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Carbon Dioxide and Water Vapor Production at Rest and During Exercise: A Report on Data Collection for the Crew and Thermal Systems Division

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INTRODUCTION

The current cabin environment control system used in the Space Shuttle program uses lithium hydroxide (LiOH) filter canisters to remove carbon dioxide (CO_2) and respiratory water from the cabin air. Although this system has been effective, it requires several filter canisters that can only be used once and must be changed frequently. These filtration units are bulky and occupy a significant portion of locker stowage. The amount of locker storage required for such canisters will be magnified as the extended duration orbiter (EDO) mission lengths increase up to 18 days [6].

To alleviate this stowage problem and decrease launch weight, the Crew and Thermal Systems Division (CTSD) at the NASA Johnson Space Center has been researching an environmental control system to be used on future Space Shuttle missions. This system, based on technology used in the Skylab missions, uses two beds of solid amine material to absorb CO_2 and respiratory water and later desorb them to space vacuum. In this way the air scrubbing medium is regenerable and reusable so that stowage and weight concerns are reduced, and crew time is not impacted to frequently change filters [6]. To identify the efficacy of this regenerable CO_2 removal system (RCRS), CTSD began isolation investigations in the Shuttle mockup.

The CTSD approached the Exercise Physiology Laboratory of the NASA Johnson Space Center requesting support of these isolation investigations by evaluating each subject's rate of carbon dioxide ($\dot{V}CO_2$) and respiratory water ($\dot{M}_e$) production. The activities chosen represented the daily energy expenditures thought to be similar to the activities of Shuttle crew members [3] and a range of energy expenditures similar to those used in the isolation study. All 23 subjects were evaluated in the Exercise Physiology Laboratory while resting (i.e., both supine and seated), walking on a treadmill, and stair stepping. Their data are presented in this report.

METHODS

The CTSD required $\dot{V}CO_2$ and $\dot{M}_e$ for each of the activities evaluated. The activity levels included supine and seated rest, treadmill walking at a rate equivalent to 540 kJ/h, and stair stepping at 1230, 1845, and 2460 kJ/h. Metabolic rates were provided by CTSD to determine the appropriate treadmill speed and stepping rates [1].

Selection of subjects by the Human Test Subject Facility was based upon characteristics of the astronaut corps. Subject characteristics are presented in Table 1.

Table 1. Subject Characteristics (Mean ±SE)

	Males	Females	Mean
Age (yr)	36.4 ±2.9	36.9 ±1.2	36.6 ±1.6
Height (cm)	180.1 ±2.2	165.9 ±1.2	173.9 ±3.5
Weight (kg)	79.0 ±4.6	65.3 ±4.5	72.6 ±3.5

Subjects completed a NASA informed consent form and were provided with a subject information sheet specific to this study. These were read and subjects were given the opportunity to have questions answered to their satisfaction, then the forms were signed to indicate that they had been understood.

Prior to the isolation studies, the metabolic responses of all subjects for the four different conditions were evaluated in one testing session. All subjects breathed through a Hans-Rudolph one-way rebreathing valve. Expired gases were analyzed by the Quinton Q-Plex® (Quinton Industries, Seattle, WA) metabolic cart. The subject's electrocardiogram was continuously monitored by a three-lead EKG configuration (Quinton Q5000 Stress Test System) for the determination of heart rate.

Data collection began with a 20-minute supine-resting period that was followed by a 10-minute seated rest. Subjects then walked on the Quinton Q65 treadmill at 2.4 km/h (1.5 mi/h), zero-percent grade for 5 minutes. At the completion of the treadmill walking, the subjects rested for approximately 5 minutes. The final phase of testing consisted of bench stepping on a 22.9 cm (9 in) bench at rates of 16, 24, and 32 steps per minute in 3-minute stages without rest between stages. At the completion of the bench stepping activity, subjects walked in place for at least 1 minute to avoid venous pooling and possible syncope before being allowed to rest. Subjects remained attached to the EKG monitoring system until their heart rate had returned to under 100 beats per minute. Subjects were allowed to remove the mouthpiece and noseclip assemblies between data collection for each activity. The metabolic gas analyzer was calibrated before and after each condition.

