Ammonia Release on *ISS*

ISS Emergency Strategy TIM
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Main Sources of Ammonia on *ISS*

Crew

- **Approximately 53% metabolic load**
- **Product of protein metabolism**
- **Limit production of ammonia by external regulation NOT possbile**

Payloads

- **Potential source**
- **Scientific experiments**
- **Thorough safety review ensures sufficient levels of containment**

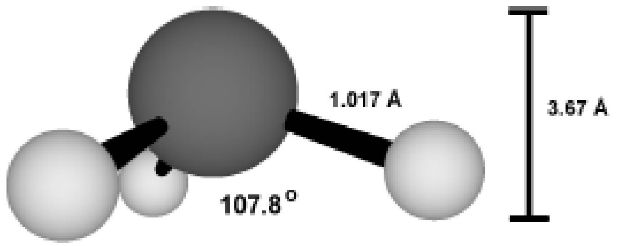
Main Sources of Ammonia on *ISS*

Systems

- **USOS Thermal Control System**
- **Provides thermal control to USOS (include Columbus and JEM)**
- **Comprised of Internal and External systems**
- **Internal Active Thermal Control System (IATCS)**
  - uses single-phase H_2O to remove internal heat
  - system pressure ~190 kPa (~28psi)
  - MDP ~690kPa (~100psi)
- **External Active Thermal Control System (EATCS)**
  - uses *liquid* NH_3 as refrigerant
  - system pressure ~2000kPa (~300psi)
  - MDP ~3500kPa (~500psi)
  - At assembly complete, two, independent NH_3 loops
  - Per loop: 272kg (600lbs) / 394L (104 gallons) / 1.7°-3.9°C (35°-39°F)
- **Heat transfer from IATCS and EATCS occurs at ammonia-to-water interface heat exchanger (IFHX) externally mounted**

Ammonia Chemistry

- Natural state is colorless, alkaline gas (RT and 1 atm)
- Pungent, very familiar odor (odor threshold ~ 1- 5 ppm)
- High H_2O solubility (at 20°C, 34% w/w)
- Flammability limits in air, 15-28% (by volume)
- High vapor pressure
  - Anhydrous NH_3 (20°C) ~ 8.5atm
  - Aqueous NH_3 (28%, 25 C) ~ 2.9atm



- Moderate base (pKa ~ 9.2); undergoes acid-base reactions forming H_2O-soluble ammonium (NH_4^+) salts
- Normal combustion yields nitrogen (at 750°-900°C with Pt, NO and NO_2 can form)
- Properties of liquid NH_3 very similar to liquid H_2O
  - H-bonding, low density, low viscosity, and high permittivity
  - widely used reaction medium
- Widely used in fertilizers, household cleaning products, commercial refrigeration, etc.
- Corrosive, can corrodes copper, brass, nickel, PVC, zinc, etc.

