Sensing Needs
for
Advanced Crew and Environmental Monitoring
and
Associated Materials Considerations
for
Space Exploration Missions

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The Prospect of Human Space Flight (1/2)

- In order for humans to safely explore space across great distances and for extended durations, there is still much work to be done, and *Bioastronautics* – the study of man in space – is *the* critical path to space exploration success
  - NASA's *Bioastronautics Roadmap* (*BR*) has identified 45 key risks associated with human space exploration, and there are many risks associated with a manned mission to Mars that have been assessed as "high"
  - These risks are as diverse as bone demineralization, radiation-induced carcinoma, immunodeficiency, and reliability of Environmental Control and Life Support (ECLS) systems, including Trace Contamination (TC) detection and mitigation

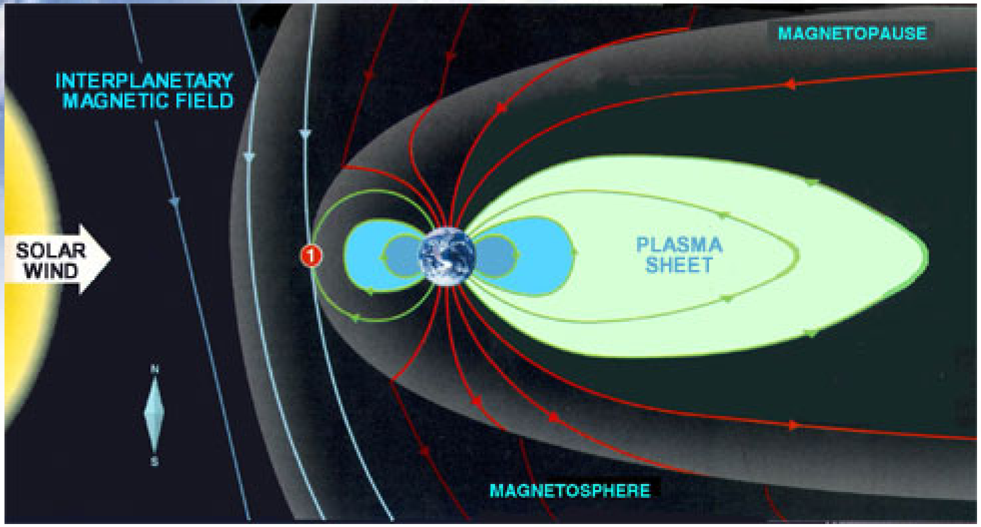
The Prospect of Human Space Flight (2 / 2)

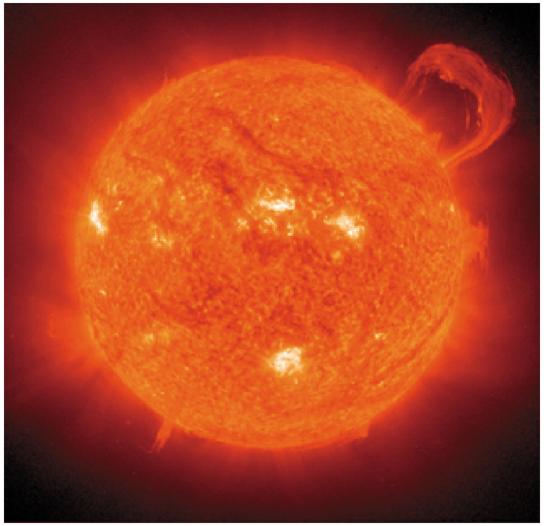
- **Experience on the International Space Station (ISS) certainly supports the assessment of these risks**
  - **Though various hardware failures and crew health issues through the years have been rectified, the solutions would not have been possible without close proximity to Earth**
  - **As ex-astronaut Bonnie Dunbar has said, "There are no Home Depots in space"**
  - **One might add, "There are no Kelsey Seybolds in space"**
- ***Sufficiently mitigating these critical risks is a matter of life and death***

The Critical Nature of Materials Selection

- **Materials selection will play a critical role in mitigating the *BR* risks**
- **Among key desired materials characteristics:**
  - ***Radiation shielding***
  - ***Mechanical properties, e.g. strength, modulus and dimensional stability, MMOD mitigation***
  - ***Lightweight***
  - ***Low toxic off-gassing***
  - ***Flame retardancy and reduced smoke emissions***
  - ***Chemical resistance***
  - ***Decreased permeability to gases, water and hydrocarbons***
  - ***Thermal stability***
  - ***Multifunctional***

Materials: A Radiation Mitigation Perspective (1/3)





"It is well known that the primary sources of radiation exposure in space are Galactic Cosmic Rays (GCRs) and Solar Particle Events (SPEs). However, due to a number of independent variables associated with these sources, there is uncertainty about the total shielding required for long-duration missions. *Research is needed to confidently predict the shielding capabilities of various materials and spacecraft components* along with corresponding research to understand crew exposure limits. *Most hydrocarbon-based composites have value as radiation shielding, thus many materials (e.g., ones developed for lightweight structures) may also be useful for radiation protection.*"

