



ISSRDC

EVA Planning: Using Neutral Buoyancy Laboratory (NBL) training to predict in-flight energy expenditure

Lauren Cox, PhD

JES Tech, EVA and Environmental Physiology Laboratory (EEPL)

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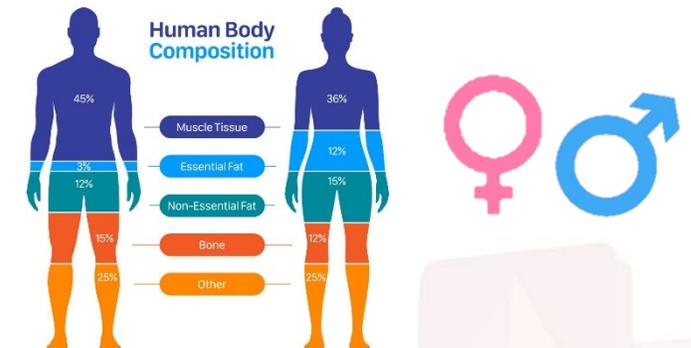
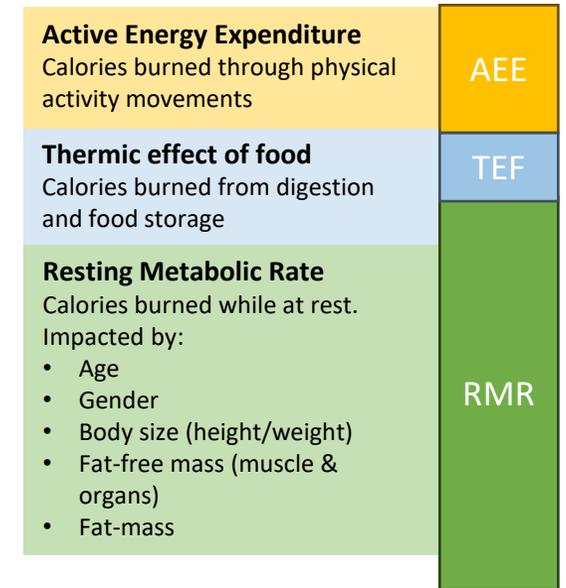
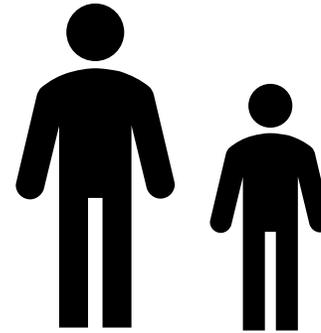
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Background

- **Metabolic Rate (“met rate”):** amount of energy expenditure over a period of time
 - Metabolism produces carbon dioxide (CO₂) and heat
 - Measured in Watts (Joule/sec), BTU/hr (British thermal unit) or kcal/hr
- Factors that can influence energy expenditure
 - Active energy expenditure (AEE; physical activity)
 - Thermic effect of food (TEF; digestion and fat storage)
 - Resting metabolic rate (RMR): energy expended while at rest - minimum metabolic rate required to keep basic body functions working
 - ↑ RMR
 - Fat-free mass, body size (height/weight), body temperature, stress
 - ↓ RMR
 - Age, female (~3% lower)



Metabolic Rate and EVA

- During Extravehicular Activities (EVAs), **spacesuits process the outputs of metabolism** (CO₂ and heat)
 - The main limiting consumable for Extravehicular Mobility Unit (EMU) operations is Metal Oxide “MetOx” canisters
 - MetOx canisters have a limited total CO₂ scrubbing capacity
 - Crewmembers wear a liquid cooling and ventilation garment (LCVG) that helps remove heat, but is limited by the Portable Life Support System (PLSS) feedwater supply & heat exchanger efficiency
- **Total Metabolic Cost is a key metric for determining EVA duration limits based on spacesuit consumables usage**
 - Total Metabolic Cost (BTU) = Met Rate * Duration
 - MetOx Cansisters have an approximate capacity of about 6900 BTUs available for an EVA
 - If EVA Met Rate averages below 1000 BTU/hr, a 6h 30min EVA is reasonable