Ammonia Exposure

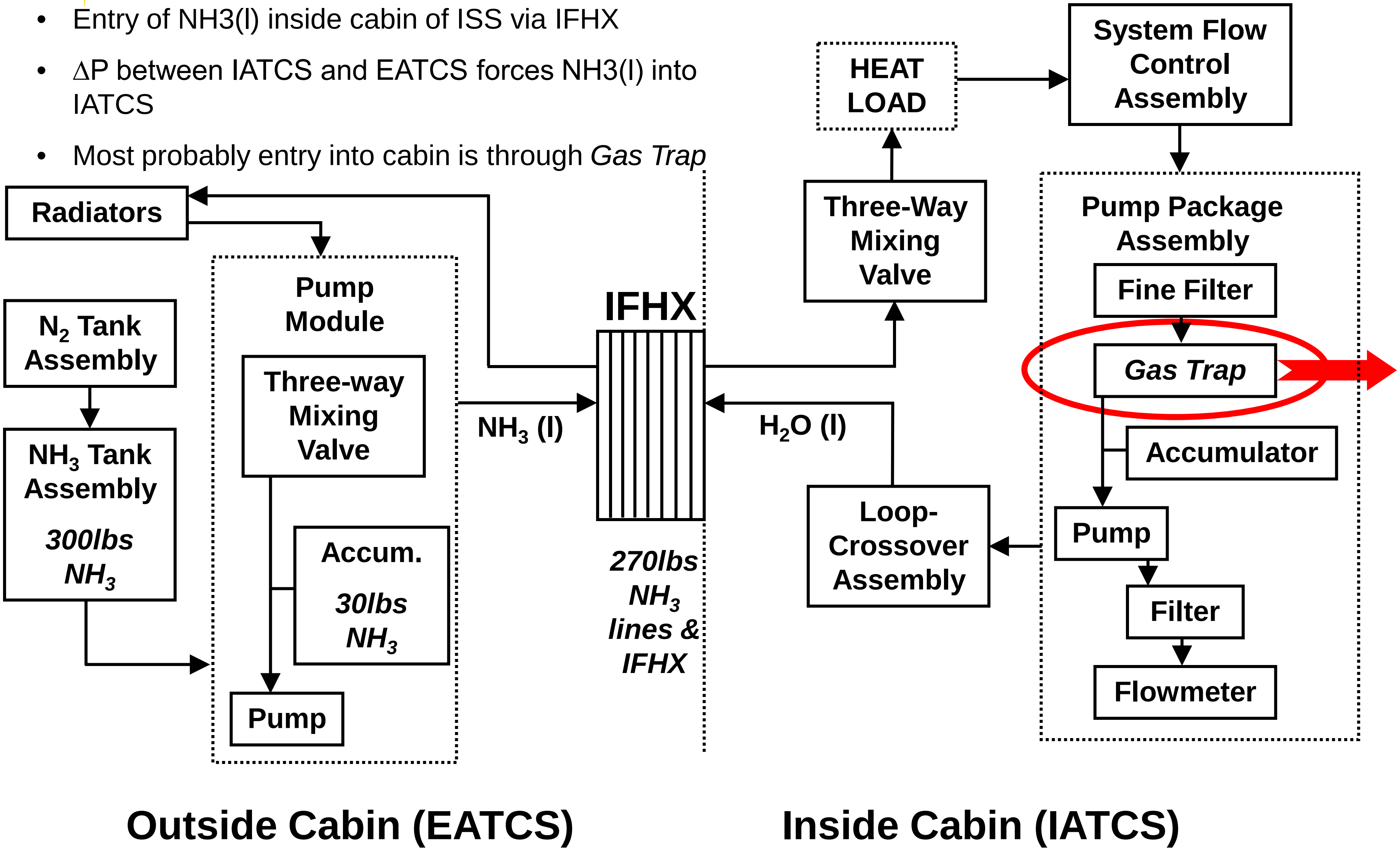
- **Principal toxic effect ammonia vapor - irritation to soft tissue (eyes, mucous membranes, respiratory tract)**
  - NH_3 (NH_4OH) reacts with soft tissue – alkali burns
  - heat released when NH_3 reacts with H_2O in soft tissue
- **Documented effects of ammonia vapor exposure**
  - Irritation to eyes and nasal passage begin as low at 100ppm (69mg/m^3)
  - Throat irritation at 400ppm (276mg/m^3)
  - Severe irritation to eyes, nose, and throat at 500ppm (345mg/m^3)
  - Laryngospasm at 1700ppm (1200mg/m^3)
- **Temporary systemic effect – metabolic acidosis – also documented**
- **Principal toxic effect *liquid ammonia* – caustic burns and freeze burns**

Ammonia Exposure Limits

- **US Spacecraft Maximum Allowable Concentrations (SMAC)**
  - 1-hour ⟶ 30ppm (20mg/m^3)
  - 24-hour ⟶ 20ppm (14mg/m^3)
  - 7-, 30-, 180-day ⟶ 10ppm (7mg/m^3)
- **RS Limiting Permissible Concentration (LPC)**
  - 360-day ⟶ 1.4ppm (1mg/m^3)
- **National Institute for Occupational Safety and Health Standards (NIOSH)**
  - recommended exposure limit, REL (10hrs TWA) ⟶ 25ppm (17mg/m^3)
  - short-term exposure limit, STEL (15min TWA) ⟶ 35ppm (24mg/m^3)
  - immediate danger to life and health, IDLH ⟶ 300ppm (207mg/m^3)
- **Occupational Safety and Health Administration (OSHA)**
  - permissible exposure limit for general industry, PEL (8hrs TWA) ⟶ 50ppm (35mg/m^3)

