
SUBS IN SPACE
NASA/Navy Collaborations
BLOW THE BALLAST!
Commercial in confidence

NASA/Navy Collaboration

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NASA/Navy Collaboration
The Early Years

- The Naval Research Laboratory (NRL) was deeply involved in development of rockets after World War 2
- NRL funded development of the Aerobee sounding rocket
  - Sounding rockets sent instruments beyond Earth's atmosphere to collect data for a short period of time
  - The Aerobee rocket launched the first mass spectrometer (Bennett MS) into low earth atmosphere to study radiation above the Earth's atmosphere
- Almost the entire work force (47) at NRL involved in the Aerobee work was transferred to NASA upon its formation in 1958 to build the space science and sounding rocket programs at Goddard
- NASA launched almost 150 Aerobee rockets per year during the early 1960s to study cosmic rays and other radiation impacting Earth

NASA/Navy Collaboration
The Early Years: Apollo Era

- Similarities
  - Partially closed environments
  - Escape is not possible by opening a door or hatch
  - Continuous exposure to the atmosphere (24/7)
  - Crew relies on air scrubbing for acceptable environment
  - Both have emergency escape options (ISS-Soyuz and submarines- surface or dissub scenarios)
- Differences
  - Crew size is drastically different
  - Differences in volume
  - Cooking-real food
  - Environment: microgravity vs. pressurized volume
  - Scrubbing is more robust on submarines
- Sounding rockets continued to launch for NASA under the guidance of the personnel transferred from NRL
- In the 1960s, a recognition of similarities between the closed environments of submarines and spacecraft led to collaboration on setting spacecraft limits on contaminants

NASA/Navy Collaboration
The Early Years: Apollo Era

- In 1968 NASA began to explore setting maximum allowable concentrations (MACs) for the expected longer duration missions to come
- NASA requested the NRC's Space Science Board to organize a panel on Air Standards for Spaceflight
  - The task was to evaluate the effect on contaminants on the health and performance of crews for long-term missions and short-term emergency limits
- Approximately 200 contaminants had been identified based upon offgas tests and simulated spacecraft environments.
- Of the 200 contaminants, 23 had contaminant limits of 90 days established by the NRC's Committee on Toxicology (COT) for submarine environments.
  - The Space Science Board recommended the established limits for these 23 compounds be used for spacecraft
  - NASA recommended 11 more compounds that required contaminant limits, plus 5 others that were required to have emergency limits

NASA/Navy Collaboration
The Early Years: Apollo Era

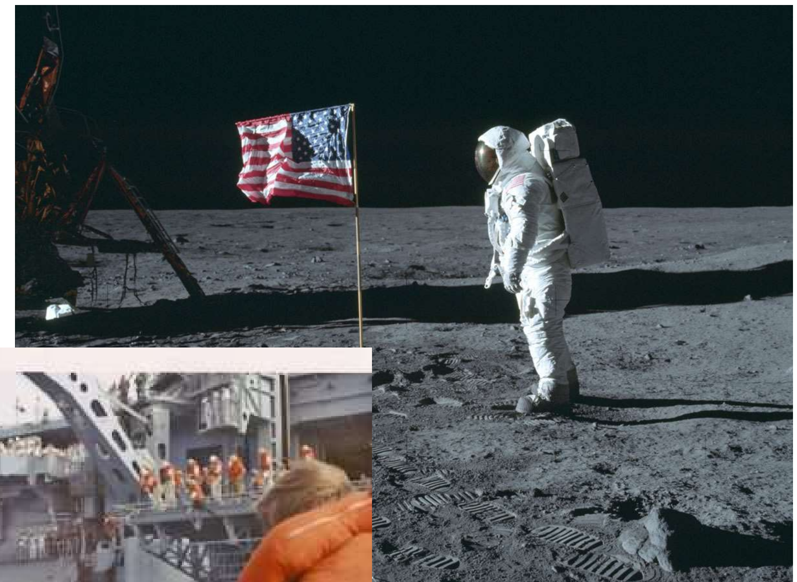
90- Day Limit			
Contaminant	**mg/m^3**	**Contaminant**	**mg/m^3**
Acetone	71	Methane	3300
Acetylene	2700	Methyl alcohol	13
Ammonia	17	Methyl chloroform	3000
Benzene	3	MEA	1
Carbon Monoxide	29	Nitrogen dioxide	1
Chlorine	0.3	Ozone	0.04
Freon 12	5000	Phosgene	0.2
Freon 114	7000	Sulfur dioxide	2.6
Ethyl alcohol	115	Toluene	188
Hydrogen	245	1,1,1 trichloroethane	1100
Hydrogen chloride	1.5	Xylene	217
Hydrogen fluoride	0.1		

Provisional Spacecraft Limits (mg/m^3)		
Contaminant	**90 Days**	**1,000 Days**
n-Butanol	30	30
2-Butanone	58	59
Carbon Monoxide	17	17
Chloroform	24	5
Dichloromethane	105	21
Dioxane	36	7
Ethyl Acetate	144	144
Formaldehyde	0.12	0.12
2-MethylButanone	82	82
Trichloroethylene	54	11
Freon 113	161	N/A

Provisional Emergency Limits	
Contaminant	**mg/m^3 (60 min)**
2-Butanone	294
Carbonyl fluoride	67
Ethylene glycol	253
2-Methylbutanone	409
Freon 113	1612

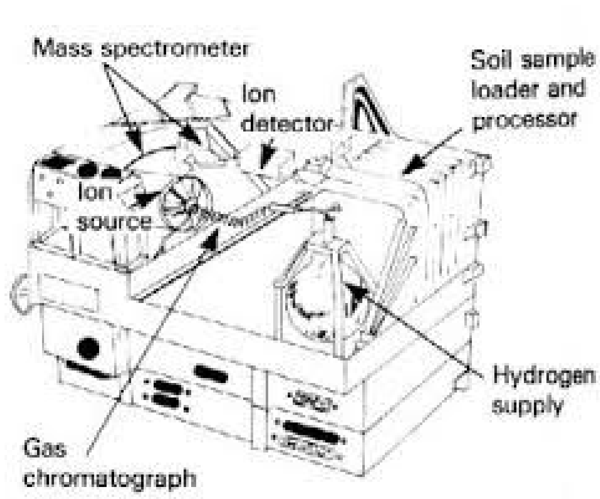
NASA/Navy Collaboration
The Early Years: Apollo Era

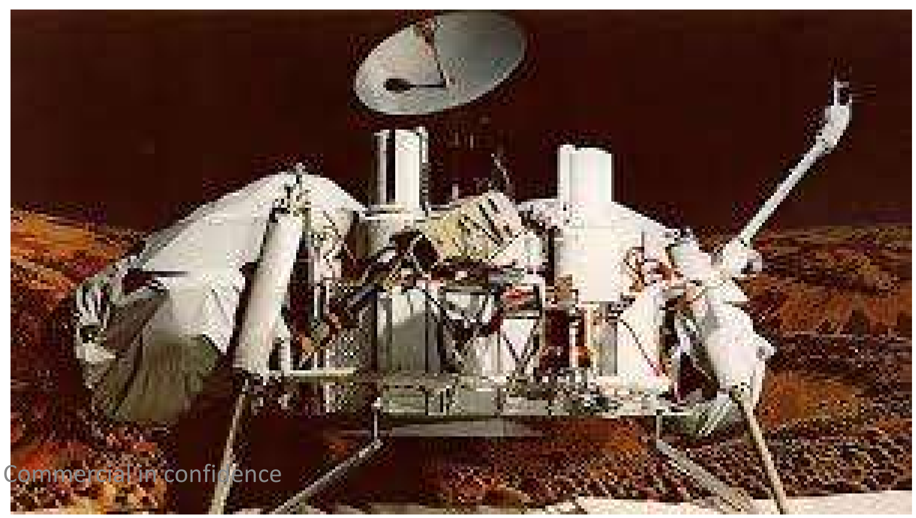
- And of course the Navy and NASA had collaborations beyond environmental concerns!