All data, except $\dot{M}_e$, were collected in 30-second intervals and stored on the Q-Plex®. $\dot{V}O_2$ and $\dot{V}CO_2$ were calculated by the Q-Plex® using the following equations:

$$\dot{V}O_2 = V_ESTPD \bullet (FIO_2 \bullet [1\text{-}FEO_2\text{-}FECO_2])/([1\text{-}FIO_2\text{-}FICO_2]\text{-}FEO_2)$$

$$\dot{V}CO_2 = V_ESTPD \bullet (FECO_2\text{-}FICO_2)$$

where V_ESTPD is the volume of expired air at standard temperature and pressure, dry (0 °C, 760 mmHg, zero-percent H_2O), FIO_2 is the fractional concentration of inspired oxygen, FEO_2 is the fractional concentration of expired oxygen, $FICO_2$ is the fractional concentration of inspired carbon dioxide, and $FECO_2$ is the fractional concentration of expired carbon dioxide [4, 7].

The calculations to predict $\dot{M}_e$ were made after the test using the following equation:

$$\dot{M}_e = 0.019 \bullet \dot{V}O_2(44\text{-}Pa)$$

where $\dot{M}_e$ is the rate of evaporative water loss in the expired air (g/min), $\dot{V}O_2$ is the oxygen uptake (L/min STPD) of the subject, and Pa is the ambient water vapor pressure (mmHg)[5].

The CTSD requested that the data for each subject be expressed as a mean response to each condition. The data were derived in the following manner. Supine-resting mean data were calculated from the last 10 minutes of the 20-minute supine-resting time interval. The seated-resting mean data were taken from the last 5 minutes of the 10-minute seated-resting period. The means for treadmill walking were averaged from the last 2 minutes of the 5-minute walk and for stair stepping from the last 1 minute of each 3-minute stage.

RESULTS

Mean absolute results for all subjects across all variables and conditions are presented in table 2, and graphically in figures 2 and 3. Mean results by gender are presented in tables 3 and 4, and graphically in figures 4 through 9.

For the prediction of expected responses for future subjects, the results are presented relative to body weight in table 5. No significant differences are present between gender when viewed in this manner. Observed mean results for all subjects relative to body weight and expected values for $\dot{V}O_2$, $\dot{V}CO_2$, and $\dot{M}_e$ derived from other sources [1, 4, 5] are also presented in table 6.

Table 2. Mean (±SE) Absolute Responses for All Subjects, n=23

	$\dot{V}O_2$ (L/min)	$\dot{V}CO_2$ (L/min)	$\dot{M}_e$ (g/min)
Supine Rest	0.21 ±0.02	0.19 ±0.01	0.12 ±0.01
Seated Rest	0.25 ±0.02	0.22 ±0.02	0.14 ±0.01
Treadmill (2.4 km/h)	0.68 ±0.05	0.58 ±0.05	0.39 ±0.03
16 steps/min	1.12 ±0.06	0.90 ±0.06	0.72 ±0.05
24 steps/min	1.50 ±0.09	1.44 ±0.10	0.97 ±0.07
32 steps/min	1.99 ±0.11	2.21 ±0.14	1.29 ±0.10

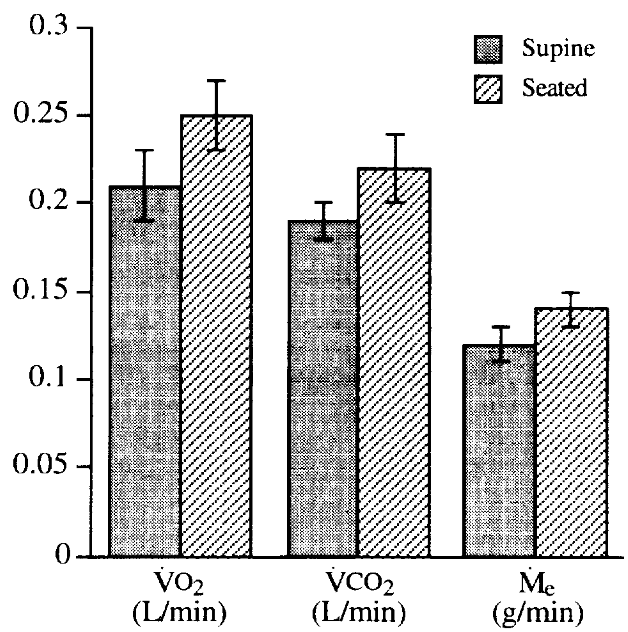

Figure 1. Mean responses of all subjects across resting conditions.