Ammonia Release into the *ISS*

- Entry of NH3(l) inside cabin of ISS via IFHX
- ΔP between IATCS and EATCS forces NH3(l) into IATCS
- Most probably entry into cabin is through *Gas Trap*



Ammonia Release Into *ISS*

- **Entry of NH_3 into habitable volume of ISS via *IFHX breach***
  - If accumulator >90%, IFHX NH_3 leak warning automatically issued and IFHX bypassed
  - Pressures and temperatures of EATCS checked to verify possible IFHX breach
- **IFHX breach can occur in one of three possible ways:**
  1. *Freezing water within IFHX core*
     - NH_3 temperature falls below 0 C (32 F), working fluids of IATCS and EATCS stagnate, IFHX heater failure or ISS attitude
     - Three levels of redundancy in NH_3 temperature control and operational safeguards
  2. *Structural failure of IFHX core*
     - Inadequate strength of material, stress corrosion, materials compatibility, propogation of micro-cracks
     - Selection of proper materials, manufacturing processes, and correct testing procedures
  3. *Over-pressurization of EATCS*
     - IFHX heater failure, flow of NH_3 at heater is low-flow or no-flow, failure of pressure relief valves and bleedlines
     - Modifications to IFHX plumbing and software control of the IFHX bypass and isolation valves
     - Mutiple RPCs to power-off for each heater; sufficient capacity in accumulator from volumetric expansion from one heater failure, IFHX isolation relief valves

Types of Ammonia Leaks Possible

- **If IFHX breach occurs, three types of leaks are possible….**

- **Micro-leak**
  - Detected via samples from ITCS water – tested every 90-days
  - Declared if ammonia concentration in water > 3 ppm
- **Moderate-leak**
  - Detected by telemetry on ITCS accumulator quantity and ITCS water sample
  - Declared if BOTH are true:
    - Increase of ITCS accumulator quantity at least 1% over steady state values, not attributed to other causes

    AND

    - Ammonia concentration in ITCS water is greater than 6 ppm
- **Rupture**
  - Detected by IFHX FDIR

  OR

  - In dual loop mode, LT accumulator quantity increases at least 50% over steady state values, not attributable to other causes
    - Currently backed up from 30 ppm maximum measurement capability

  OR

  - Calculated lab pump outlet pressure is greater than 768 kPa, not attributable to other causes

  OR

  - Lab pump inlet pressure is greater than 401 kPa, not attributable to other causes

In the Event of an Ammonia Release on ISS

- ***(1) Maintain crew safety and***
- ***(2) Maintain ISS operations***
- **Current procedures isolate crew to ROS – Service Module – with PPE (PBA, ИПК-1М, ammonia respirators)**
- **Probability exists NH_3 will contaminate Service Module**
- **Probability of maintaining crew safety and ISS operations is *function* of PPE capabilities, NH_3 monitoring capabilities, and NH_3 removal capabilities**
- **Options to increase this probability:**
  - Increase NH_3 monitoring capability
  - Increase NH_3 removal capability
  - Increase PPE capability
  - Ideally, ALL THREE!