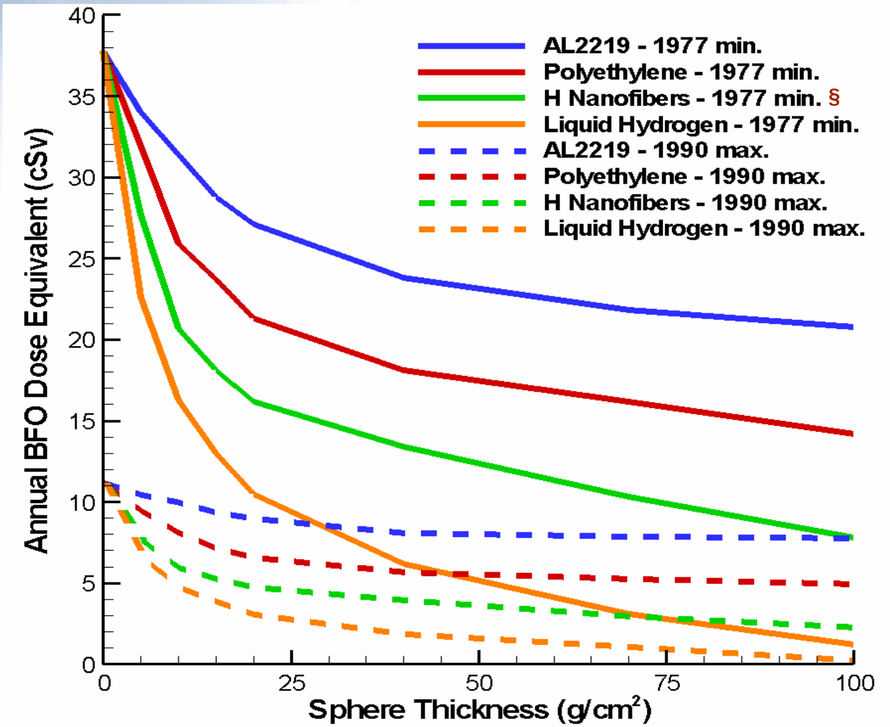
—— NASA's Exploration Systems Architecture Study – Final Report, NASA TM-2005-214062, p. 629, November 2005 (aka ESAS Report)

Materials: A Radiation Mitigation Perspective (2/3)

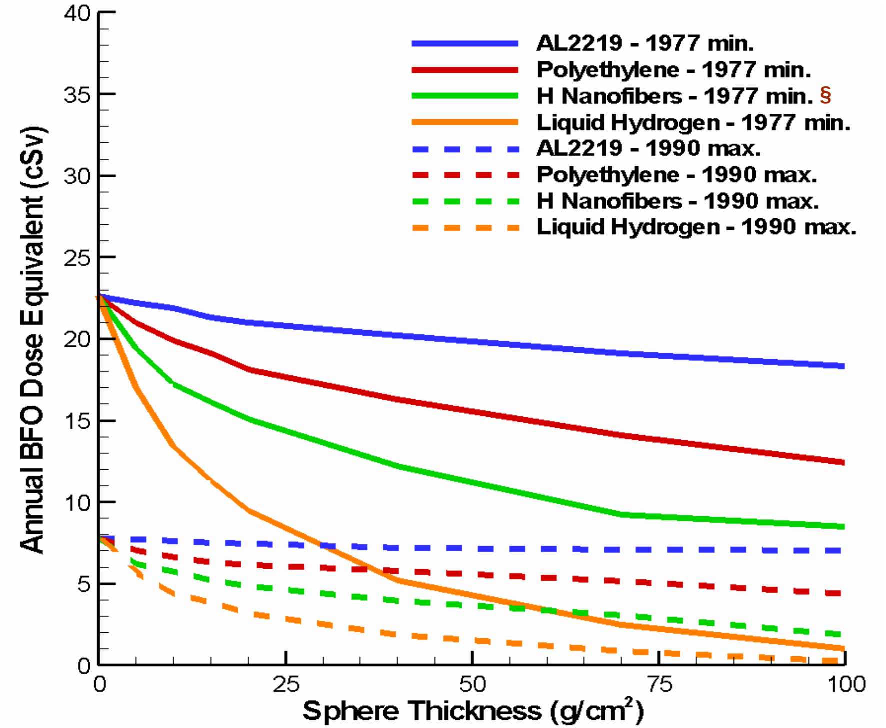
- Desired characteristics specific to radiation mitigation:
  - *High hydrogen content*
  - *Minimal secondary particle production, especially neutrons*
- Suitable materials:
  - *Aluminum (baseline reference material)*
  - *High-density polyethylene (HDPE)*
  - *Boron- and lithium-doped polymers*
  - *"Graded-Z" materials*
  - *Lithium hydride*
  - *Nanomaterials*
- HDPE is currently being used to line Russian Segment (RS) sleep quarters to mitigate radiation exposure

