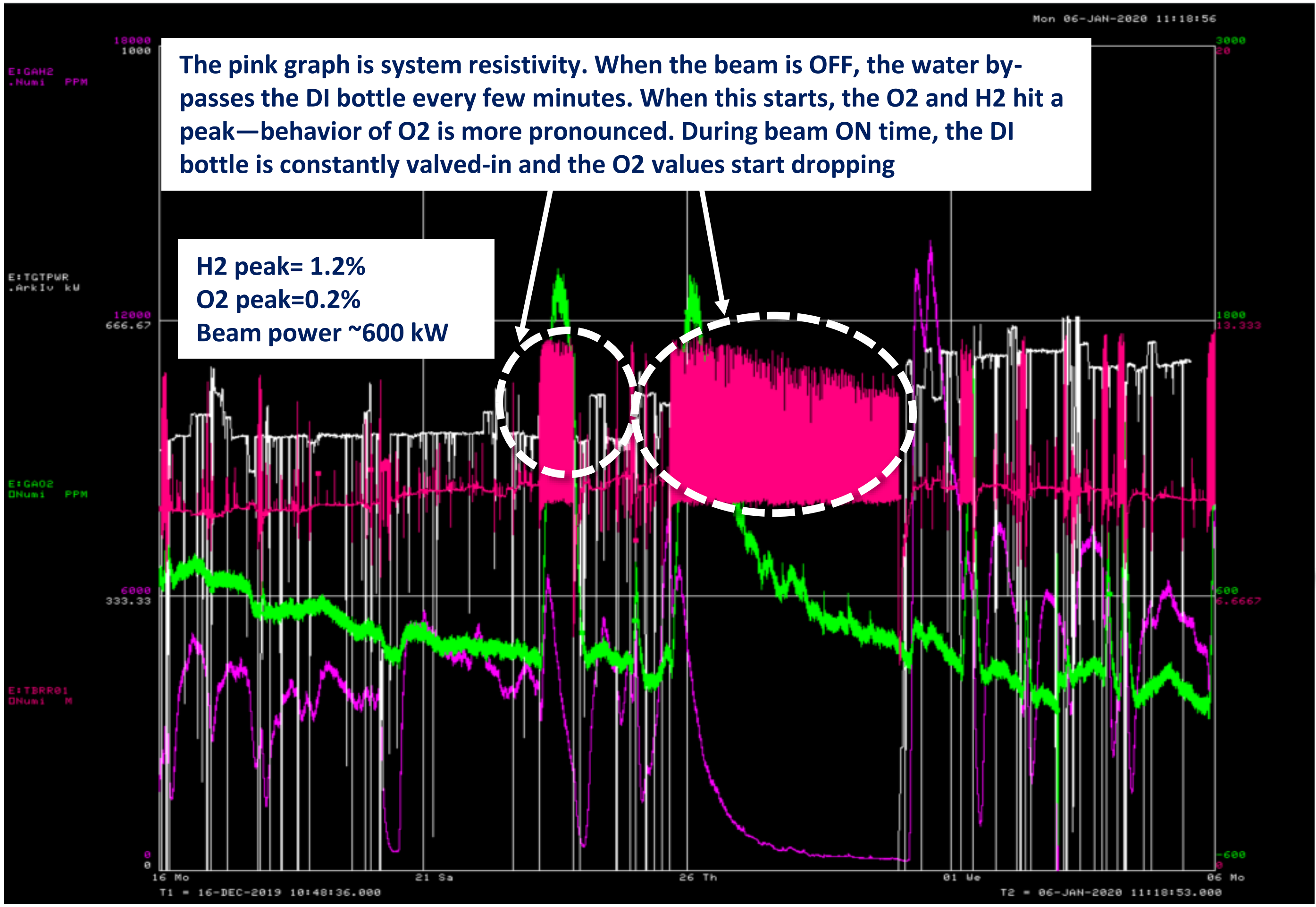
Conceptual Design of the System: Hydrogen control

- Option C: H+O re-combinator in the recirculation loop.
- A Hybrid option will involve pairing a H+O re-combination system with either Option A or Option B.