Ammonia Monitoring Capability on *ISS*

existing

- **ИПД Kit (RS) – Draeger Tubes**
  - Type 0.25/a: 0.3-3ppm (0.2-2mg/m^3)
  - Type 0.25/a: 0.3-28ppm (0.2-20mg/m^3)
- **ГАНК-4М (RS)**
  - Electrochemical Sensor: 7-143ppm (5-100mg/m^3)
  - Tape Sensor: 0.7-143ppm (0.5-100mg/m^3)
- **Draeger CMS (RS) – Draeger Chip Measurement System**
  - Ammonia Chip: 0.2-2000ppm (0.1-1380mg/m^3)
  - Still undergoing on-orbit testing? Certified?

added

- ***Extended-Range Ammonia Detection Kit (US) – Draeger Tubes (located FGB)***
  - Low- range 2/a: 5-30ppm (3.5-21mg/m^3)
  - Mid-range 5/a: 30-700ppm (21-490mg/m^3)
  - High-range 0.5%/a: 500-10,000ppm (345-7000mg/m$^{3)}$

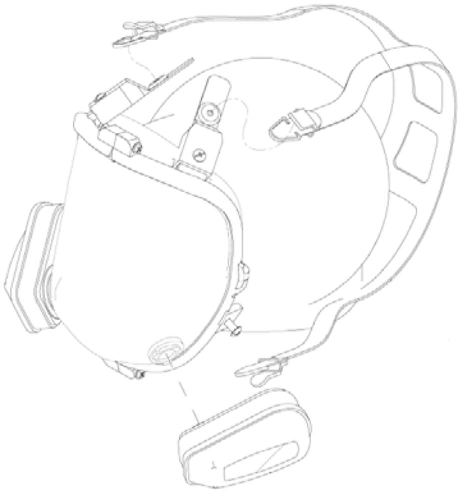
Ammonia Removal Capability on *ISS*

existing

- **ROS Capability:**
  - **BMP (in SM)**
    - Effective removal flow is 0.58 x 27 m3/h = **15.7 m^3/h**
      - Assumes 58% efficiency under normal regeneration cycling.
  - **FVP (in FGB)** *[limited NH_3 capacity = 0 to 133 grams]*
    - Effective removal flow is 1.0 x 20 m^3/h = **20 m^3/h**
  - **SKV (in SM)**
    - Efficiency varies depending upon the latent load removed and the air flow through the heat exchanger core. For the SKV 50% bypass:
      - For 2 person latent load efficiency = 24%
      - For 3 person latent load efficiency = 32%
    - For 2 people removal flow rate = 0.239 x 144 m^3/h = **34.4 m^3/h**
    - For 3 people removal flow rate = **46.2 m^3/h**
- **USOS Capability:**
  - **TCCS (in Lab)** *[limited NH3 capacity = 0 to 100 grams]*
    - Effective removal flow up to saturation is = **15.3 m^3/h**
  - **CCAA (in Lab and A/L) – due to inactive ITCS assumed unusable**
    - For 50% bypass:
      - For 2-person latent load efficiency = 12%
      - For 3-person latent load efficiency = 17%

Additional ammonia removal capability has not been implemented.

Personal Protection Equipment on *ISS*



existing

- **ИПКs (ROS)**
  - 70 minutes O_2
  - Use in ammonia release needs to be verified
- **PBAs (USOS)**
  - 10 minutes O_2
  - Positive-pressure minimizes chance of ammonia entering side of mask