Materials: A Radiation Mitigation Perspective (3 / 3)

Annual Lunar Surface GCR BFO* Exposures



Annual Martian Surface BFO* Exposures



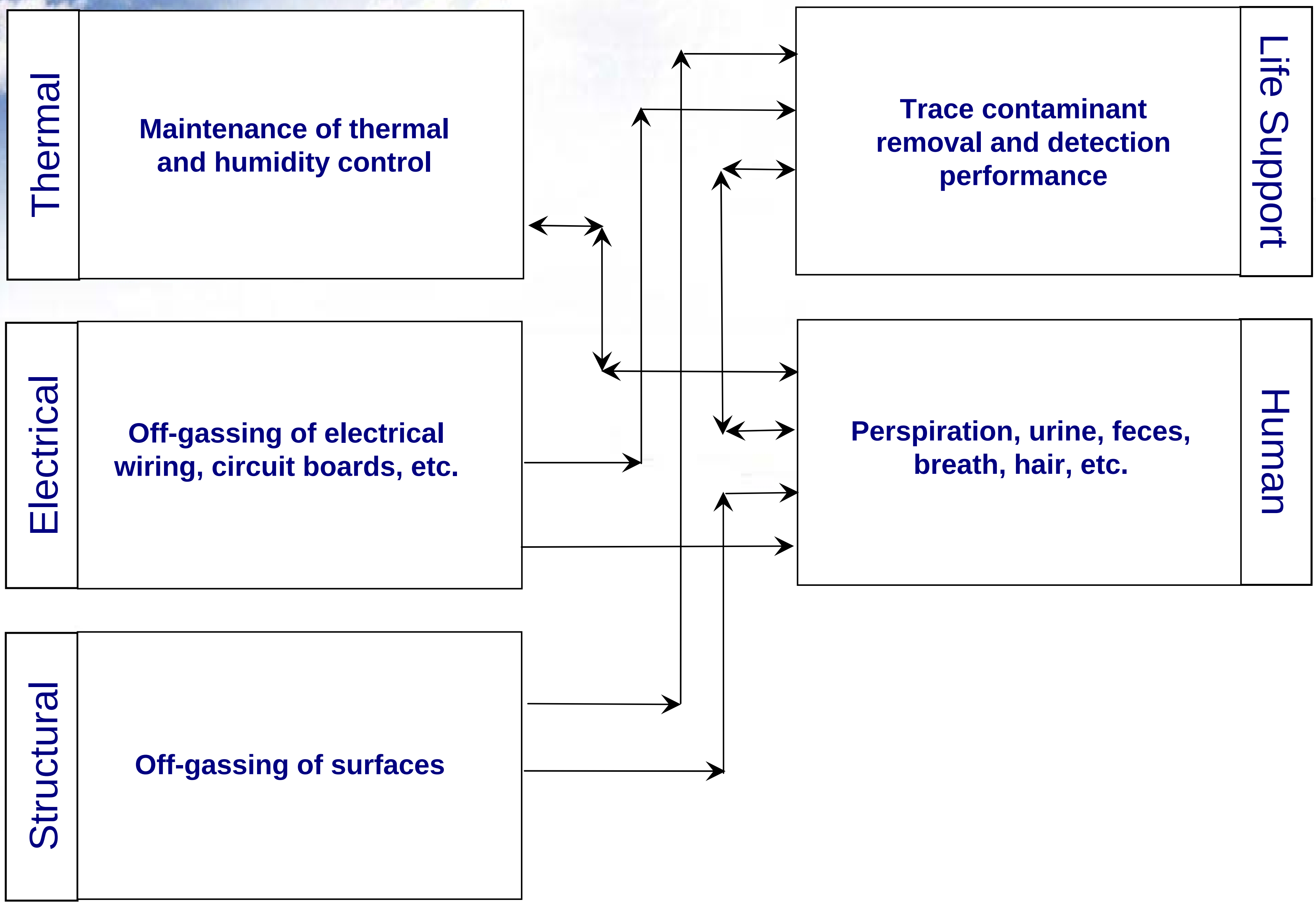
** BFO – Blood-Forming Organs*

§ Hydrogenated Graphite NanoFiber (HGNF) performance (upon which this data is based) has not yet been duplicated