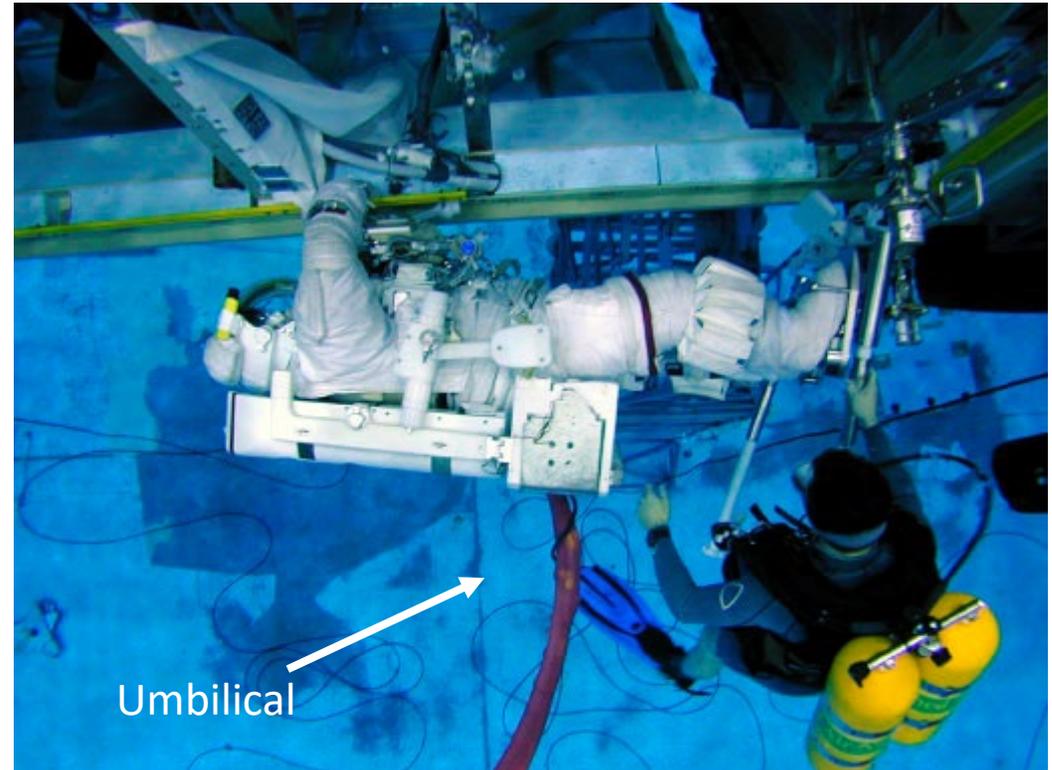


Metox EVA Capacity	
8000 BTU	Initial Capacity of Metox Canisters
- 600 BTU	Emergency Reserve
- 500 BTU	Estimated Prebreathe Use
6900 BTU	Capacity Available for EVA

Measuring Met Rate during EVA Simulations/Training

At the Neutral Buoyancy Laboratory (NBL)

- Breathing gas flow is supplied to Class III EMU suits via long umbilicals
- Returning breathing gas flow is analyzed by Vaisala GMP252 sensors installed on the NBL Environmental Control System (ECS) Panels
- CO₂-based Met Rate approximation approach
 - Measure the Concentration of CO₂ in the returning flow from the umbilical
 - Measure the Flow Rate of the gas supplied
 - Estimate the volume of CO₂ produced
$$VCO_2 = \text{Concentration} * \text{Flow Rate}$$



CO₂-based method and RER correction factor

- At the NBL, CO₂ produced during suited operations is measured
 - O₂ consumption is estimated by Respiratory Exchange Ratio (RER) which is the ratio of CO₂ production to O₂ consumption: $RER = \frac{VCO_2}{VO_2}$

$$Energy\ Expenditure\ \left(\frac{kcal}{hr}\right) = 60 * \left(\frac{4.039 * VCO_2}{RER} + 1.157 * VCO_2\right)$$

- We assume RER of 0.85 for in-suit metabolic rate calculation, then apply statistical correction factor to adjust for error
 - RER = 0.7 → fat as fuel source RER = 1.0 → carbohydrate as fuel source
 - RER is higher at higher workloads, and therefore, we need a correction factor to adjust for the fact that increased RER will lower metabolic rate, because RER is on denominator
 - Based on statistical modeling analysis, met rate values calculated using an assumed RER of 0.85 are adjusted with this equation:

$$MR_{adj} = \exp[(\ln(MR_{RER}) + 1.642327) / 1.231614]$$

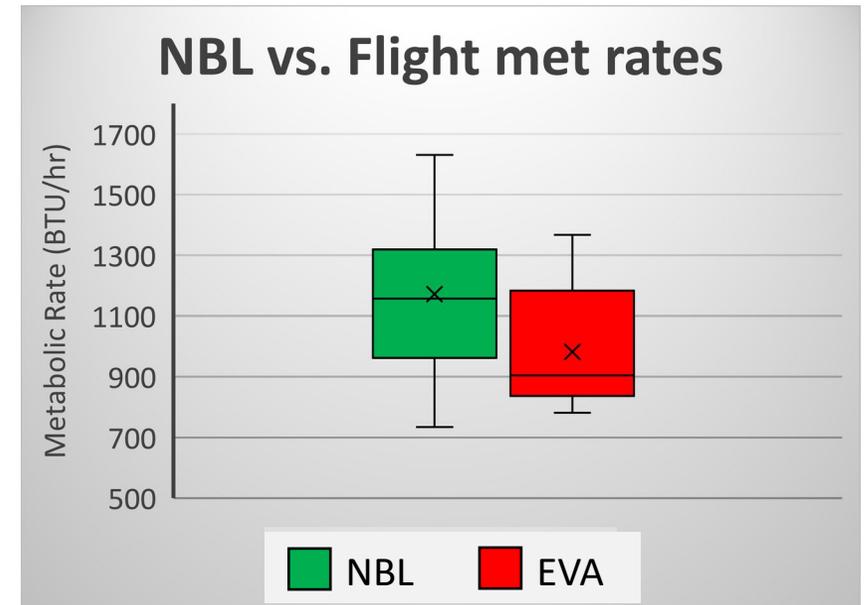
Where: MR_{RER} is the met rate value calculated with RER = 0.85
 MR_{adj} is the new adjusted met rate value

Interpretation of Met Rate Data

- Metabolic Rates do not give information on an individual's fitness
- Changes in an individual's met rate during EVA
 - Reflect how much physical work is being performed
 - Metabolic Rate data enables comparison of the physical workload associated with various types of EVA tasks by analyzing changes in metabolic rate over the course of an EVA timeline (e.g. demating fluid connectors vs. worksite setup tasks)
- Key factors on relative metabolic rate:
 - Task – the more physical work required, the higher the metabolic rate
 - Effort – the faster one works (particularly underwater), the higher the metabolic rate
 - Technique also can impact task workload and duration
 - Total Metabolic Cost = Met Rate * Duration; Total Metabolic Cost is a key metric for determining EVA duration limits based on spacesuit consumables usage (e.g. MetOx canister limits)