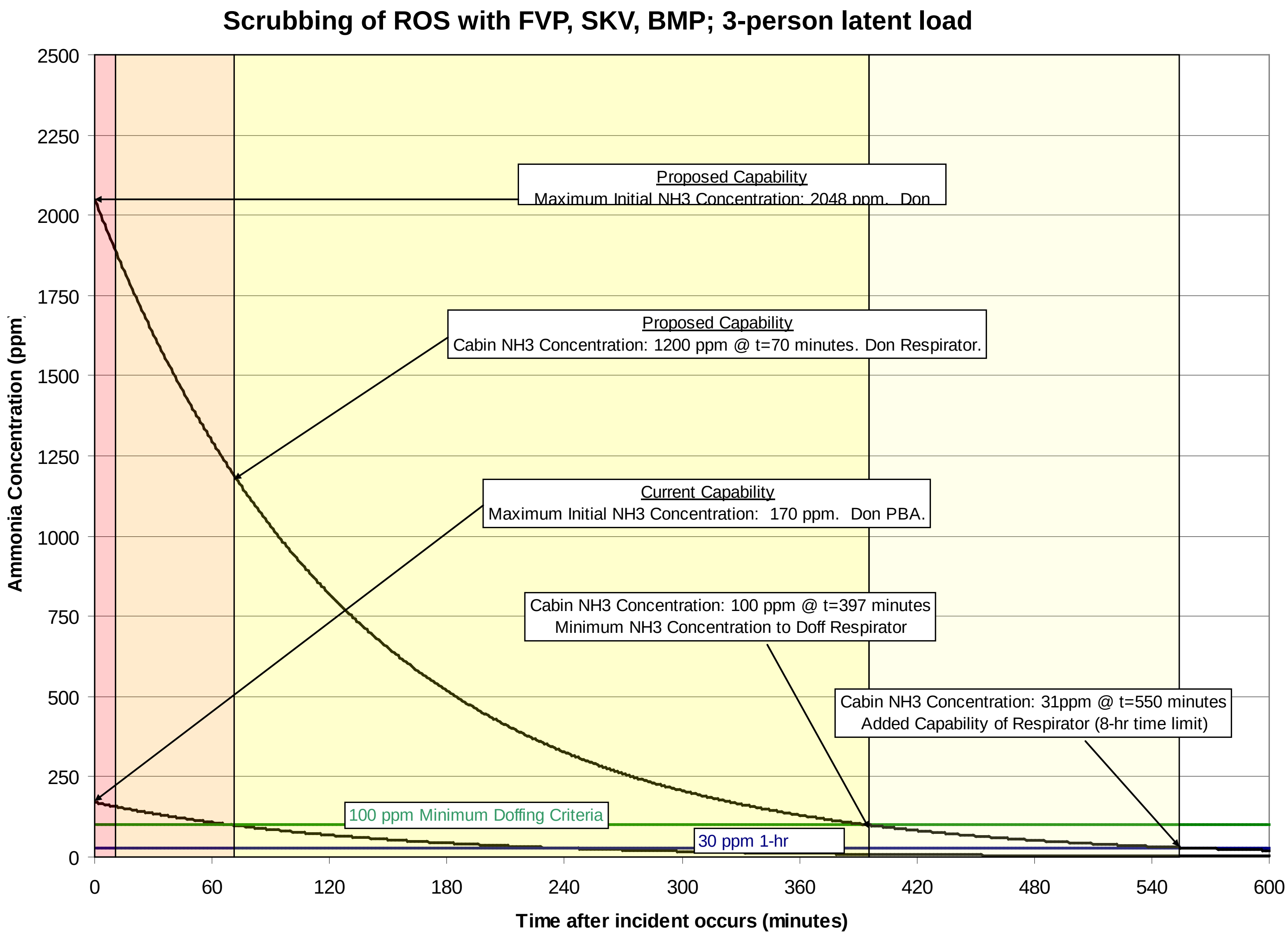
added

- ***Ammonia Respirator Kit***
  - Small, medium, or large hooded respirators
  - 6 pairs of ammonia-specific cartridges
  - Maintains moisture in air to maintain scrubbing capability of SKV
  - Certified to 1200ppm NH_3
  - Stored in FGB

Ammonia Release on *ISS*

- **Probability of maintaining crew safety and ISS operations is *function* of PPE capabilities, NH3 monitoring capabilities, and NH3 removal capabilities**
- **Options to increase this probability:**
  - *Increase NH_3 monitoring capability*
    - Extended Range Ammonia Detection Kit
    - Monitoring up to 10,000ppm NH_3
  - *Increase NH_3 removal capability*
    - Best removal means – humidity condensate
    - Hooded respirators maintains scrubbing capability via humidity condensate
    - Additional hardware not possible in reasonable timeframe
  - *Increase PPE capability – hooded, 3M respirators*
    - Provides time for scrubbing
    - Allows humidity condensate removal
    - Key objectives met
      - Good Fit – Ensuring clean air
      - Keeping the A/C system wet
      - Comfort – need to wear for a number of hours no matter what extra removal capability have