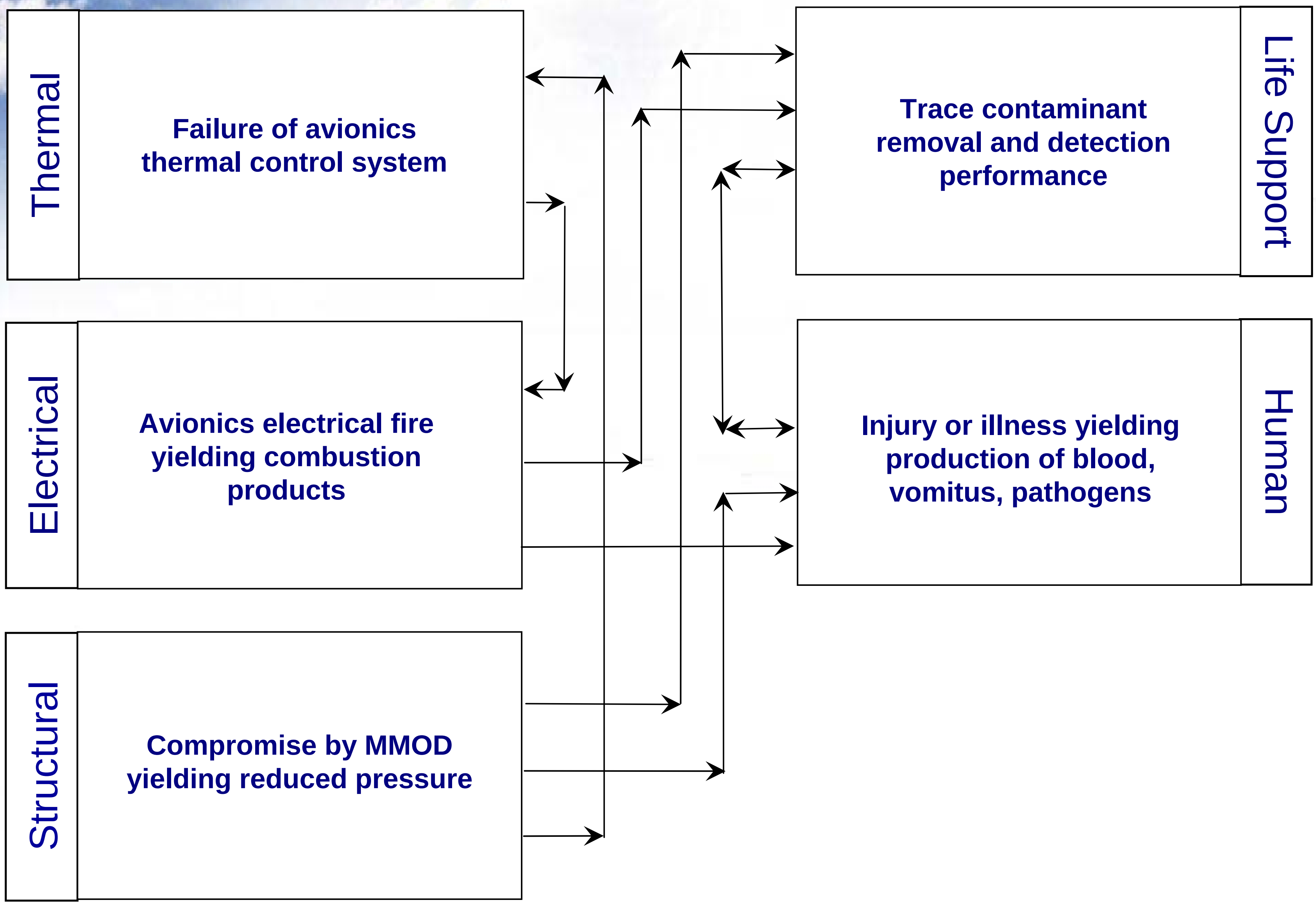
Materials: An Advanced Life Support Perspective

- **Desired characteristics specific to Advanced Life Support (ALS) – Trace Contaminant (TC) control:**
  - ***Low toxic off-gassing***
  - ***Flame retardancy and reduced smoke emissions***
  - ***Chemical resistance***
  - ***Decreased permeability to gases, water and hydrocarbons***
- **TCs are generated from various sources, e.g.,**
  - ***Materials off-gassing***
    - ***Structural***
    - ***Electrical wiring and electronics***
  - ***Compromise of reactant enclosures***
  - ***Combustion events***
  - ***Human metabolism and pathology***
- **TC detection, control and analysis is very tenuous for long-duration space flight**

Interaction of Systems : Nominal / Chronic



Interaction of Systems : Emergency / Acute



Recent ISS Life Support Anomalies

- **ECLS system performance is currently very tenuous for long-duration space flight**
- **A selection of recent ISS Failures:**
  - **Repeated CO_2 Removal System (CRS) (CDRA (CO_2 Removal Assembly) and Vozdukh) failures caused by Zeolite dust**
    - ***The causes of CDRA failures were not discovered until the unit was returned to Earth***
    - ***Zeolite CO_2 adsorption is a decades-old technology***
    - ***Newly-designed CDRA bed delivered, problems continue***
  - **Continued Elektron failures have threatened to place ISS at critical O_2 reserves**
  - **Major Constituent Analyzer (MCA) failure threatened abandonment of ISS**
  - **Volatile Organic Analyzer (VOA) failure**
  - ***For extended periods there has been no real-time trace contaminant visibility at all***