NBL Met Rate Compared to Flight

- At the NBL, metabolic rate is measured with a CO₂-based method to compute the volume of CO₂ produced
- In-flight ISS EVA met rates are calculated using the O₂ tank pressure decreases to approximate the volume of O₂ consumed
- Met Rates are typically higher in the NBL environment compared to in-flight ISS EVAs in true weightlessness
 - Varies from crew-to-crew but typically about 100-300 BTU/hr higher in the NBL compared to in-flight
 - This is likely due to water drag
 - However, some task-based 1G differences can lead to lower NBL met rates compared to in-flight
 - From historical data collected, NBL to Flight scale factor of 0.84
 - Predicted Met Rate = NBL Met Rate*0.84
- Met Rate Predictions started with US EVA 69



Category	NBL (BTU/hr)	Actual Flight EVA (BTU/hr)
EVA Setup (Free-Float)	1289	1012
Bolts (BRT)	1140	936
Bolts (BRT)	1140	874
Cable Routing (Free-Float)	1327	874
Bolts (BRT)	1140	936
Electrical Connectors (Free-Float)	1140	936
Miscellaneous Work (Free-Float)	1157	835
EVA Cleanup (Free-Float)	919	953

EVA Planning: Met Rate Predictions

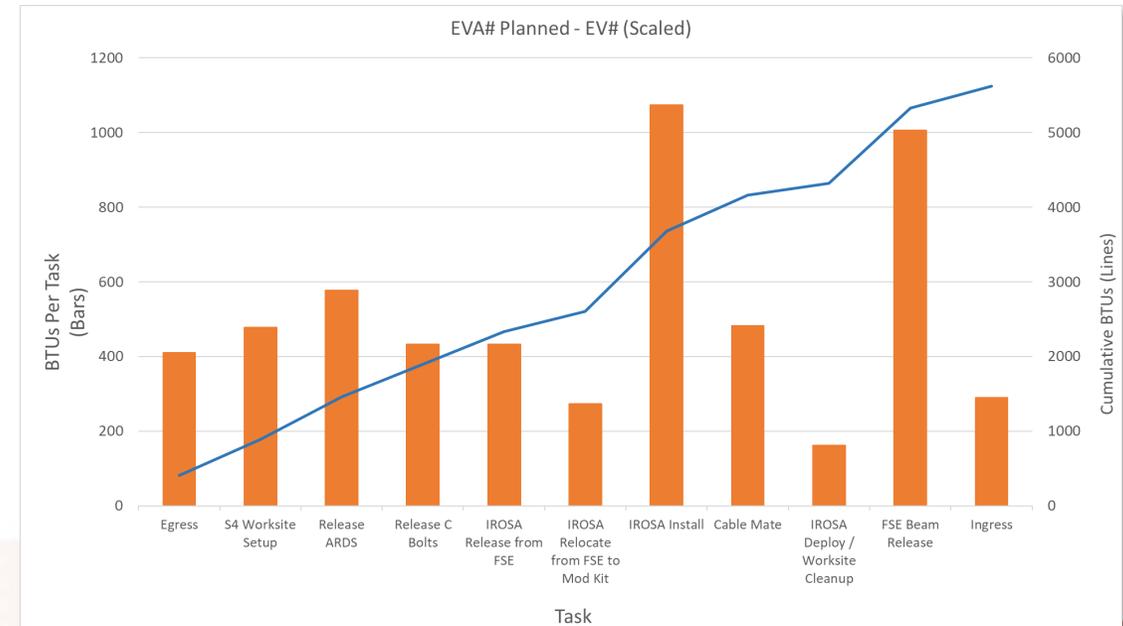
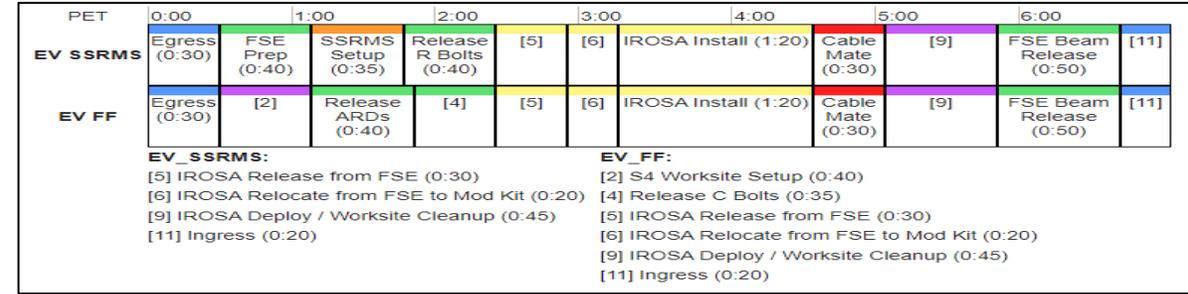
Data Collection
Crew Training Runs at NBL (Met Rate, Timelines, ISS Task Categories)

- EV crewmembers identified
- EVA timeline set
- ISS Task Categories assigned to EVA activities

Met Rate Predictions
Individualized met rate profiles generated

Task	Metabolic Rate Percentage (BTU/Hr)		
	10th	50th (Median)	90th
EGRESS/SETUP	1148.29	1381.60	1622.55
SSRMS INGRESS	1104.19	1359.33	1522.48
REMOVE FAILED PM, INSTALL AGB	872.46	1093.91	1290.46
REMOVE SPARE PM	710.16	859.35	1065.98
INSTALL SPARE PM	704.92	810.99	958.21
EGRESS SSRMS	937.13	1024.38	1371.93
CABLE ROUTING	1161.30	1283.77	1466.01
ICR	662.61	729.81	1189.20
NTA REMOVAL	762.09	1063.86	1323.81
CLEANUP/INGRESS	1064.12	1234.06	1368.94
Total	749.05	1101.72	1407.73