NASA/Navy Collaboration
The Early Years: 1970s

- The first robotic mission to Mars was called the Viking Lander
- Viking Lander had among its suite of instruments a very unique gas chromatograph-mass spectrometer (GC/MS)
- The mass spectrometer was a robust magnetic sector instrument that used an ion pump to maintain the vacuum
- This instrument's reliability and small size drew the interest of the NASA medical community and the U.S. Navy





NASA/Navy Collaboration
The Early Years: 1970s

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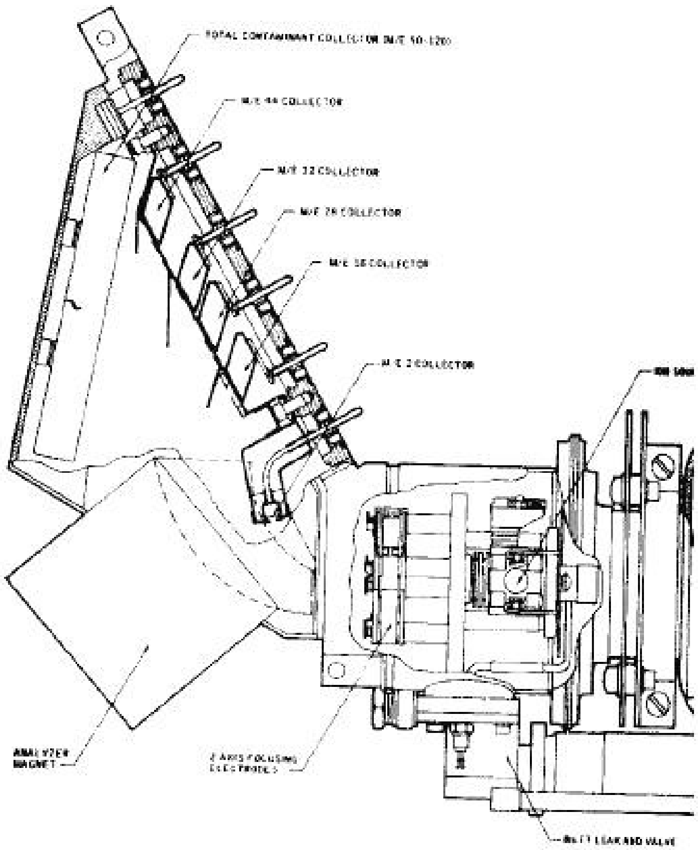


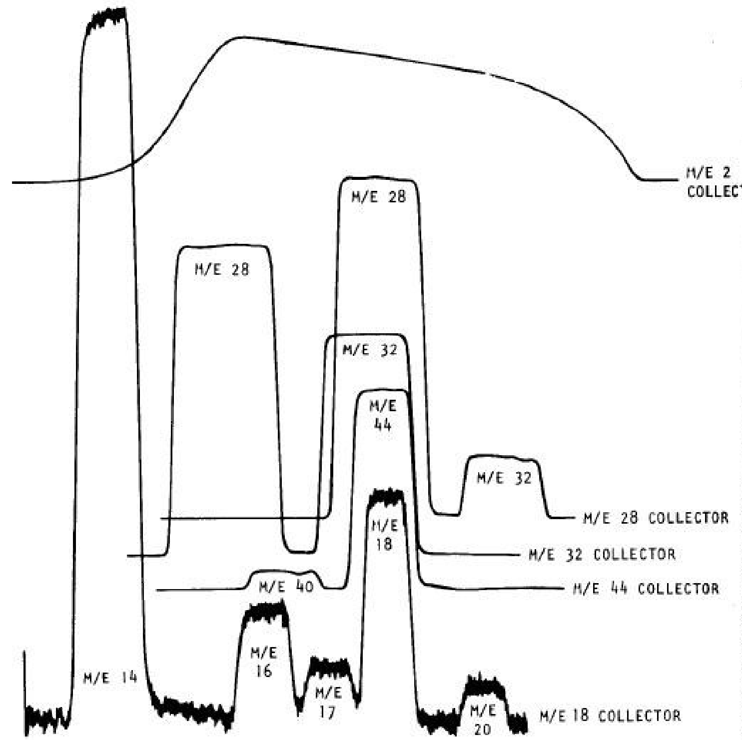


FIGURE 3. Typical Mass Peaks and Collector Alignment

NASA/Navy Collaboration
The Early Years: 1970s

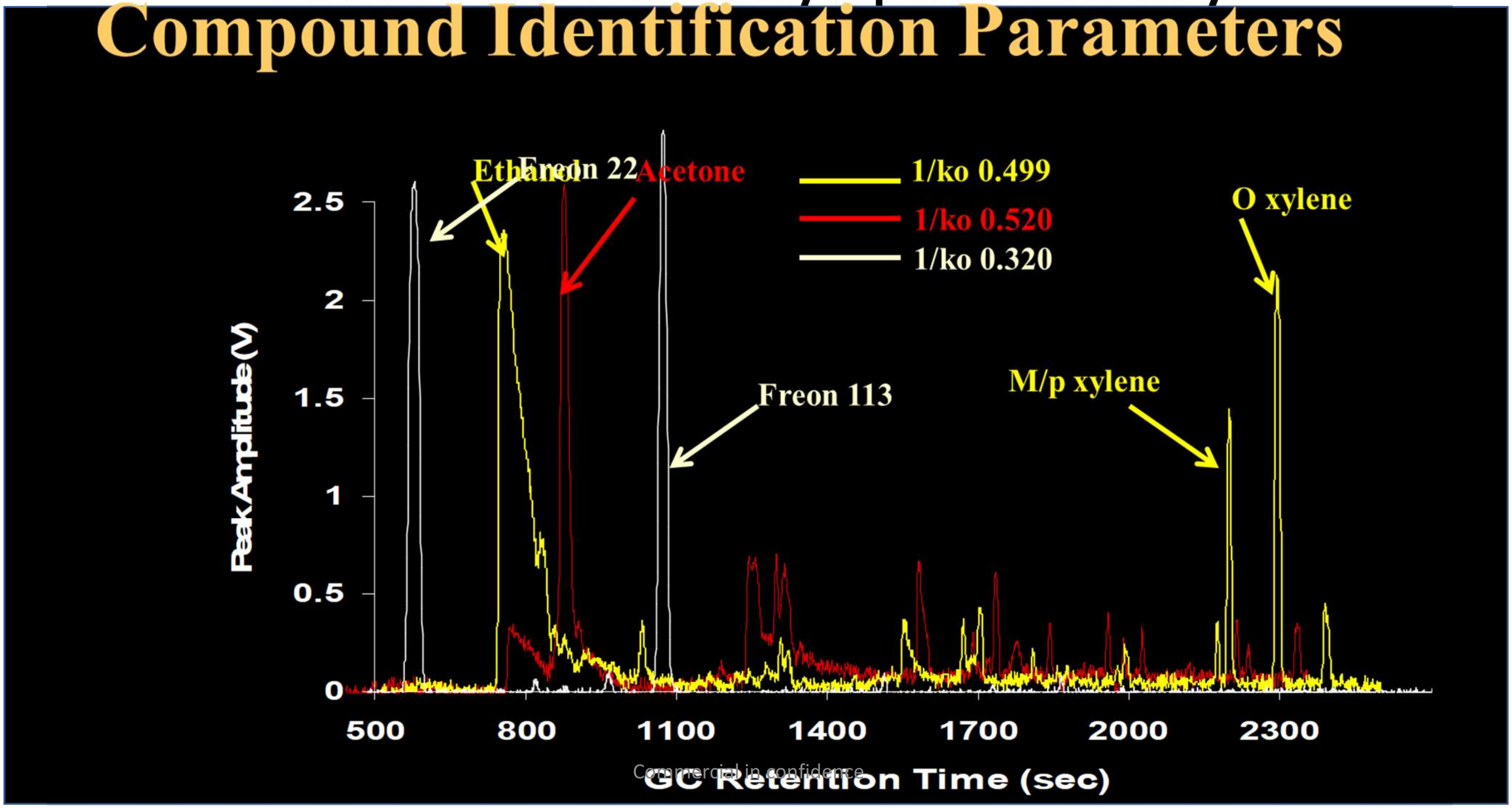
NASA/Navy Collaboration 1990s

- In the early 1990's the NASA toxicology group had discovered ion mobility spectrometry and was considering what uses it might have for spaceflight
- The first application of this new technology was as an experiment for detecting hydrazine onboard spacecraft.
  - The hydrazine monitor was a modified Graseby Chemical Agent Monitor (CAM)
  - Although the flight of the unit was successful, it became a victim of funding cuts in the space station program

NASA/Navy Collaboration
1990s

- During the initial work with the hydrazine monitor we began to think if, a gas chromatograph were interfaced to the detector and there was no dopant, would it be possible to measure trace organic compounds in the air
- The new ISS was going to require monitoring of trace contaminants in the air, but gas chromatography/mass spectrometry did not seem to the answer during this time.
- The advantages of this technology, ion mobility spectrometry, was that no vacuum pump was required and there was potential for reliable long-term operation and no periodic calibration