Existing Capability Supports 171 ppm



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Backup Charts

Ammonia Release into *ISS*

- **Cabin conditions rapidly deteriorate after an IFHX breach.**
- **The time to effect for "pin-hole" sized breach of the HX (0.05" dia) is measured in minutes**
  - *Time to gas trap breach: 10.75 minutes*
  - *Time to 700 ppm: 10.9 minutes*
  - *Time to 2000 ppm: 11.18 minutes*
  - *Time to 16%: 37.32 minutes*
- **The time to effect for "gross" breach of the HX (0.5" dia) is measured in seconds.**
  - *Time to gas trap breach: 10.6 seconds*
  - *Time to 700 ppm: 10.6 seconds*
  - *Time to 2000 ppm: 10.8 seconds*
  - *Time to 16%: 31.3 seconds*
- **This analysis does not address detailed failure mechanisms, or the likelihood of system failures. This analysis parametrically addresses the time to effect as a function of the equivalent area of the HX breach.**

Ammonia Release into *ISS*

Time=0 when HX breaches																
Current Config (383 m^3)																
cm^2	in	sec	sec	cm^2	in	sec	psia	sec	psia	sec	psia	sec	% vol	sec	psia	sec
Cross-sectional area of HX breach	Equivalent hole size of HX breach	time to fill ITCS accum	time to rupture gas trap	Cross-sectional area of gas trap breach	Equivalent hole size of gas trap breach	time to 700 ppm	cabin pressure at 700 ppm	time to 2000 ppm	cabin pressure at 2000 ppm	time to 1%	cabin pressure at 1%	time to PCA open	conc at PCA open	time to 16% (LFL)	cabin pressure at 16% (LFL)	1.5x Nominal cabin pressure
0.0103	0.05	38	645	0.031	0.0787	654	14.41	671	14.43	779	14.54	1172	4.32%	2239	15.05	n/a
0.051	0.1	38	190	0.125	0.157	191.75	14.41	196	14.43	220.25	14.54	313	4.34%	588.75	16.27	1342
0.203	0.2	9	47.5	0.503	0.315	48	14.41	49	14.43	55	14.54	79	4.38%	150.25	16.91	278
0.456	0.3	5.3	21.5	0.95	0.433	21.5	14.41	22	14.42	25	14.54	36.25	4.37%	69.25	17.01	127
0.811	0.4	3.5	16.4	1.544	0.552	16.4	14.4	16.7	14.42	18.2	14.53	24.7	4.40%	44.8	17.06	87
1.267	0.5	3	10.6	2.268	0.669	10.6	14.4	10.8	14.41	12	14.54	16.6	4.33%	31.3	17.08	59
Assembly Complete (636 m^3)																
0.0103	0.05	38	645	0.031	0.0787	660	14.41	689	14.43	861	14.54	1449	4.32%	2959	15.05	n/a
0.051	0.1	38	190	0.125	0.157	193.25	14.41	199.75	14.43	239.5	14.54	380.75	4.32%	778	16.34	n/a
0.203	0.2	9	47.5	0.503	0.315	48.25	14.41	50	14.43	60	14.54	96.5	4.32%	198.25	16.94	n/a
0.456	0.3	5.3	21.5	0.95	0.433	21.75	14.41	22.25	14.42	27.75	14.54	44.5	4.43%	92	17.04	n/a
0.811	0.4	3.5	16.4	1.544	0.552	16.5	14.41	16.9	14.42	19.6	14.54	29.5	4.41%	59.1	17.07	n/a
1.267	0.5	3	10.6	2.268	0.669	10.7	14.41	11.1	14.42	12.9	14.54	20.2	4.43%	41.8	17.09	86

Micro-leak Scenario

- **Micro-leak occurs**
- **Ammonia starts to mix with water in ITCS loop and ammonia concentration in water starts to rise.**
- **No noticeable accumulator increase.**
- **Diffusion into cabin through Teflon flex hoses and gas trap**
  - For LTL IFHX leak, 22% diffusion occurs through gas trap, 78% through flex hoses
  - For MTL IFHX leak, 11% diffusion occurs through gas trap, 89% through flex hoses
- **Concentration in cabin will equilibrate with concentration in the water loop.**
- **Condensing heat exchangers and TCCS systems will be able to keep up with diffusion for a micro-leak**