Task	EV1	Category
Egress		EVA Setup (Free-Float)
S4 Worksite Setup		Worksite Setup (Free-Float)
Release ARDS		Bolts (Free-Float)
Release C Bolts		Bolts (Free-Float)
IROSA Release from FSE		Bolts (Free-Float)
IROSA Relocate from FSE to Mod Kit		Worksite Setup (Free-Float)
IROSA Install		R&R work (Free-Float)
Cable Mate		Electrical Connectors (Free-Float)
IROSA Deploy / Worksite Cleanup		Worksite Cleanup (Free-Float)
FSE Beam Release		R&R work (Free-Float)
Ingress		EVA Cleanup (Free-Float)



EVA Task Categories

- Task Categories are also defined by restraint type (if applicable)
 - Free-Float, Articulated Portable Foot Restraint (APFR), Space Station Remote Manipulator System (SSRMS), and Body Restraint Tether (BRT)

Task	Category			
EVA setup/cleanup	EVA Setup (Free-Float)	EVA Cleanup (Free-Float)		
Worksite setup/cleanup	Worksite Setup (Free-Float)	Worksite Cleanup (Free-Float)		
Other work	Miscellaneous Work (Free-Float)	Cable routing (Free-Float)		
Bolts	Bolts (Free-Float)	Bolts (BRT)	Bolts (APFR)	Bolts (On SSRMS)
Fluid Connectors	Fluid Connectors (Free-Float)	Fluid Connectors (BRT)	Fluid Connectors (APFR)	Fluid Connectors (On SSRMS)
Electrical Connectors	Electrical Connectors (Free-Float)	Electrical Connectors (BRT)	Electrical Connectors (APFR)	Electrical Connectors (On SSRMS)
R&R (or install) work	R&R work (Free-Float)	R&R work (BRT)	R&R work (APFR)	R&R work (On SSRMS)

As-Planned vs As-Executed Analysis

Purpose: Evaluate accuracy of current EVA met rate estimation method for US EVAs 85-88

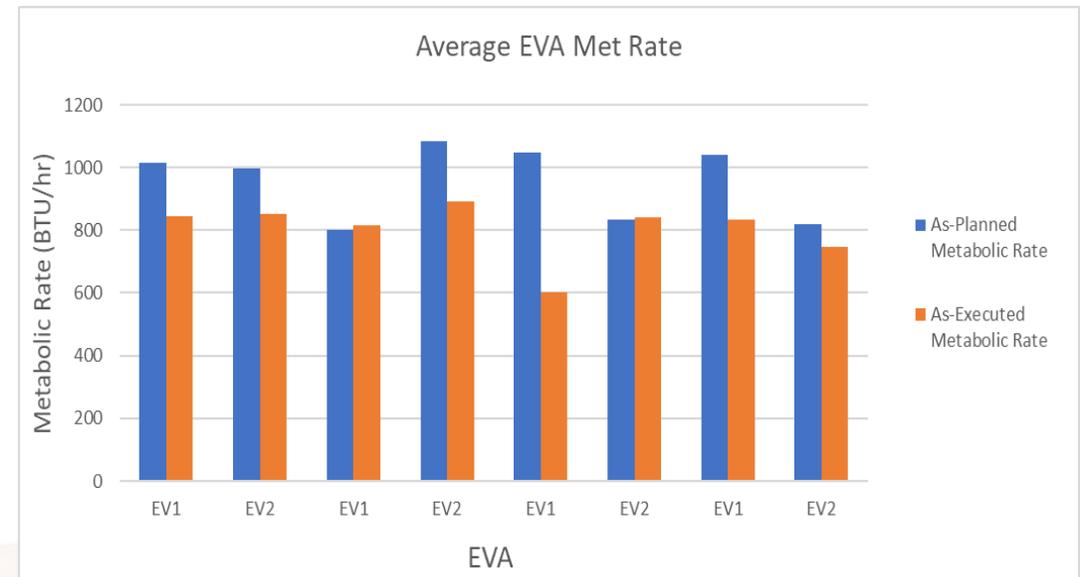
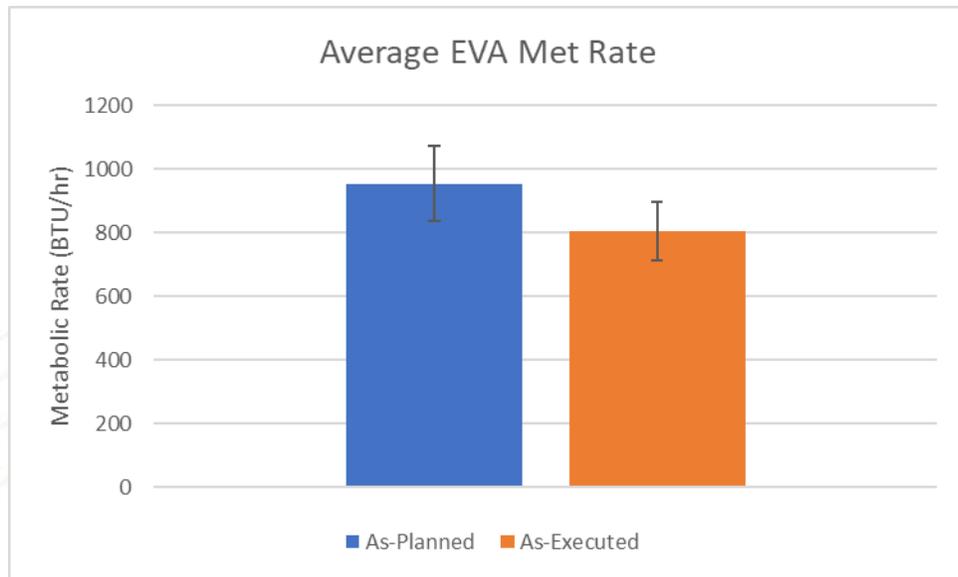
- In-flight metabolic data (“As-Executed”) from four recent ISS US EVAs compared to predicted (“As-Planned”)
- Met Rate data from 8 EV crewmembers
- Cumulative (Total) EVA Metabolic Cost
- Average EVA Met Rate
- EVA Task Category Met Rate
- EVA Task Category Metabolic Costs