NASA/Navy Collaboration
1990s: Ion Mobility Spectrometry



NASA/Navy Collaboration 1990s

- Target compounds for the VOA

Compound Name	Concentration (mg/m3)	Compound Name	Concentration (mg/m3)
Methanol	0.1-1.5	Ethanol	0.2-3.5
1-butanol	0.3-4.0	2-methyl 2-propanol	0.1-2
Ethanal (qual. only)	0.1-1.2	Benzene	0.1-1.5
m,p xylenes	0.4-5.0	(F22) chlorodifluoromethane	0.3-5.0
o xylene	0.2-2.7	1,1,1, trichloroethane	0.1-1.6
Toluene	0.2-2.6	(F113) 1,1,2-trichloro-1,2,2-trifluoroethane	0.2-2.5
DCM	0.1-1.2	Hexane	0.2-2.4
Propanone	0.1-1.2	Pentane	1.0-12
2-butanone	0.1-1.5	2-methyl, 1,3-butadiene	0.4-5.0
ethyl acetate	0.2-2.4	(halon 1301) trifluorobromomethane	0.1-2.2
2-propanol	0.2-3.2		

  - Frequently detected in archival samples from spacecraft at measurable concentrations (i.e., ethanol)
  - Although rarely detected in spacecraft air, the compound has moderate to high toxicity (i.e., benzene)
  - Can affect the performance of the ECLS systems (i.e,., 2-propanol)

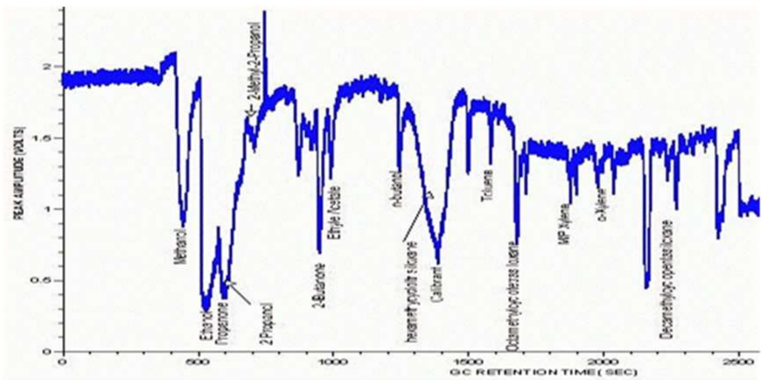
NASA/Navy Collaboration
1990s

- The Volatile Organic Analyzer (VOA) was selected as the trace contaminant monitor for ISS
- NASA initiated a risk mitigation program to test potential ISS hardware and the VOA risk mitigation experiment (VOA/RME) flew on two Shuttle missions

VOA/RME on STS-89 Shuttle Mission

NASA/Navy Collaboration 1990s

- More on the VOA/RME in a few minutes, BUT FIRST
- The data from the VOA/RME experiments showed excellent results in comparison with archival grab sample container collections
- Important lessons were learned
  - The sample volume used was too large as the VOA/RME was sensitive to trace organic compounds
  - Most importantly, a few peaks appeared in all runs. After reviewing the drift time of the peaks and the GC retention time, plus review of the GC/MS data for the archival samples it was thought they were siloxanes. Standards verified that indeed the peaks were siloxanes and they were added to the target list.



NASA/Navy Collaboration
1990s

A FORCE OF NATURE!

- In 1994, Hilary and I discovered that we were both working with ion mobility spectrometry for use in closed environments. Hilary on submarines and me on spacecraft
- We continued having discussions and following each other's progress throughout the 1990s at the ISIMS conferences, and via occasional visits and discussions
- Hilary told me about SAMAP and I attended my first conference in 2000
- I was at Hilary's house with Mike and a colleague on 9/11/2001, as we had met to discuss a possible submarine trial using the VOA/RME

NASA/Navy Collaboration
1990s

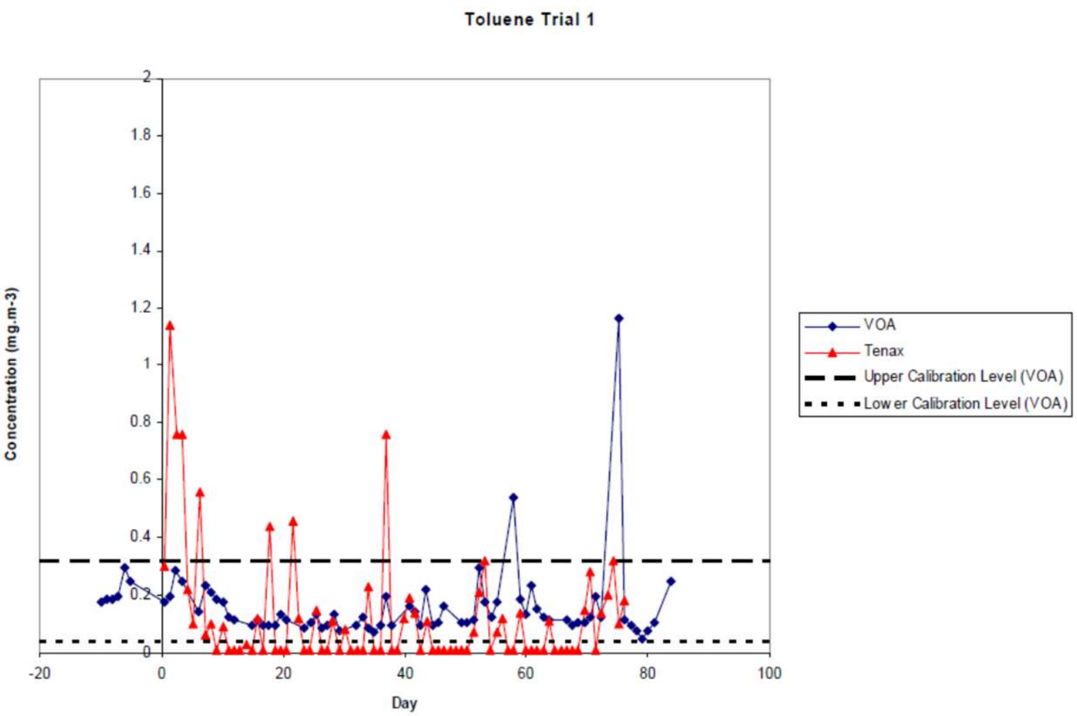
- Getting the VOA/RME to the UK Navy for a sea trial was not straight forward: What you would think it would be

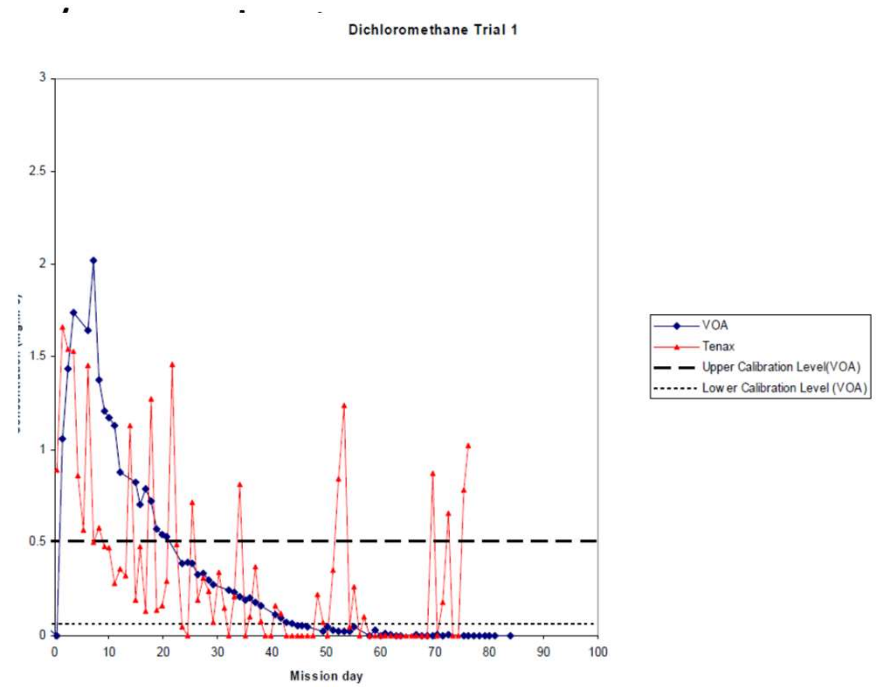
- At the SAMAP meeting in 2000, Dr. Bollan was able to bring together the U.S. Navy, U.K. Navy, and NASA. A process was created to allow the transfer of the VOA/RME to the U.K. Navy for a submarine trial