Micro-Leak Response

- **No PPE is needed**
- **No USOS evacuation is needed.**
- **Gas traps will be removed to minimize diffusion and protect gas traps**
  - May be re-evaluated
- **If in single loop, system may be configured to dual loop mode**
  - Will help to identify which loop the leak is in.
- **EVA task to isolate and vent the Ammonia side of the leaking IFHX will be performed as soon as possible.**
  - HX will be R&Red but may not be connected until ITCS contamination has been dealt with.
- **No guarantee on how long this will remain a micro-leak based on the great pressure differences between the different sides of the HX.**

Moderate Leak Scenario

- **Micro-leak develops to moderate leak or moderate leak occurs.**
- **Ammonia mixes with water in ITCS loop and ammonia concentration in the water rises.**
- **Noticeable accumulator increase (~1%) over steady state values.**
- **Diffusion into cabin through Teflon flex hoses and gas trap**
  - For LTL IFHX leak, 22% diffusion occurs through gas trap, 78% through flex hoses
  - For MTL IFHX leak, 11% diffusion occurs through gas trap, 89% through flex hoses
- **Concentration in cabin will equilibrate with concentration in the water loop.**
  - Greatest level can measure in water is 6 ppm, but the 1% accumulator increase would equate to much larger concentration in the water.
- **Crew should be able to notice smell at these levels, but if the rate of increase is slow they may not.**
- **Condensing heat exchangers and TCCS systems may or may not be able to keep up with diffusion, depends on the size of the moderate leak.**

Moderate Leak Response

- **PPE may be needed if crew is experiencing irritation**
  - Filtering masks may be used, if available. Current half masks do not provide protection from eye irritation.
- **No USOS evacuation is needed as long as levels stay below:** ***still under evaluation***
  - Russian limit = 7 ppm for 15 days
  - 180 day SMAC limit is approximately 10 ppm
- **Gas traps may or may not be removed**
  - Criteria still under evaluation
- **If in single loop, system will be configured to dual loop mode**
  - Will help to identify which loop the leak is in.
- **If time allows and leak is in MTL IFHX, a number of racks will be jumpered in preparation for loss of MTL.**
- **If system is in dual loop mode and the leaking IFHX has been identified, system may be reconfigured to single loop**
  - Provides greater volume and delay hazardous conditions from being reached sooner.
- **EVA task to isolate and vent the Ammonia side of the leaking IFHX will be performed as soon as possible.**
  - HX will be R&Red but may not be connected until ITCS contamination has been dealt with.
- **No guarantee on how long this will remain a moderate leak based on the great pressure differences between the different sides of the HX.**
- **At any time if accumulator qty or Draeger measurement indicates ammonia concentration greater than 30 ppm, leak will be elevated to a rupture.**

Rupture Scenario

- **Rupture happens**
  - Three layers of freeze protection have failed, or there has been micrometeoroid hit that damages internal but not external side of HX, or has been internal corrosion induced failure.
- **Accumulator quantity will increase quickly to max out position on ITCS accumulator.**
  - Only takes 3.5 lbs of ammonia given accumulator initial quantity ~75%
- **Pressure in ITCS loop will increase until a breach is caused.**
  - Lowest burst pressure is gas traps at 212-300 psia
- **ITCS will leak water with 4.4% ammonia by weight into the cabin**
  - Calculated for an LTL leak
- **Concentration in cabin locally (USOS) will rise quickly based on the amount leaked in.**
  - For 2.2 lbs, in the USOS 262 ppm ammonia
  - For 22 lbs, in the USOS 2500 ppm ammonia
- **If FDIR annunciated warning, crew will push ATM button isolating IMV and preventing the diffusion to the RS.**
  - SCRs in the system to elevate the warning to an emergency and automatically tie response to the emergency trigger.