As-Planned vs As-Executed Results: Average EVA Met Rate

- Predicted Average Met Rates based on NBL data were higher compared to in-flight EVA Met Rates
 - Difference varies by EVA and crewmember
 - Percent error ranged from 1.2 – 42.6%

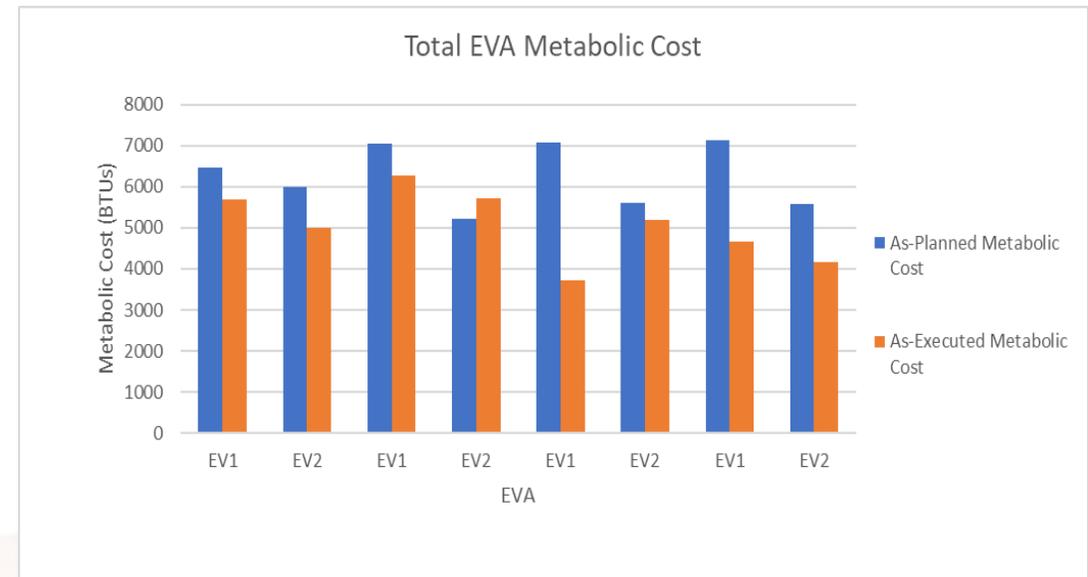
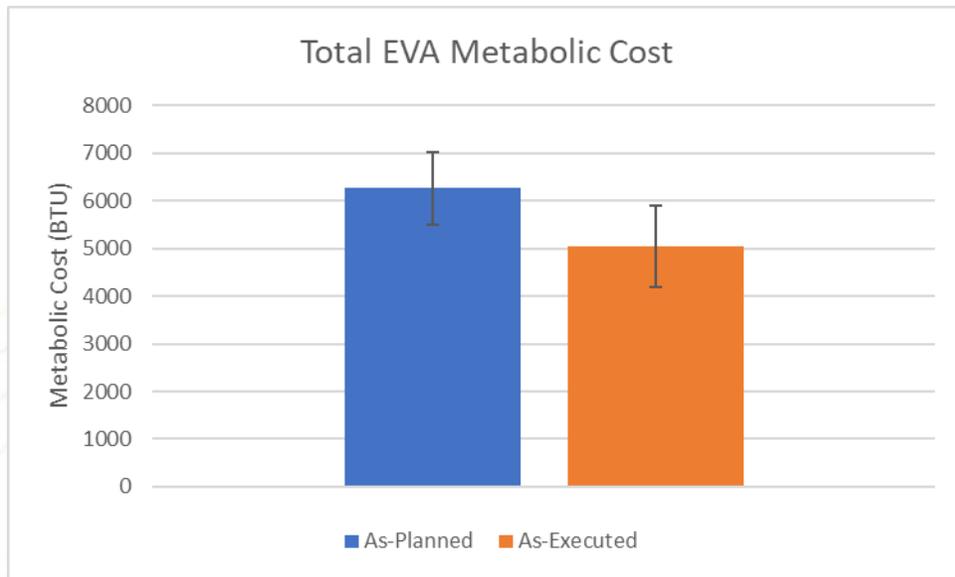
Variable	As-Planned		As-Executed	
	M	SD	M	SD
Average Metabolic Rate (BTU/hr)	954.53	116.72	803.78	91.29