NASA/Navy Collaboration
2000s: VOA/RME submarine Trials

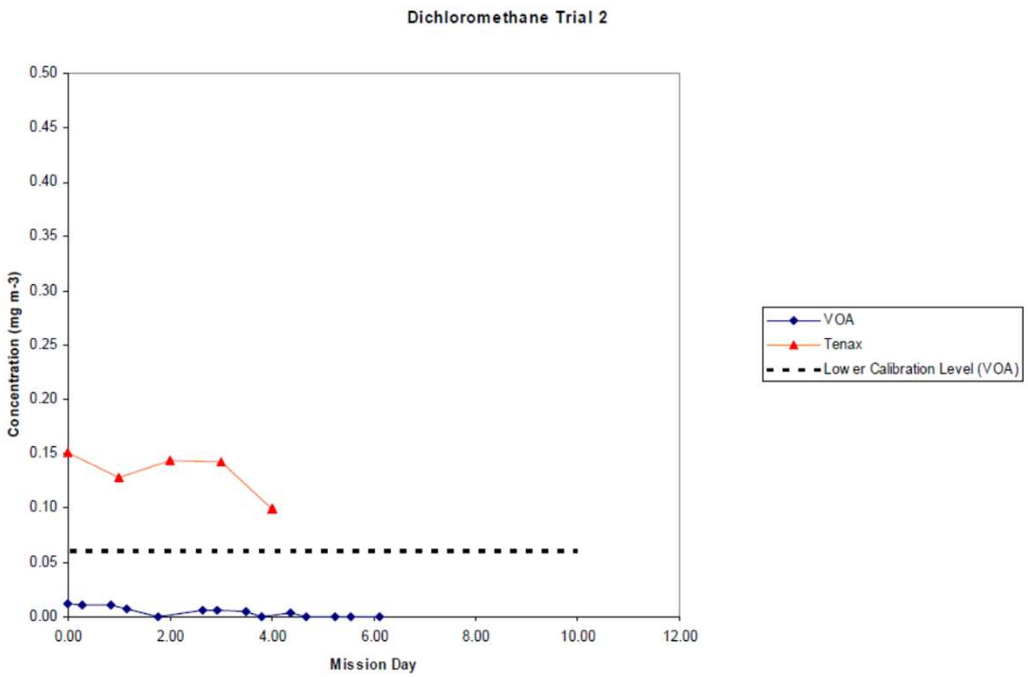
- The installation and first sea trial of the VOA/RME occurred in 2001
- Two objectives of the trial were to learn more about the dynamics of the contaminants in the atmosphere and to assess the data acquired via retrospective samplers
  - The retrospective samplers were glass tubes filled with Tenax that were sealed via torch after the sample was collected.

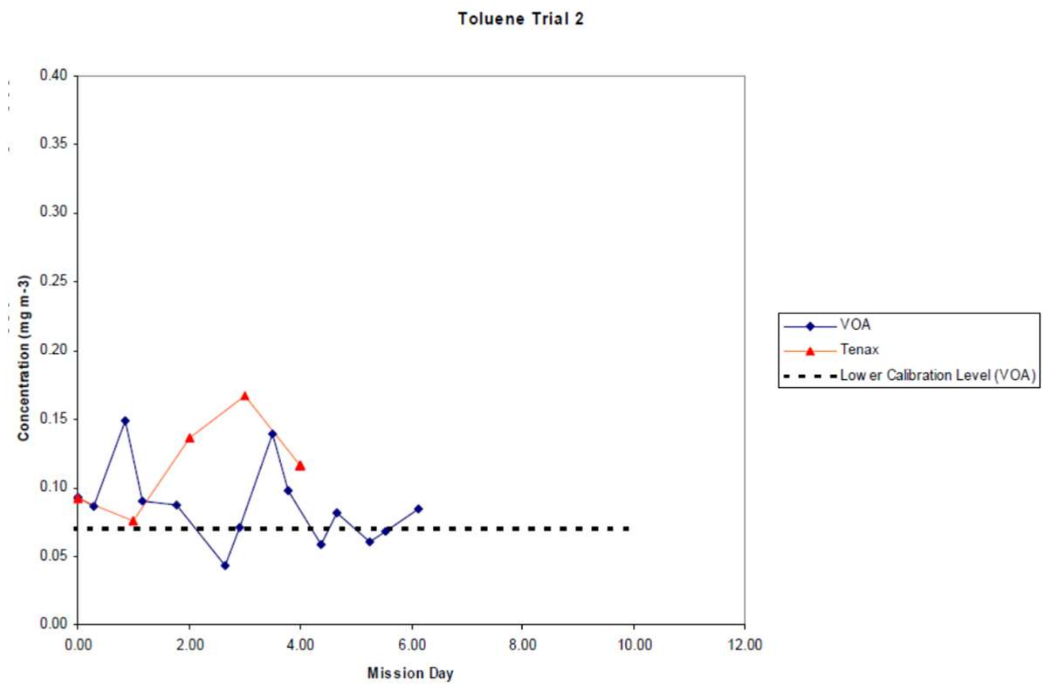
NASA/Navy Collaboration
2000s: VOA/RME submarine Trials





NASA/Navy Collaboration
2000s: VOA/RME submarine Trials

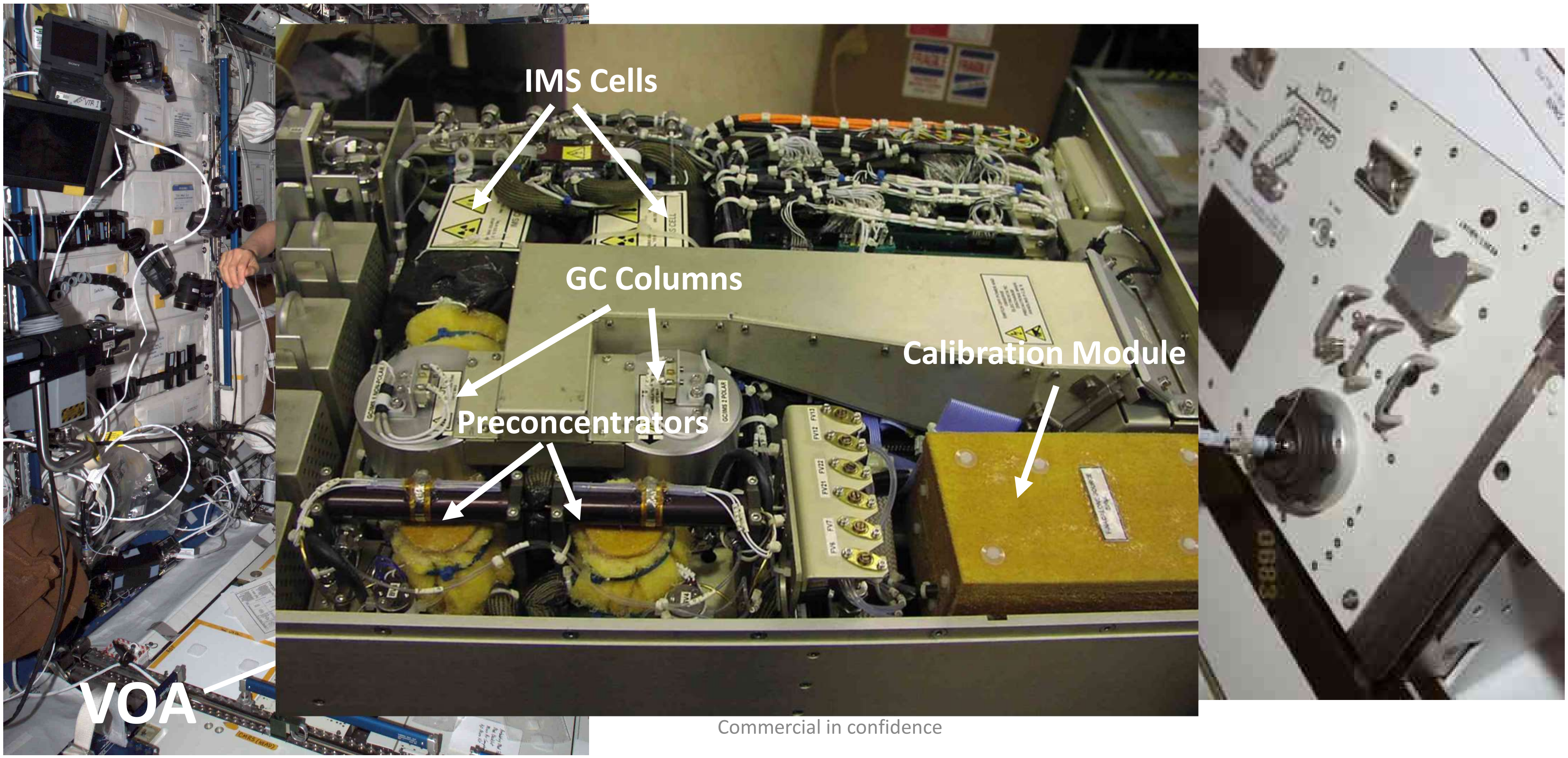




NASA/Navy Collaboration
2000s: VOA/RME submarine Trials

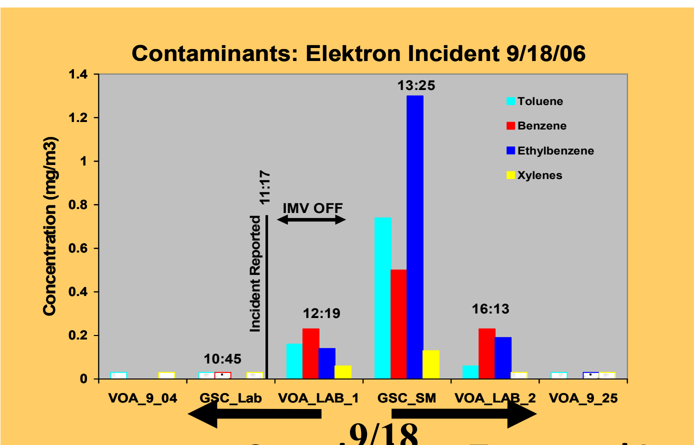
- I believe the VOA/RME is the first instrument to be in space and below the waters of the ocean
- The stainless steel tubes showed more consistent results than the glass sealed tubes
- The levels of ethanol were higher with the VOA/RME, but this is because ethanol is not trapped efficiently on Tenax
- Concentrations of contaminants are not necessarily steady for the entire patrol
- The compounds and their relative concentrations were remarkably similar for submarine and ISS
- Older submarines are no dirtier than newer submarines
- The air contaminant concentrations are well below specified limits
- The air tends to be very clean on submarines and on spacecraft