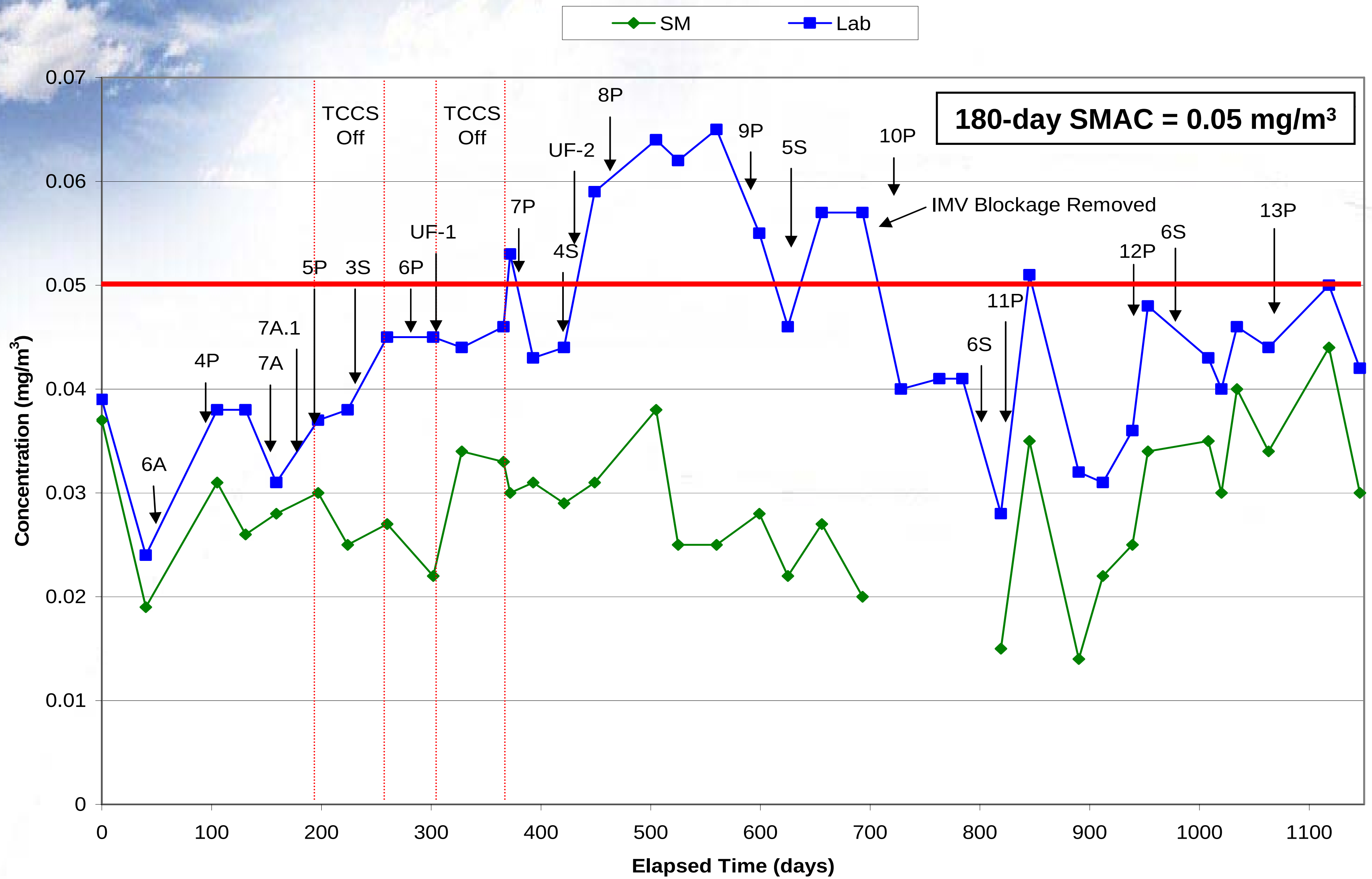
ISS Trace Contamination Control & Detection (1/2)

- **Hundreds of molecular species that are the result of ISS off-gassing, human metabolism, etc. are considered to be potentially harmful to the crew if allowed to accumulate**
- **The ISS TC Control System (TCCS) as well as Condensing Heat Exchangers (CHX) provide TC control**
- **As noted, TC detection is inconsistent and often non-existent in ISS**
  - ***Aside from major constituents, the Major Constituent Analyzer (MCA) tracks CH_4 and H_2, but output not considered at all reliable for these molecules***
  - ***The RS equivalent analyzer (ΓA) tracks CO, but less is known about RS equipment performance***
  - ***MCA and VOA have both failed***
- ***No real-time continuous biological detection in ISS***

ISS Trace Contamination Control & Detection (2/2)

- For example, one of the most problematic TCs has been formaldehyde (H2CO)
  - It is off-gassed from a variety of sources, as well as produced metabolically
  - It is among the most toxic TCs
  - Ground-based material screening methods are very limited in their sensitivity
  - For long duration missions, source accumulation contributes to generation rate growth that eventually overloads active controls
  - The technology for real-time monitoring below the 180-day SMAC (0.05 mg/m3 – ppb range) is not currently available (rather, flight proven?)
  - For nine months H2CO concentration (indicated from returned air samples) was above the 180-day SMAC, and as high as 0.065 mg/m^3 (30% above SMAC)

Formaldehyde Concentrations on US and RSS



From J. L. Perry, *Formaldehyde Concentration Dynamics of the International Space Station Cabin Atmosphere*, August 2004.