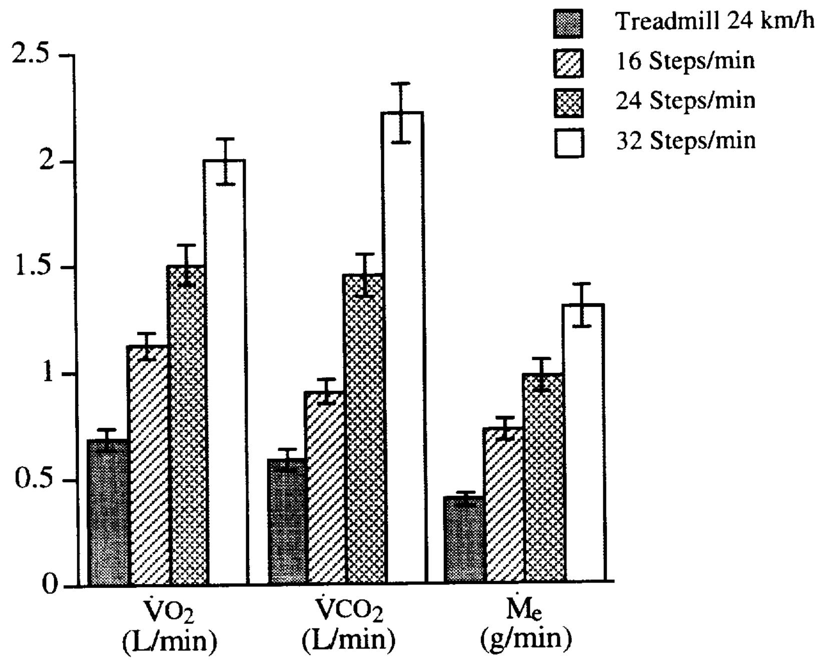

Figure 2. Mean responses of all subjects across exercising conditions.

Table 3. Mean (±SE) Absolute Responses for All Male Subjects, n=12

	$\dot{V}O_2$ (L/min)	$\dot{V}CO_2$ (L/min)	$\dot{M}_e$ (g/min)
Supine Rest	0.21 ±0.02	0.21 ±0.02	0.12 ±0.01
Seated Rest	0.27 ±0.02	0.24 ±0.02	0.15 ±0.01
Treadmill (2.4 km/h)	0.75 ±0.05	0.64 ±0.04	0.43 ±0.02
16 steps/min	1.22 ±0.06	0.98 ±0.07	0.80 ±0.06
24 steps/min	1.66 ±0.09	1.59 ±0.10	1.08 ±0.09
32 steps/min	2.24 ±0.13	2.45 ±0.18	1.46 ±0.11

Table 4. Mean (±SE) Absolute Responses for All Female Subjects, n=11

	$\dot{V}O_2$ (L/min)	$\dot{V}CO_2$ (L/min)	$\dot{M}_e$ (g/min)
Supine Rest	0.20 ±0.01	0.18 ±0.01	0.11 ±0.01
Seated Rest	0.24 ±0.03	0.20 ±0.02	0.13 ±0.01
Treadmill (2.4 km/h)	0.62 ±0.06	0.51 ±0.06	0.35 ±0.04
16 steps/min	1.01 ±0.06	0.81 ±0.06	0.65 ±0.05
24 steps/min	1.34 ±0.08	1.30 ±0.09	0.87 ±0.06
32 steps/min	1.74 ±0.09	1.98 ±0.11	1.12 ±0.09