NASA/Navy Collaboration
2000s: VOA on ISS



NASA/Navy Collaboration
2000s: VOA on ISS

- The VOA had a fuse issue, which was repaired on orbit, an Elektron (oxygen generator) occurred within 6 months of the repair.
- The VOA monitored the concentration of the compounds released, which included ethylbenzene, a non-target compound



Sample date, Type, and Location

NASA/Navy Collaboration 2000s: Carbon Dioxide

- NASA used lithium hydroxide for the CO_2 scrubbing on the Apollo missions and on Shuttle
- Molecular sieve beds plus the Russian scrubber (Vozdukh), are used on ISS to scrub CO_2
- MEA is not used on ISS, although I suspect (not confirmed) that the Russian CO_2 scrubber uses a version of their submarine CO_2 scrubber, replacing the liquid with a solid amine
- NASA is currently testing amine swing beds on orbit
- NASA brought forward some new research on CO_2 that suggested the concentrations in spacecraft and submarines is too high

NASA/Navy Collaboration
2000s: Carbon Dioxide

- Dr. John James provided the following information at the 2013 SAMAP conference
  - Apollo & Shuttle: 7.6 mmHg (10,000 ppm)
  - ISS: 180 day SMAC = 5.3 mmHg
  - Exploration: 1000d SMAC = 3.8 mmHg
  - ISS Chit constraint: 4 mmHg
  - US Submariner & industrial limits = 3.8 mmHg
  - UK Submariner limit = 5.3 mmHg
  - ASHRAE standard for buildings = 0.8 mmHg
- A study by Satish showed a degradation in performance ~1.9 mmHg

NASA/Navy Collaboration 2000s: Carbon Dioxide

- Dr. James' presentation generated much discussion that is still ongoing
  - Do humans adapt to the higher levels of CO_2 and eventually mitigate the effect?
  - After more than 5 years, studies are still continuing and NASA is actively involved in pursuing methods to measure CO_2 in the blood on orbit and to determine where the CO_2 levels begin to effect performance
  - For the present, NASA has lowered the long-term CO_2 limit to an average of 3 mmHg or below over 24 hours

NASA/Navy Collaboration 2000s: Oxygen Generators

- Various types of oxygen generators, generally known as self-contained oxygen generator (SCOG) are used in a variety of military and aerospace applications
  - Submarines
  - Airplanes
  - Spacecraft
- NASA became aware of the potential hazards of SCOG in 1997, when upon activation, a SCOG burned uncontrollably for 10-20 min in the MIR spacecraft before it became exhausted
- Fortunately, there were no injuries or significant damage to the MIR spacecraft
- However, one look at the SCOG shows that it easily have been much worse!

NASA/Navy Collaboration 2000s: Oxygen Generators

- NASA assisted the Russian's investigation into the SCOG failure and determined it was due to contamination

- The HMS Tireless at sea under the Polar ice cap when a crewmember activated a SCOG
- Within a short period of time the SCOG exploded and 2 crewmembers were killed

NASA/Navy Collaboration 2000s: Oxygen Generators

- NASA's White Sands Facility and the NASA Engineering and Safety Center (NESC) offered their expertise to investigate the failure
- It was discovered that the briquette was internally contaminated with liquid oil and this can result in a runaway pressure event
- Furthermore it was postulated that the briquette might have been cracked due to rough handling
- This was an example of shared expertise to improve the safety of both submariners and astronauts

NASA/Navy Collaboration 2010s

- The Toxicology Environmental Chemistry (TEC) laboratories have worked on two major projects in the last 10 years that have crossed over into collaboration with the U.S. and U.K. Navies
  - The Air Quality Monitor (AQM), which was the replacement for the VOA
  - The Multi-Gas Monitor (MGM) and Anomaly Gas Analyzer (AGA) which measure major constituent gases (O2, CO2), combustion products (CO, HCl, HCN, and HF), and others (water, ammonia and hydrazine)
- The AQM (Draper Labs, MA) is based upon a slightly different version of the VOA technology. Think VOA (time of flight MS) and AQM (quadrupole MS)
- The MGM and AGA (Vista-Photonics, NM) use laser and photoacoustic spectrometry
- Both the AQM and MGM have flown on ISS and were used in a submarine sea trial with the U.S. Navy

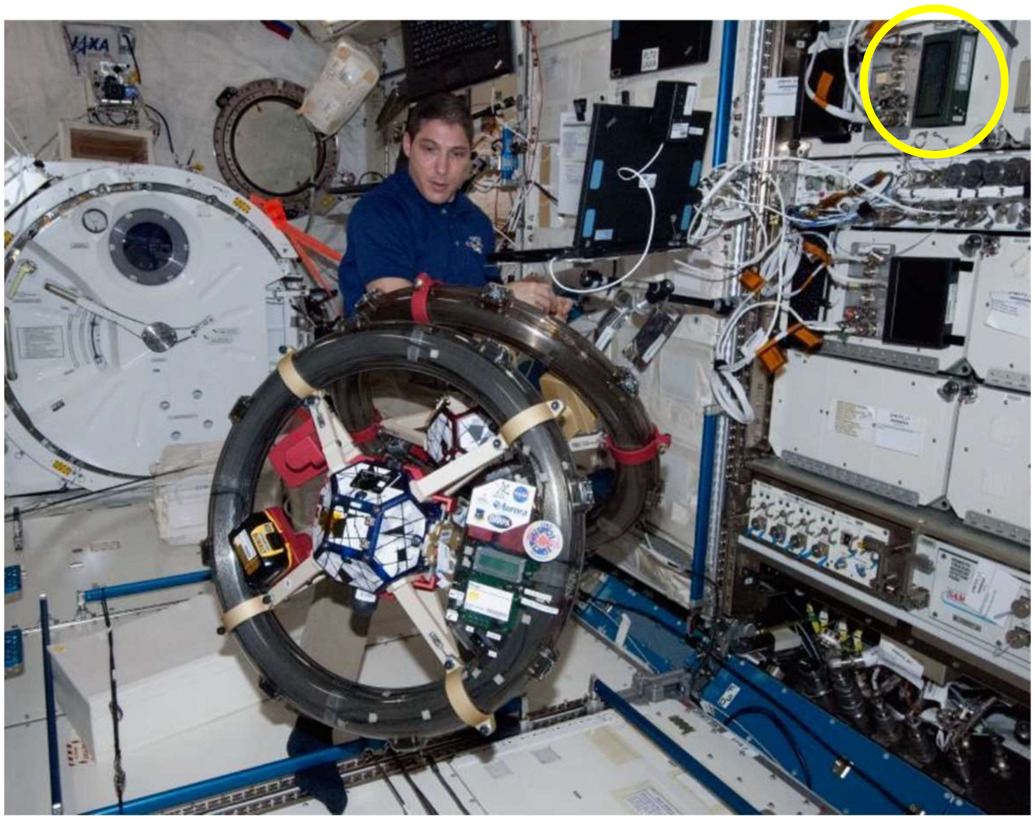
NASA/Navy Collaboration
2010s: AQM Submarine Trial