Ambiguity Regarding Crew Symptoms (1 / 2)

- **Sample analyses typically suggest all tracked TC species below 180-day SMACs (with the exception of H2CO)**
- **However, ISS crew has reported a preference for operating both CDRA and Vozdukh during crew exchange**
  - ***Crew notes a significant increase in "mental clarity"***
  - ***Increase in CRS performance accomplishes two things:***
    - ***Reduces CO_2 concentration (from 5 to 3 mm Hg)***
    - ***Increased filtration with both CRS systems operating reduces TC concentration***
  - ***US and Russian toxicology experts have not suggested any synergetic effects of CO_2 with total non-methane Volatile Organic Carbons (VOCs), humidity, or temperature***

Ambiguity Regarding Crew Symptoms (2/2)

- Flight surgeons have that stated ground tests typically indicate at least one crewmember (CM) per flight will have sensitivity to CO_2 at concentrations > 3 mm Hg (this is far below the SMAC!)
- But this doesn't explain why that, according to crew reports, *the entire crew* feels a "significant increase in mental clarity" when both CRSs are operating
- If all species are below their SMACs, then why does the crew report increased well-being at (*perhaps*) lower levels of concentration?
  - Due to microgravity effects (SMACs developed in 1-g)?
    - Concentrations are diffusion-driven
    - Differences in absorption or reaction at the cellular level
  - *Rate of increase* of CO_2 is also a significant factor
- More accurate sensing and improved analysis: <u>a necessity</u>
- ***No consensus explanation for this phenomenon***

Communication Breakdown

- **The real-time Crewmember–Flight Surgeon–EECOM–Engineering communication path is virtually non-existent**
  - **Crew sickness during STS-96 (ISS 2A.1) – critical reporting to engineering was delayed until post-mission – *TC? CO_2? Humidity? All of the above?***
  - **Similar lack of real-time reporting of crew symptoms during recent Orbiter missions to ISS**
  - **Recently an EECOM flight note stated that "Crewmember misconfigured EVA tool because of CO_2 symptoms" – *jumping to conclusions?***
  - **Very recently (STS-121 (ISS ULF1.1)) reports of crew headaches also delayed**
- **Even in ground tests, e.g., headaches during testing in (old) Weightless Environment Training Facility (WETF) unreported**
- ***This communication gap only adds to the problems of low detection performance and consequent incomplete analysis***

The Future of Manned Space Exploration?

- ***The canary effect – adverse health conditions perceived by the crewmember – is often the first line of defense***

- ***This is positively unacceptable for long-term, long-range space exploration***

- **Without proper diagnosis:**
  - ***There can be no real-time treatment***
  - ***There can be no design response***