As-Planned vs As-Executed Results: Total EVA Metabolic Cost

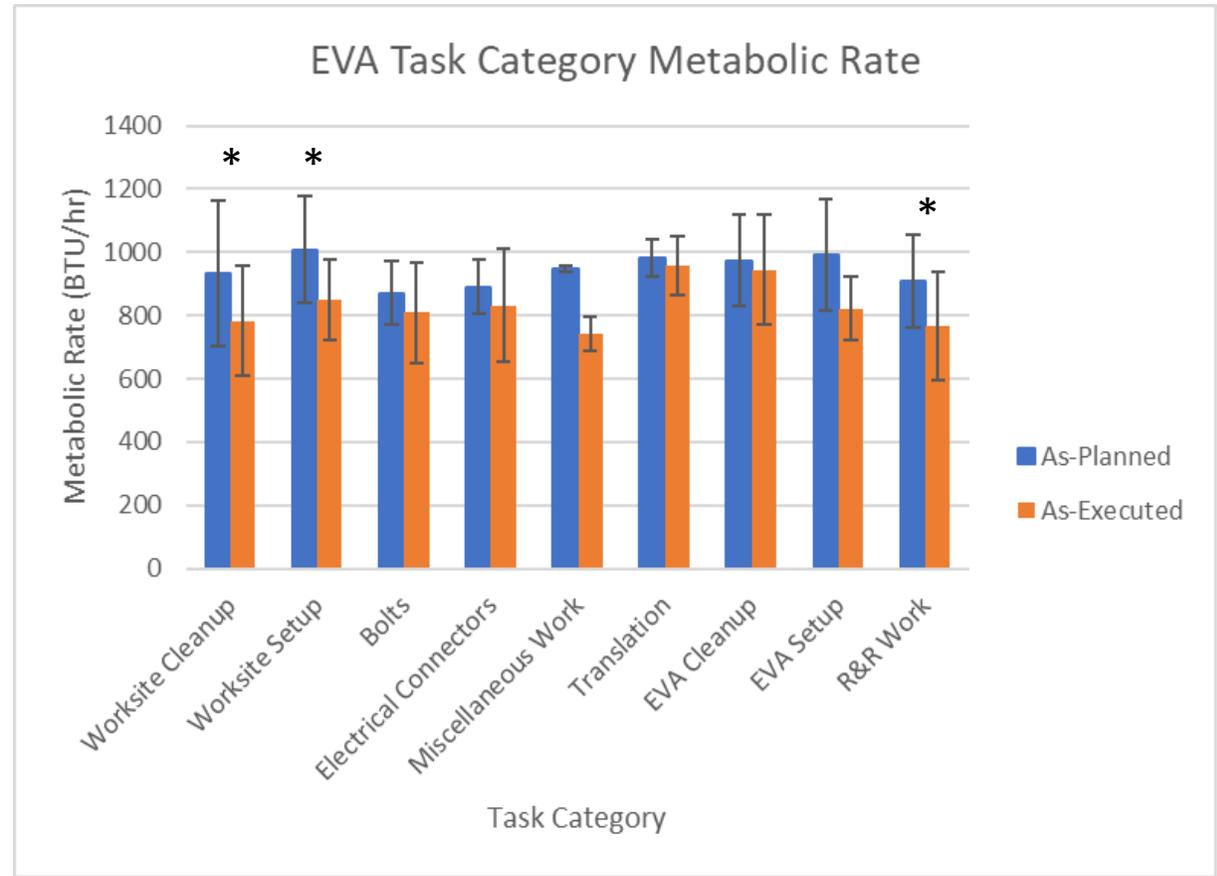
- Predicted Total Metabolic Cost overestimated compared to in-flight EVA Total Metabolic Cost
 - Percent error ranged from 9.8 – 47.6%
 - Difference varies by EVA and crewmember

Variable	As-Planned		As-Executed	
	M	SD	M	SD
Total Metabolic Cost (BTU)	6266.73	764.59	5051.56	852.40