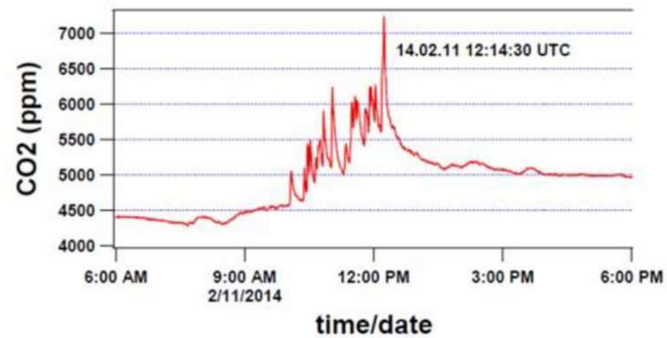
- Discussions of AQM performance on ISS at Technical Interchange Meeting led to development of a plan for AQM (and MGM) trial on a U.S. and/or U.K. submarine
  - SAMAP AND ICES meetings provided a venue for discussions
  - Furthermore, "Subs in Space" meetings in Houston in 2015 and 2017 were important for collaboration discussions between NASA and the UK and US navies
- This trial occurred on a U.S. submarine and was to evaluate the potential of the AQM (Air Quality Monitor) and MGM (Multi-Gas Monitor) to update the U.S. submarine's monitoring suite for a new class of submarine under design
- Although ISS has two AQMs onboard to enhance quantitative accuracy, it was believed that the U.S. Navy's target list could be covered by one unit.
- The slightly polar 624 GC column was selected as it seemed best suited for the target compounds
- The AQM was scripted to collect data every 8 hours and data was stored on the unit
- Five archival GSCs (similar to those used on ISS) and SAHAP badges were also present to take samples during the submarine trial

NASA/Navy Collaboration 2010s: MGM on ISS

- The multi-gas monitor (MGM) launched to ISS as an experiment in November 2013
  - MGM measures 4 gases: oxygen, carbon dioxide, ammonia, and water vapor
  - Four tunable diode lasers measure the four gases every few seconds and records a 30 second rolling average
  - Total power draw is approximately 2.5 watts
  - Once calibrated, accuracy is maintained for years

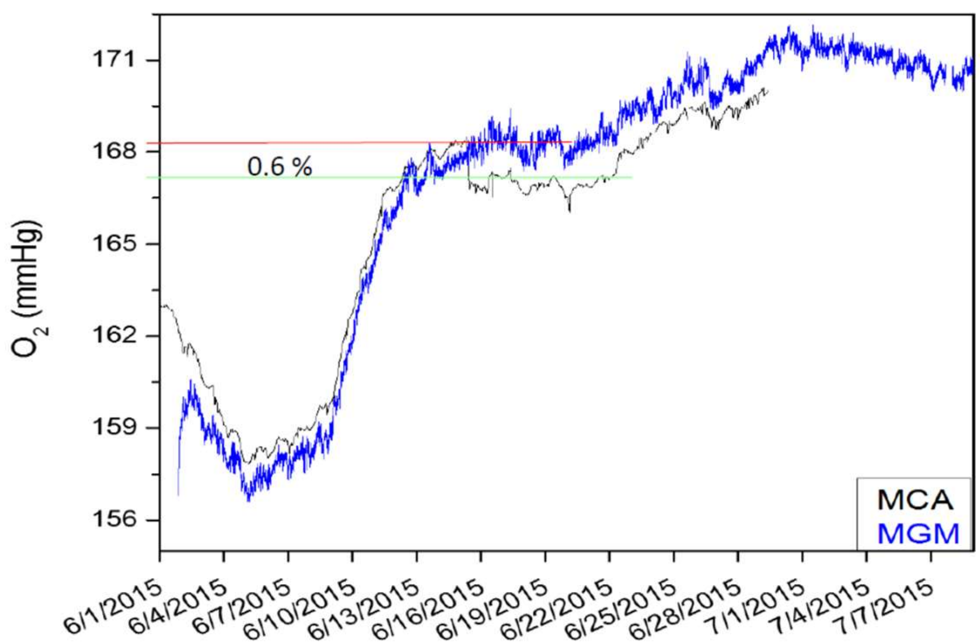
NASA/Navy Collaboration
2010s: MGM Experimental Results on ISS

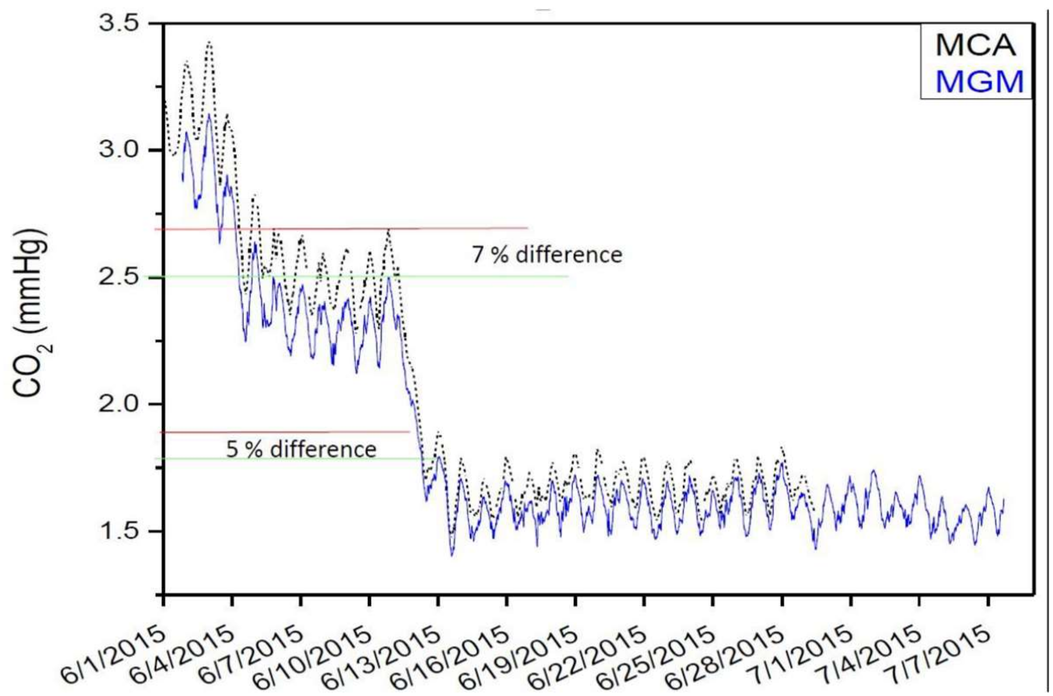




MGM (yellow circle) detecting thruster release from the SPHERES experiment

NASA/Navy Collaboration
2010s: MGM Experimental Results on ISS
Compare MGM data to the onboard MCA data





NASA/Navy Collaboration 2010s: MGM Submarine Trial

- The submarine trial was 76 days in duration
- A slightly different version of the MGM was used for the submarine trial, but the core (i.e., sensors) were the same
- The unit was calibrated and checked in the Toxicology laboratory at JSC prior to deployment
- Once installed the only crew intervention would be if the screen went blank; however that did not happen and no crew intervention was necessary
- In addition to the 4 gases monitored by the other instrument, this one also independently measures pressure, temperature, and water vapor
- When installed on the submarine the CO_2 and water vapor were checked against the CAMS Mark II and compared favorably. The CAMS calibration is checked weekly

NASA/Navy Collaboration
2010s: Results: MGM Submarine Trial

		CAMS	MGM				CAMS	
	Clock	Pressure	Pressure	Pressure	MGM O2		O2	O2
Date	Hour	torr	torr	% Diff	%	torr	torr	% Diff
1-Sep	2	760	756	0.5	20.9	158	161	1.9
1-Sep	9	761	755	0.8	20.9	158	160	1.4
1-Sep	16	759	757	0.3	20.8	157	160	1.6
1-Sep	23	761	756	0.7	20.8	157	159	1.1
4-Sep	0	767	770	0.4	19.5	150	159	5.7
4-Sep	7	762	760	0.3	20.3	154	154	0.2
4-Sep	14	781	759	2.9	20.0	152	162	6.5
4-Sep	21	794	756	4.9	20.4	154	162	4.9
13-Sep	1	773	755	2.4	19.9	150	154	2.5
13-Sep	8	767	767	0.0	19.7	151	151	0.1
13-Sep	15	775	761	1.8	19.8	151	153	1.5
13-Sep	22	758	763	0.7	19.5	149	148	0.5
25-Sep	2	802	791	1.4	20.3	161	165	2.7
25-Sep	9	816	799	2.1	20.4	163	169	3.6
25-Sep	16	791	804	1.6	20.3	163	162	0.7
25-Sep	23	800	782	2.3	20.4	160	164	2.8
4-Oct	3	789	792	0.4	20.8	165	165	0.2
4-Oct	10	796	787	1.1	20.8	164	167	2.0
4-Oct	17	801	793	1.0	20.8	165	168	1.8
14-Oct	1	761	762	0.1	20.9	159	160	0.5
14-Oct	8	766	758	1.0	20.9	158	161	1.6
14-Oct	15	769	764	0.7	21.0	160	162	1.0
14-Oct	22	753	777	3.1	20.8	162	154	4.8
21-Oct	1	796	788	1.0	21.0	165	169	2.1
21-Oct	8	809	797	1.5	21.0	167	170	1.6
21-Oct	15	816	806	1.2	21.0	169	171	1.0
21-Oct	22	820	812	1.0	21.1	171	174	1.5
25-Oct	2	804	796	1.0	21.1	168	169	0.6
25-Oct	9	811	801	1.2	21.1	169	174	2.9
25-Oct	16	822	810	1.5	21.1	171	176	2.9
25-Oct	23	821	814	0.9	21.2	173	174	0.8
3-Nov	3	743	734	1.2	21.0	154	157	1.8
3-Nov	10	751	740	1.5	20.9	155	158	2.1
3-Nov	17	751	759	1.1	20.9	159	158	0.4
16-Nov	5	753	761	1.1	20.9	159	156	1.9
16-Nov	12	761	743	2.4	20.7	154	159	3.3
16-Nov	19	761	756	0.7	20.9	158	160	1.3