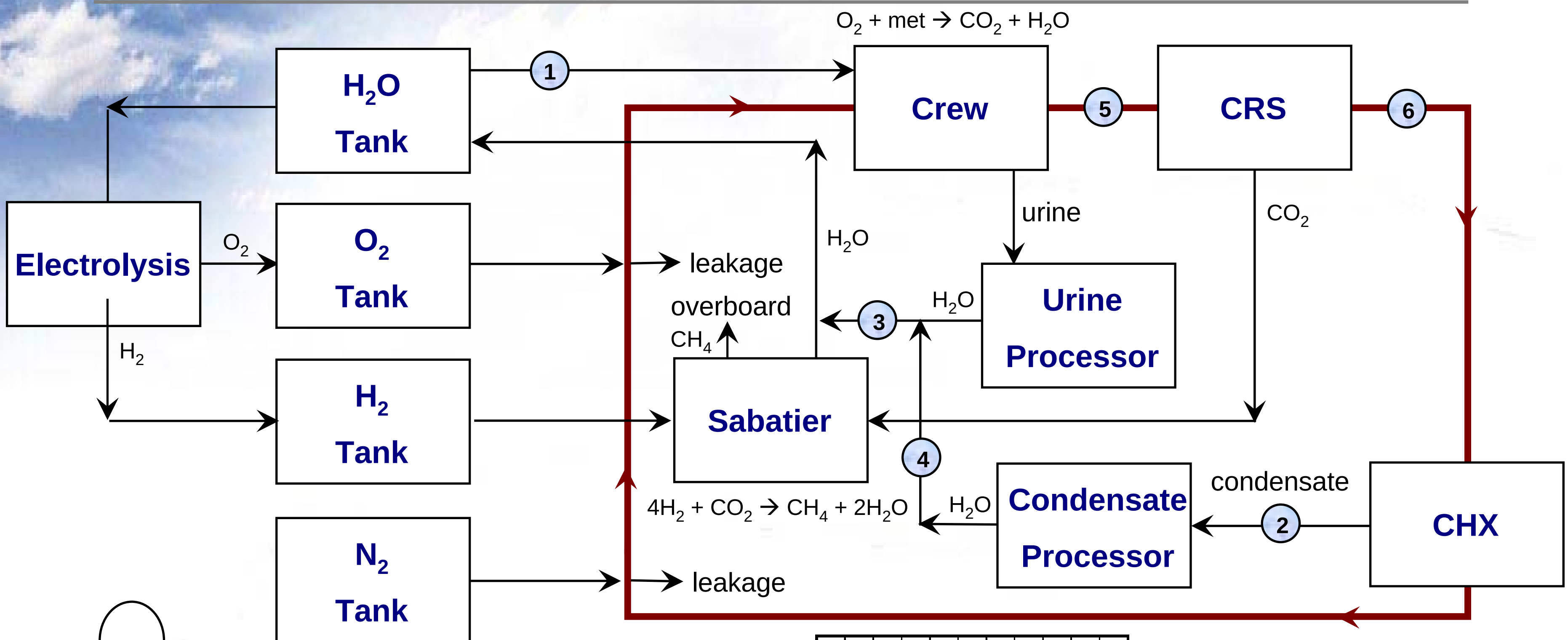
The Necessity of Diagnostic Data

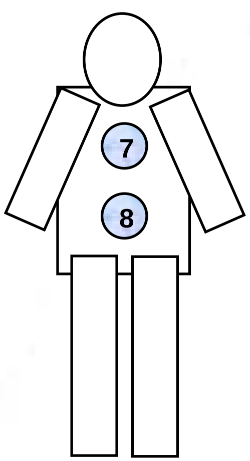
- **A comprehensive and coordinated collection of data is required for accurate diagnosis, prognosis and treatment**
  - **Stimulus perceived by the human (“canary effect”) is a valuable diagnostic tool, but advanced sensing devices are needed to detect the presence of chronic or acute illness before subject-reported symptoms:**
    - **Increased concentration of trace contaminants or their by-products when absorbed by the human system**
    - **DNA structure anomalies for early detection of radiation-induced carcinoma**
    - **Early presence of pathogens and antigens**
- ***A superior integrated sensing web and diagnostic capability is required to yield safe long-range manned space exploration***

Life Science Sensor Requirements

- **Among the critical requirements expressed by NASA Space Life Sciences for sensors that will facilitate this diagnostic capability:**
  - *Non-invasive*
  - *Portable*
  - *Low mass & volume*
  - *High accuracy*
  - *Rugged and reliable*
  - *Adaptive and intelligent*
  - *Easy to calibrate*
  - *Multifunctional*
- **Cutting-edge technologies will be required to acquire critical information in various *in situ* settings**
  - *Multifunctional lab-on-chip technologies*
  - *Enabled by microfluidics and nanotechnology*