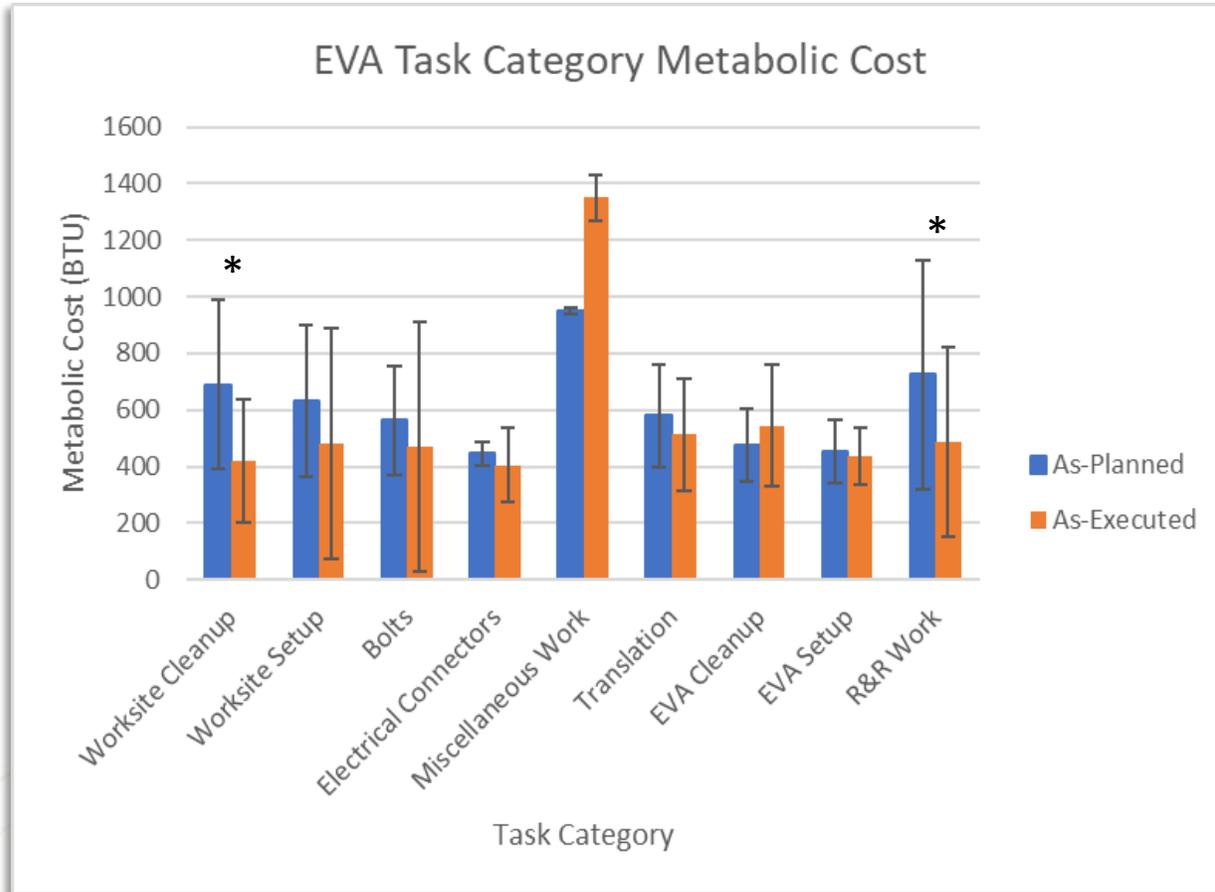


As-Planned vs As-Executed Results: EVA Task Categories

- Predicted vs In-Flight Met Rate Differences
 - 6 of 9 task categories not significantly different
 - Worksite Cleanup
 - As-Planned: $M = 932 \pm 228$ BTU/hr
 - As-Executed: $M = 782 \pm 174$ BTU/hr
 - Worksite Setup
 - As-Planned: $M = 1008 \pm 168$ BTU/hr
 - As-Executed: $M = 850 \pm 127$ BTU/hr
 - R&R Work
 - As-Planned: $M = 908 \pm 149$ BTU/hr
 - As-Executed: $M = 767 \pm 172$ BTU/hr



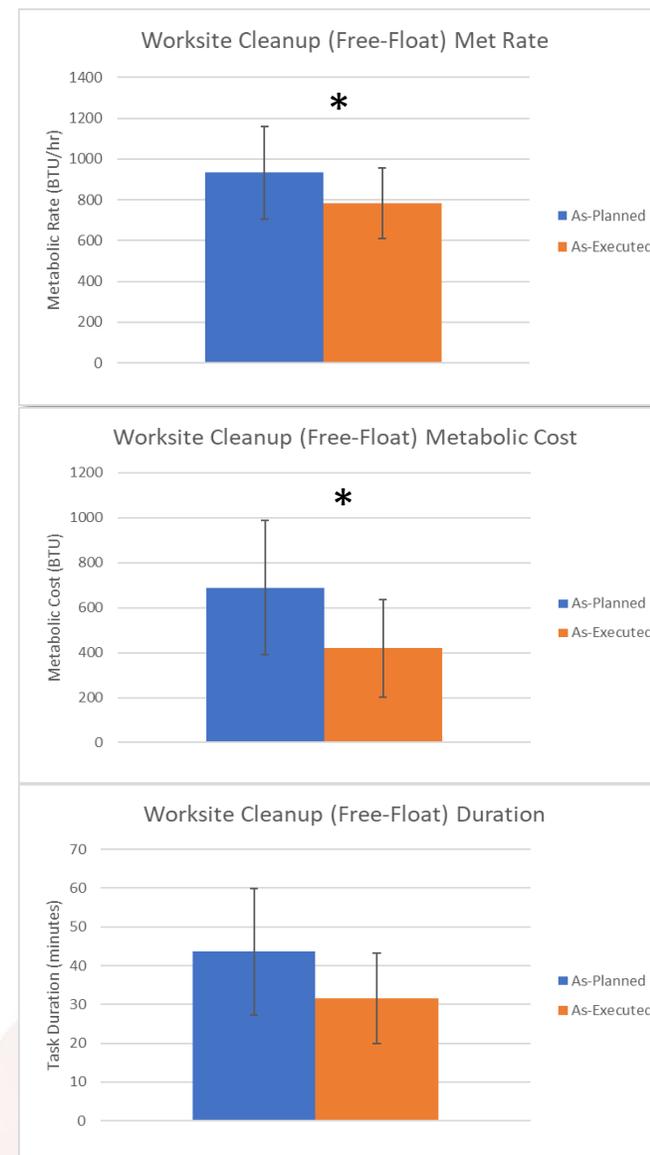
As-Planned vs As-Executed Results: EVA Task Categories



- Predicted vs In-Flight Metabolic Cost Differences
 - 7 of 9 task categories not significantly different
 - Worksite Cleanup
 - As-Planned: $M = 689 \pm 299$ BTU
 - As-Executed: $M = 419 \pm 217$ BTU
 - R&R Work
 - As-Planned: $M = 932 \pm 228$ BTU
 - As-Executed: $M = 782 \pm 174$ BTU

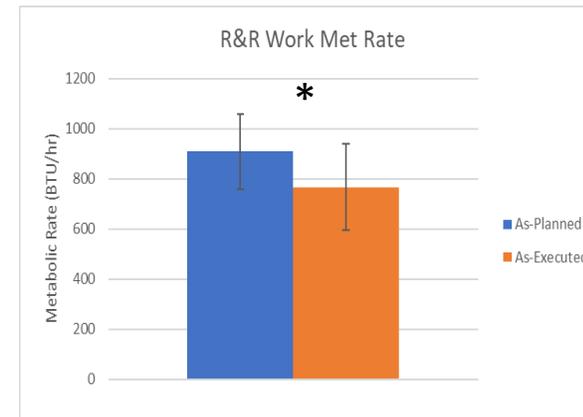
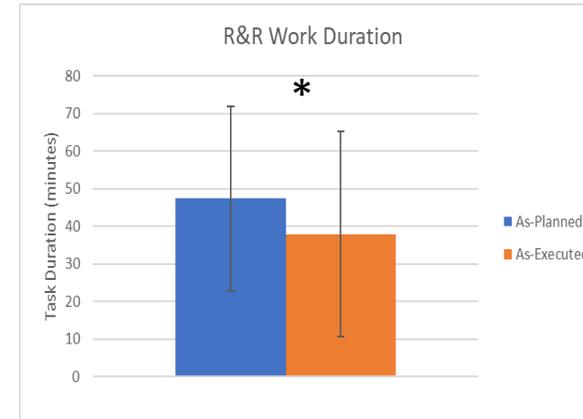
Closer Look: Worksite Cleanup

- As-Planned Task Duration not significantly different from As-Executed
 - Elevated predicted Met Rate driving elevated Metabolic Cost
 - Worksite Cleanup tasks vary greatly during NBL training
 - Limited data points – 7 instances of Worksite Cleanup