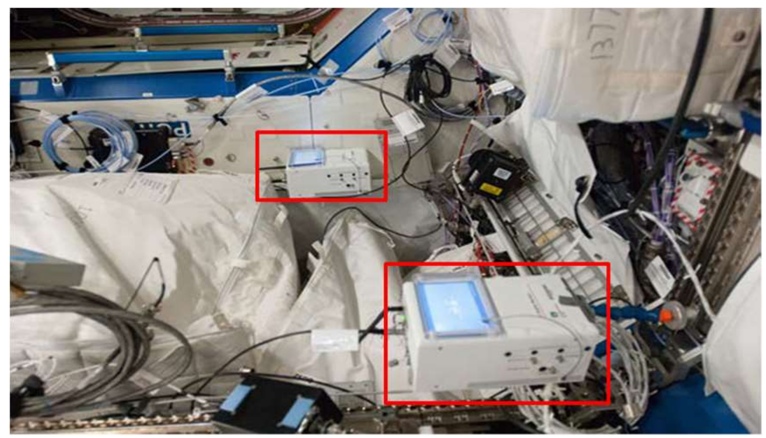
Note: MGM ppO2 values were calculated from % O2 using total pressures recorded by MGM

NASA/Navy Collaboration
2010s: AQM

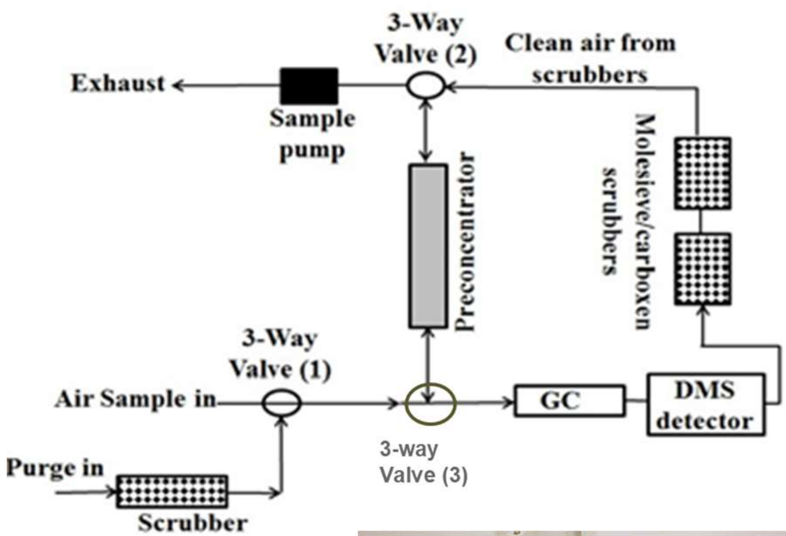
- The first pair of AQMs launched to ISS in early 2013. Two AQMs, each with a different GC column are used to cover all the target compounds

GFE TARGET COMPOUNDS

Target Compounds	Unit 2218	Unit 2221	Target Compounds	Unit 2218	Unit 2221
Methanol	X		Trimethylsilanol		X
Acetaldehyde		X	Benzene	X	
Acrolein	X		n-butanol		X
Ethanol		X	Toluene	X	X
Acetone	X		Hexanal	X	
2-Propanol	X		Hexamethylcyclotrisiloxane	X	x
Dichloromethane		X	m/p-Xylene	X	X
Hexane	X		o-Xylene	X	X
Dichloroethane	X		Octamethylcyclotetrasiloxane	X	X
2-Butanone (MEK)		X	Decamethylcyclopentasiloxane	X	X
Ethyl Acetate		X	Ammonia		X



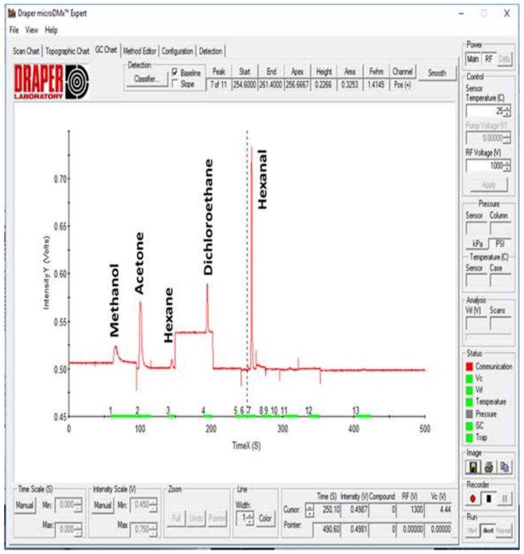
NASA/Navy Collaboration 2010s: AQM

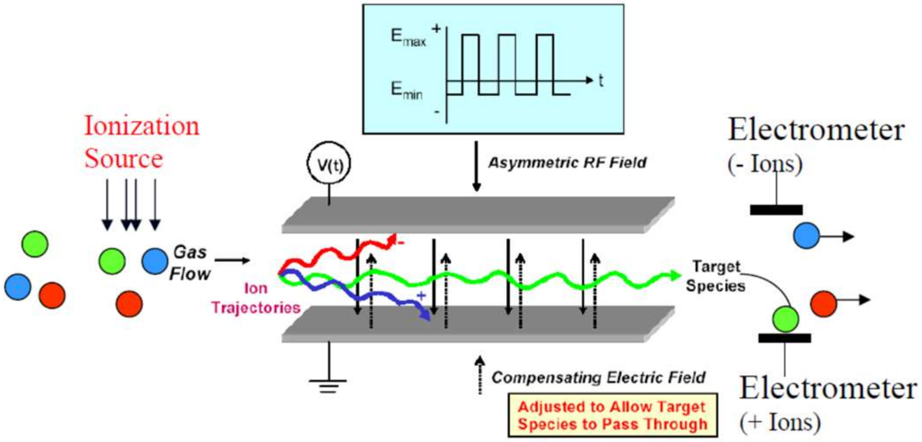


- Each AQM is approximately shoe-box size
- Once calibrated, they remain accurate for a minimum of 3 years
- Although similar to the VOA technology, the AQM uses differential mobility spectrometry (DMS). DMS actually favors detection of smaller molecules (<400 amu)
- The AQM is portable and can run on batteries (VOA was fixed position)
- The AQMs are scripted to run every 73 hours
- Data is saved to an onboard computer then transferred via wireless connection to the ISS server. The data is downlinked to the ground once per week.
- The AQM can be controlled from the ground via remote desktop

Replaceable sieve packs are the only maintenance required (~ 6 months)