Advanced Life Support Sensor Web





(X) Sensor

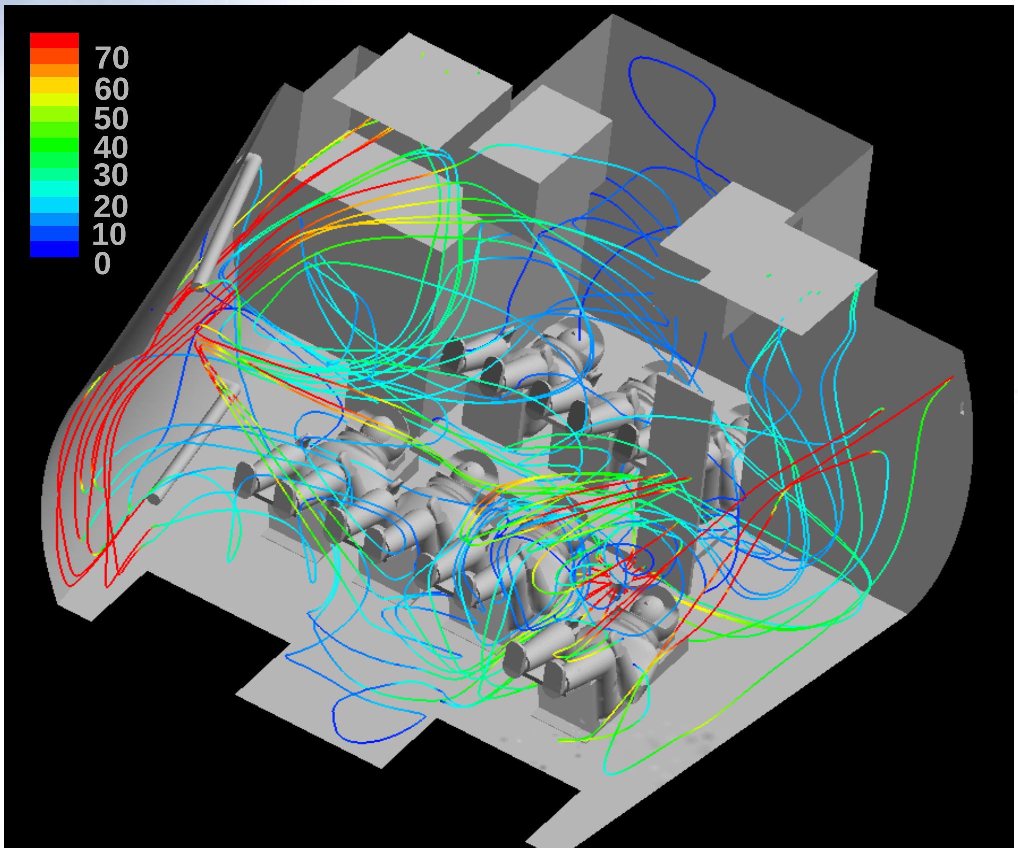
		ph	Mineral Analysis	Pathogens	Trace Contaminants	CO2 Concentration	O2 Concentration	H2O Concentration	Radiation Dosimetry	DNA	Toxicology	Biochemistry
1	Water Tank	x	x	x	x							
2	Condensing HX Condensate	x	x	x	x							
3	Urine Processor Effluent	x	x	x	x							
4	Condensate Processor Effluent	x	x	x	x							
5	Crew Cabin Air			x	x	x	x	x				
6	Plant Colony Air			x	x	x	x	x				
7	Crew Suit Sensor					x	x	x	x			
8	Crew (Saliva+Urine+Blood Analysis)									x	x	x

Fly-by-Wireless Life Science Sensing

- **However, in order for TC and radiation sensing to be most effective, sensor data needs to be mapped to the space vehicle or habitat as a function of space and time**
  - ***This will require position information for each crewmember as a function of time***
  - ***Complementary Computational Fluid Dynamics (CFD) and other 3-D analyses will pinpoint the performance of specific systems and possible crew health hazards***
    - ***Off gassing from surfaces or experiments***
    - ***Residue concentrations from combustion events***
    - ***Effluents via crew metabolism or pathology***
    - ***Radiation mitigation performance as a function of material and geometry***

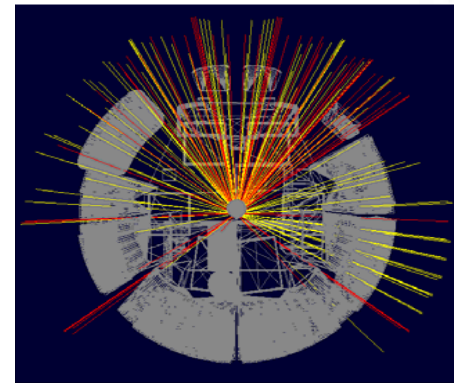
4-D Mapping for TC and Radiation Analysis

CFD TC Analysis

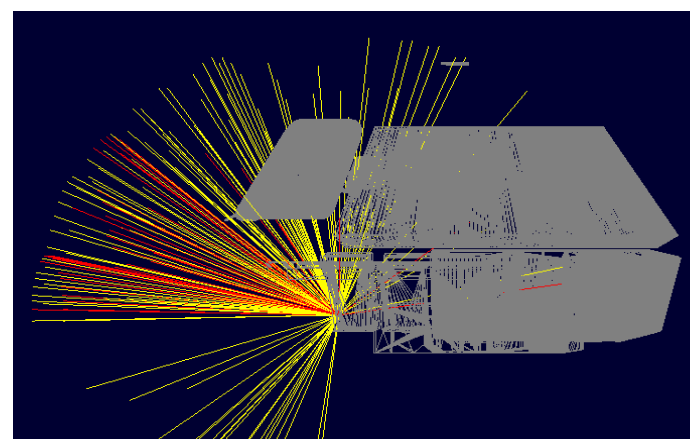


3-D Radiation Analysis

Bottom View



Side View



Fly-by-Wireless for Life Science Conclusions

- **The study of TC and radiation exposure mitigation on ISS fits very well with NASA's *ISS Utilization Plan***
- **4-D mapping each CM's TC and radiation exposure to the ISS will significantly facilitate this study, allowing:**
  - ***Advanced knowledge of materials in their* in situ *settings***
  - ***Provide information necessary for developing related countermeasures***
  - ***Aid in the development of a 1000-day SMAC, critical for long duration manned space exploration***
  - ***Provide visibility to and diagnosis of chronic ISS concerns***
  - ***Provide a solution pathway to ISS and future Constellation vehicles for long-term crew health and safety***