Rupture Response

- **Crew hears alarm for ITCS warning or smells ammonia**
- **Crew dons PBA, pushes ATM button, and evacuates & isolates USOS.**
- **Once in RS uses ammonia Draeger tubes to determine ammonia concentration in RS.**
  - Plan to use IVA Ammonia Detection Kit
  - Currently can use Russian Draeger tubes – measure only up to 30 ppm
  - As a back-up could look at GANK reading (measures up to ~ 142 ppm)
    - Not validated for on-orbit decisions
- **Crew transfers to Russian gas mask if needed.**
  - If not doffs masks
- **USOS PPRVs will crack with increasing pressures, USOS volume will need to be vented to eliminate as much ammonia vapor as possible.**
  - CCAAs could continue to be run to collect water and eliminate ammonia as long as LTL is still operable (would mean leak was in MTL)
- **Crew/ground determines if RS hardware will be able to clean RS to acceptable levels in PPE time remaining.**
  - If not, evacuate.
  - Currently this limit is an initial concentration of 171 ppm in RS.

Increasing Ammonia Removal Capability on *ISS* – Options Reviewed

- **COTS industrial unit to remove NH_3**
  - Pros: Proven applied technology designed for specific application.
  - Cons: Too large for ISS application and don't operate at 28 or 120Vdc.
- **Find material to put in LiOH can to use in Russian CO_2 absorber unit**
  - Pros: Utilizes existing interfaces and hardware on-orbit. Applicable to RS and can be used with PFA for USOS application.
  - Cons: Limited capability based on sizing of existing interfaces.
- **Increase latent loading - by some aspirator**
  - Pros: Speeds up removal rates.
  - Cons: Need to design something for ISS and certify for use in RS. No practical application available.
- **Purge**
  - Pros: Decreases concentration faster
  - Cons: Not enough make-up air in RS to consider partial vent. No knowledge of compatibility of RS valve seals and with high concentrations of NH_3.
- **Use CFU to entrain air with water**
  - Pros: All hardware exists on-orbit.
  - Cons: Not yet able to quantify the removal rate, need more time to look into.
- **Use acid treated charcoal in the HEPA filters on USOS**
  - Pros: Good to absorb ammonia given no CCAA condensation. Not sure airflow on Russian Segment high enough to implement there.
  - Cons: Not sure of effectiveness due to flowrate limitations, very large to stow on-orbit.

Increasing PPE on *ISS* – Options Reviewed

- **Increase number of PBAs on-orbit**
  - Pros: We own this hardware.
  - Cons: PBAs are ineffective for this application; they don't last long enough to provide meaningful help. Designed for evacuation. No units available for this application.
- **Increase number of Russian gas masks on-orbit**
  - Pros: PPE use time is long 20-140 min. compared to PBAs. Sealed system, safe to use at all concentrations.
  - Cons: Crew may reach limits of being on O2. Not putting latent load into the atmosphere to assist in removal. Still relatively short use time compared of that needed to restore the atmosphere. Large, hot, and uncomfortable to wear for a long time. Need to buy these from the Russians.
- **Fly 3M filtering respirators with NH_3 removal cartridges**
  - Pros: Not increasing ppO2 or total P of ISS over long time; Putting latent load back into cabin helping humidity condensate removal of NH3; Other cartridges Russians fly fit this mask and solve other issue of not being able to use US provided goggles with ½ masks already on-orbit for toxic/post fire events. No additional chemical qualification needed. Can use NIOSH qual data since using in the same application.
    - PPE time @ 500 ppm is **211** min for 60 L/min.
    - PPE time @ 500 ppm is **494** min. for 30 L/min.
  - Cons: New hardware to obtain and certify. Is a respirator and not a positive pressure device; poor fit causes leakage.
- **Investigate flying other re-breather**
  - Pros: Long PPE use time compared to PBAs. Sealed system, safe to use at all concentrations.
  - Cons: Crew may reach limits of being on O2. Not putting latent load into the atmosphere to assist in removal. New hardware to obtain and certify.
- **Adapt Hooded Respirator**
  - Pros: Eliminates fit problems with glasses and facial hair. Small to stow. Cartridge gives 54% additional capacity than 3M mask.
  - Cons: One time use, hot, no purge capability, issues if ammonia is on hair, need to recertify with new media.