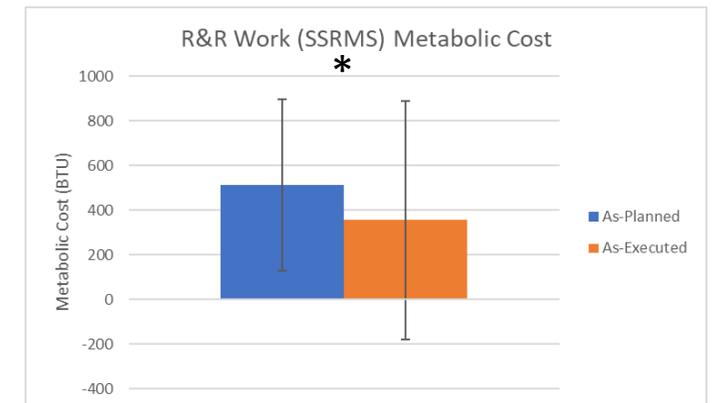
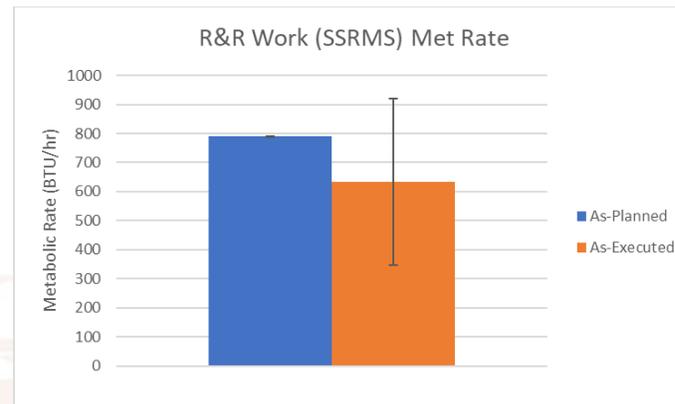
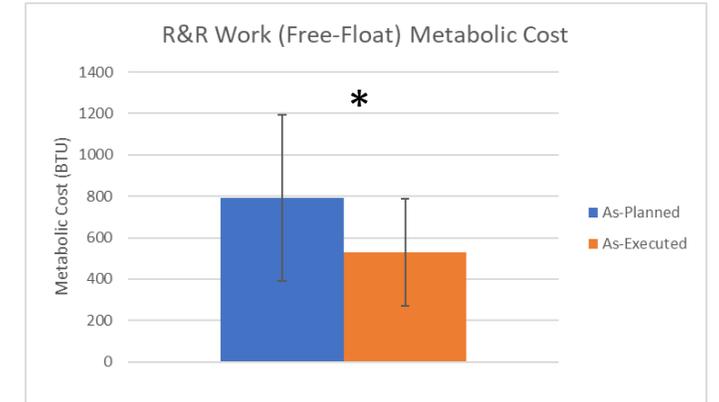
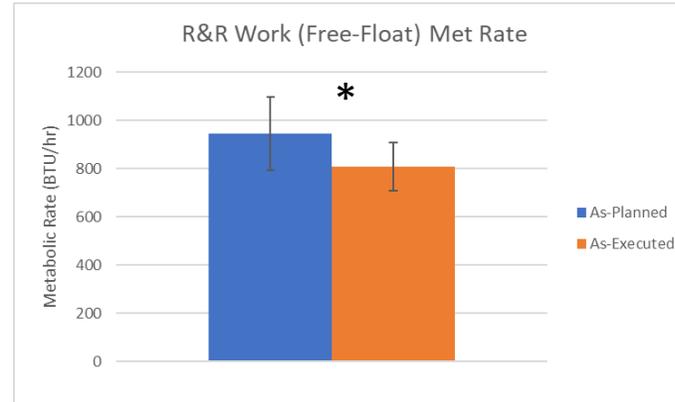
Closer Look: R&R Work

- As-Executed R&R Work Met Rate, Metabolic Cost, and Task Duration significantly different than As-Planned values
 - Multiple Restraint Types for R&R Task Category
 - Free-Float
 - APFR
 - BRT
 - SSRMS
- NBL training activities labeled R&R work can vary depending on EVA Trainor



Closer Look: R&R Work Restraint Type

- EVAs 85-88
 - R&R Work (Free-Float) n=16
 - R&R Work (SSRMS) n=5
- R&R Work (Free-Float) Predicted Met Rates higher than In-Flight Met Rates



Conclusions

Predicting EVA Met Rates enhances the EVA planning process and ensures planned EVAs will be able to be completed within the consumables range

- Current method can overestimate some task category met rates and metabolic cost
 - This means EVA **met rate predictions are conservative** to not violate MetOx limitations (6600 BTUs)
- More NBL crew training data will continue to improve the prediction model
 - Optimize substitution method for missing EVA task category training data in work
 - NBL correction factor (0.84) based on historical data, may be different depending on the EVA Task Category

Limitations

- Executed EVA timeline
- EVA Task Categories consistency
 - Labeling highly dependent on FOD EVA Trainers

4 task category replacements required

EV1	
Timeline Tasks	category
EGRESS/POST-DEPRESS	EVA Setup (Free-Float)
SSRMS Setup/CP9 Cable Move	Worksite Setup (Free-Float)
CP9 EHDC R&R	R&R work (On SSRMS)
CP9 WAP Cable Routing	Miscellaneous Work (On SSRMS)
SSRMS Cleanup	Worksite Cleanup (Free-Float)
Beta Cloth Repositioning	Miscellaneous Work (BRT)
Connector Tool Fit Check	Miscellaneous Work (BRT)
AMS Cleanup	Worksite Cleanup (Free-Float)
CLEANUP/INGRESS/PRE-REPRESS	EVA Cleanup (Free-Float)

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Questions?

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