NASA/Navy Collaboration 2010s: AQM Operation





Draper Labs, microAnalyzer V2.0 Series Product Family Manual

NASA/Navy Collaboration 2010s: AQM On-Orbit Results

Unit 2214 (AQM1)	3-Jan	GSC_Jan3	%Diff_Jan3	14-Feb	GSC_Feb14	%Diff_Feb14	3-Apr	GSC_Apr3	%Diff_Apr3	8-May	GSC_May8	%Diff_May8
Methanol	0.29	0.36	19	0.31	0.34	9	0.29	0.39	26	0.29	0.35	17
Acetone	0.36	0.33	-9	0.28	0.31	10	0.34	0.32	-6	0.38	0.31	-23
Hexane	ND	ND	ND-ND	ND	ND	ND-ND	ND	ND	ND-ND	ND	ND	ND-ND
2_Propanol	0.16	0.17	6	0.35	0.38	8	0.20	0.17	-18	0.15	0.15	0
Dichloroethane	ND	ND	ND-ND	ND	ND	ND-ND	ND	ND	ND-ND	ND	ND	ND-ND
Toluene												
Hexanal	ND	ND	ND-ND	ND	ND	ND-ND	ND	ND	ND-ND	ND	ND	ND-ND
mp- Xylene												
o-Xylene												
Acrolein	ND	ND	ND-ND	ND	ND	ND-ND	ND	ND	ND-ND	ND	ND	ND-ND
Benzene	ND	ND	ND-ND	ND	ND	ND-ND	ND	ND	ND-ND	ND	ND	ND-ND
Octamethylcyclotetrasiloxane												
Decamethylcyclopentasiloxane												
Hexamethylcyclotrisiloxane												
Unit 2225 (AQM2)												
Acetaldehyde	0.11	0.26	58	0.12	0.22	45	0.13	0.24	46	0.10	0.28	64
Ethanol	3.40	5.70	40	2.57	3.10	17	3.88	5.60	31	4.00	6.60	39
Dichloromethane	ND	ND	ND-ND	ND	ND	ND-ND	ND	ND	ND-ND	ND	ND	ND-ND
TMS	0.18	0.18	0	0.14	0.13	-8	0.16	0.16	0	0.17	0.14	-21
2-Butanone	ND	ND	ND-ND	ND	ND	ND-ND	ND	ND	ND-ND	ND	Trace	ND-ND
Ethyl Acetate	Trace	Trace	Trace-Trace	ND	ND	ND-ND	0.06	0.037	MATCH	0.060	0.028	MATCH
n_Butanol	0.09	0.09	-3	0.07	0.08	9	0.08	0.067	-19	0.090	0.065	-38
Toluene	ND	ND	ND-ND	ND	ND	ND-ND	Trace	ND	Trace-ND	0.03	Trace	MATCH
mp- Xylene	ND	ND	ND-ND	ND	ND	ND-ND	ND	ND	ND-ND	ND	ND	ND-ND
o-Xylene	Trace	ND	Trace-ND	Trace	ND	Trace-ND	0.03	ND	MATCH	Trace	ND	Trace-ND
Octamethylcyclotetrasiloxane	Trace	ND	Trace-ND	Trace	ND	Trace-ND	Trace	ND	Trace-ND	Trace	ND	Trace-ND
Decamethylcyclopentasiloxane	0.19	0.29	34	0.16	0.18	11	0.17	0.18	6	0.20	0.24	17
Hexamethylcyclotrisiloxane	0.08	0.25	68	0.05	0.27	81	0.07	0.06	-17	0.08	0.17	53

Unit 2214 (AQM1)	Matches/#GSCs 2016-2017 (Aug)
Methanol	12/14
Acetone	14/14
Hexane	14/14
2_Propanol	14/14
Dichloroethane	14/14
Toluene	
Hexanal	14/14
mp- Xylene	
o-Xylene	
Acrolein	14/14
Benzene	14/14
Octamethylcyclotetrasiloxane	
Decamethylcyclopentasiloxane	
Hexamethylcyclotrisiloxane	
Unit 2225 (AQM2)	11/17
Acetaldehyde	9/17
Ethanol	15/15
Dichloromethane	15/15
TMS	15/15
2-Butanone	15/15
Ethyl Acetate	15/15
n_Butanol	15/15
Toluene	15/15
mp- Xylene	15/15
o-Xylene	15/15
Octamethylcyclotetrasiloxane	15/15
Decamethylcyclopentasiloxane	15/15
Hexamethylcyclotrisiloxane	12/15

NASA/Navy Collaboration
2010s: AQM Submarine Trial

- Although most target compounds for the submarine trial were the same as ISS target compounds, two compounds (ethylbenzene and trimethylbenzene) were unique to this trial. The AQMs were calibrated for these compounds as well as the other target compounds.
- The AQM was installed in the main fan room, the source of all shipboard air, which should make it representative of the air within the submarine.

Methanol	Hexamethylcyclotrisiloxane
Acetone	Octamethylcyclotetrasiloxane
Hexane	Trimethylbenzene
Dichloroethane	Decamethylcyclopentasiloxane
Toluene	Acrolein
Hexanal	2-Propanol
Ethylbenzene	Benzene
m/p Xylenes	Acetaldehyde
o Xylene	Ethanol

- **On the left, the AQM is shown in its location in the fan room**
- **On the right is the AQM target list for the submarine trial**

NASA/Navy Collaboration 2010s: AQM Submarine Trial

Results: GSC and AQM Comparison Concentrations (mg/m^3)

TARGET COMPOUNDS	Main Fan Room GSC at Installation	AQM-Auto	Main Fan Room GSC at ~6 weeks	AQM-Auto	Main Fan Room GSC at ~10 weeks	AQM-Auto	Main Fan Room GSC at ~14 weeks	AQM-Auto	Main Fan Room GSC: 28 Hours After pulling in	AQM-Auto
Methanol	TRACE	<0.09	0.10	<0.09	0.080	**<0.09**	0.093	**<0.09**	TRACE	**<0.09**
Acetaldehyde	0.056	ND	0.44	0.10	0.65	**0.10**	0.45	**<0.08**	0.087	**<0.08**
Ethanol	0.13	0.13	2.1	**0.98**	3.4	**1.17**	6.1	**0.50**	0.37	**0.16**
Propenal (Acrolein)	<0.025	ND	<0.025	**0.02**	TRACE	**0.02**	TRACE	ND	<0.025	**0.02**
Acetone	0.31	0.30	0.38	0.50	0.51	0.56	0.61	0.55	0.12	0.20
2-Propanol (Isopropanol)	0.25	0.28	TRACE	**Trace**	0.051	**Trace**	0.57	**0.13**	TRACE	**Trace**
DCM	<0.025	ND	<0.025	ND	<0.025	ND	<0.025	Trace	<0.025	ND
DCE	<0.025	ND	<0.025	ND	<0.025	Trace	<0.025	Trace	<0.025	ND
Hexane	<0.025	ND	TRACE	ND	0.028	ND	0.048	0.057	<0.025	ND
Benzene	<0.025	ND	TRACE	ND	TRACE	ND	TRACE	ND	<0.025	ND

Match when using ISS criteria
No match when using ISS criteria
Manual analysis

Match: ND/Trace, ±0.05<0.1mg/m^3, ±50 >0.1<0.5mg/m^3, ±40 >0.5mg/m^3

NASA/Navy Collaboration 2010s: AQM Submarine Trial

- The AQM successfully completed the submarine trial
- While not perfect, the data matched reasonably well with the GSCs
  - A new scrubbing material (LiOH) was used in the sieve packs in place of Carboxen to help mitigate some effects from CO_2 that were observed on ISS.
  - Although the testing in lab showed good results, it was clear during the trial there was a contaminant from the LiOH that reduced sensitivity to some compounds.
- It was difficult to compare SAHAP badge results to AQM and GSC data as the SAHAP badges collect a sample over 30 days; whereas AQM and GSC is at a specific point in time

NASA/Navy Collaboration
FUTURE WORK

- Discussions have occurred with the U.S. and U.K Navies about another trial with both the MGM (or possibly the AGA) and the AQM
- The AGA would provide tremendous capability in a small footprint

- The AGA uses the same technology as MGM, but measures more gases. AGA engineering units have been tested and flight units will be ready for launch in late 2020 or early 2021
- In addition to the four gases mentioned above, the AGA also measures combustion products: carbon monoxide, hydrogen chloride, hydrogen fluoride, and hydrogen cyanide. It also targets hydrazine
    - Photoacoustic spectrometry is used for detection of carbon monoxide, hydrogen cyanide, and hydrazine
- This instrument is designed for ISS (replacing several other instruments) and for Orion

Parameter	Measurement Range	Accuracy	Accuracy	Accuracy
Pressure	9.5-15.6 psia	±0.1psia		
Oxygen	14-50%	±1% (absolute) ≤26%	±2% (absolute) >26%	
Carbon Dioxide	0.3-21 mmHg	±10% ≥ 0.8 mmHg	±0.2 < 0.8 mmHg	
Carbon Monoxide	5-1000 ppm	±10% ≥ 5 ppm	±5 ppm < 55 ppm	
Hydrogen Cyanide	2-50 ppm	±25% ≥ 55 ppm	±1 ppm < 5 ppm	
Hydrogen Fluoride	2-50 ppm	±25% ≥ 55 ppm	±1 ppm < 5 ppm	
Hydrogen Chloride	2-50 ppm	±25% ≥ 55 ppm	±1 ppm < 5 ppm	
Ammonia	10-30,000 ppm	±25% ≥ 150 ppm	±10% 20-150 ppm	±20% <20 ppm
Hydrazine	2-10 ppm	±2 ppm		

NASA/Navy Collaboration
FUTURE WORK

- The AQM in the new trial would use scrubbing material in the sieve packs that is identical to that used on ISS
- In the future other collaborations should occur as new technologies are developed in both monitoring and scrubbing systems
- Join investigations of anomalous events will continue in the future
- It is expected that there will also continue to be close work when considering contaminant limits on spacecraft and submarines

NASA/Navy Collaboration

- Stay tuned: there is talk of subs in space to explore planetary moons!!!!