On-going research, experimental measurements, and design work

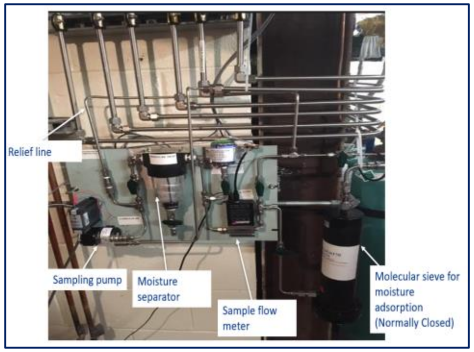
- Currently measuring H2, O2, and H2O on NuMI Target RAW System to compare theoretical H2 production to actual numbers.



The pink graph is system resistivity. When the beam is OFF, the water by-passes the DI bottle every few minutes. When this starts, the O2 and H2 hit a peak—behavior of O2 is more pronounced. During beam ON time, the DI bottle is constantly valved-in and the O2 values start dropping

H2 peak= 1.2%
O2 peak=0.2%
Beam power ~600 kW

Gas sampling system



This behavior has been documented at other labs. As per Sekiguchi-San, of Target Systems group at J-Parc, ion-exchange system does affect H2 production rate

On-going research, experimental measurements, and design work

- However, the O2 production rate seems to be low in our NuMI systems.
- Perhaps too low to apply re-combination system talked about in Option C.
- Are our experimental numbers correct? Contacted the 6-8 analysis labs to see if they can perform gas analysis of our gas sample to confirm our measurements. None of the labs can handle radioactive sample. Talking to SwRI at this time for help.
- If the O2 production rate is too low, do we introduce pure oxygen to the re-combination system? This may require an additional layer of safety systems.

Future work

- Following is the plan to reach a consensus on the design of the H2 control system:

Estimated hours for preliminary design of LBNF H+O recombination system

Task #	Task	Engineering /drafting effort, hrs.$_1$	Modeling effort, hrs.$_2$	Project management, hrs.	Review effort, hrs.$_3$	Start date$_4$	End date$_4$	Deliverable	Remarks
1	Determine H2 production rate for 2.4 MW operation for all ~~the RAW systems in Target Hall and Absorber Hall. Must~~ include error bar.	20	24	10	16	12/13/2019	12/16/2019	**Done**	Kamran has all the data to start this task
2	~~Determine Ar gas flow rate per RAW system to keep H2~~ below explosive limit for Horn A, Horn B, and Horn C systems	40	24	8	16	1/6/2020	1/10/2020	**Done**	This task can begin after ~~Task #1. Kamran just needs~~ a rough estimate of Ar diffusivity in water
3	Determine Ar41 generation rate in all RAW systems using Argon as a purge gas. The 2.5% rule must be incorporated here. Kamran may need diffusivity of Ar40 from engineering in RAW water for this calculation, perhaps?	24	24	8	16	1/13/2020	1/15/2020		This task can begin after Task #1. Although, some engineering analysis can begin now
4	Determine the hold time needed for Ar41 to acceptable values. Kamran will need diffusivity of Ar41 in Ar40 and also the diffusivity of Ar40 in the RAW water from engineering.	24	24	8	8	1/16/2020	1/22/2020		This task needs completion of Task#3. Although, some engineering analysis can begin now
5	Design (preliminary) the Argon purge recirculation system for RAW systems using Argon purge.	120	4	8	8	1/9/2020	1/30/2020	Design document and presentation highlighting the system feasibility and design	This task can begin now! Also, includes investigation of vendors for catalyst, recomb, and gas removal systems.
6	Obtain the catalytic recombination efficiency from J-Parc operations	6	2	8	8	12/13/2019	12/16/2019	**Done**	This task is independent of all tasks. Dependent upon J-~~Parc's progress. As per Jim~~ Hylen, we have this information already.
7	Make a decision on what is the appropriate H+O recombination system for our operations: a). Catalytic recombination b). Absorber tailpipe c).Decay tank system or any suitable combination of the above	20	8	16	16	2/3/2020	2/13/2020		This task requires the completion of all the above tasks.
8	Create a conceptual design of the H+O recombination using all the above inputs including a BOE	200	12	8	80	1/22/2020	4/16/2020	Design document and presentation highlighting the system feasibility and design	This task can start after Tasks 1, 2,3,4, and 5 have reached 80-90% maturity. Current candidates: Holding tank vs. tail pipe vs. hybrid system

On-going tasks

Thank you!

Questions and discussion…