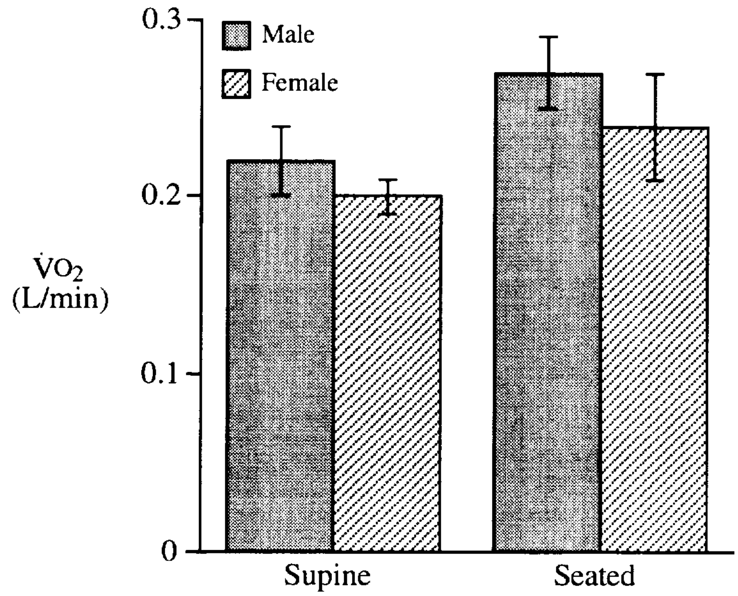

Figure 3. Gender comparisons of $\dot{V}O_2$ response across resting conditions.

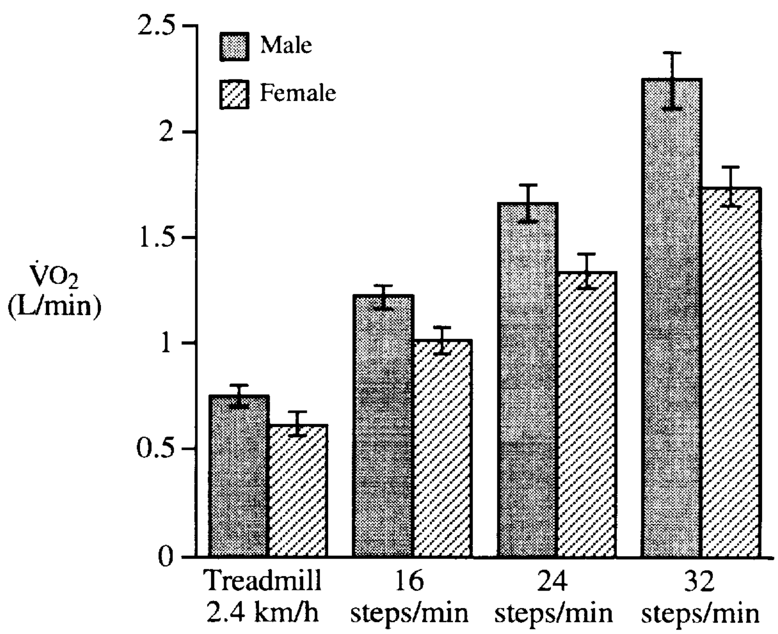

Figure 4. Gender comparisons of $\dot{V}O_2$ response across exercising conditions.

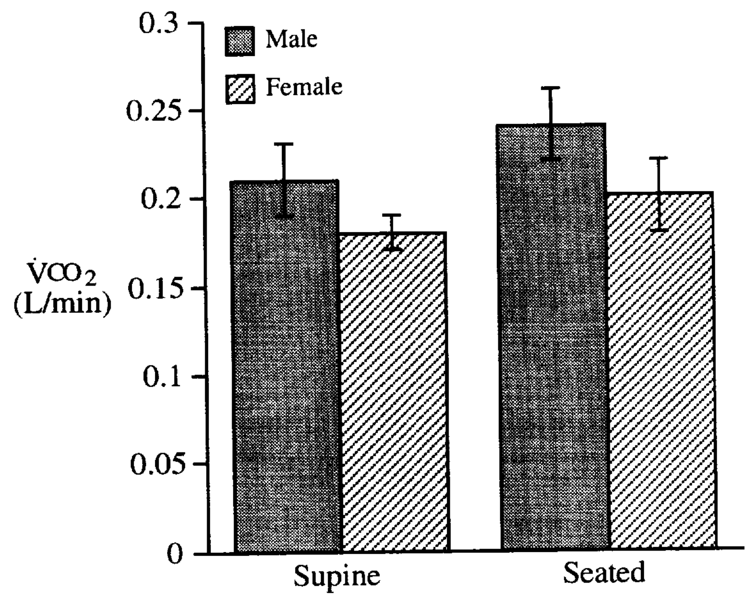

Figure 5. Gender comparisons of $\dot{V}CO_2$ response across resting conditions.

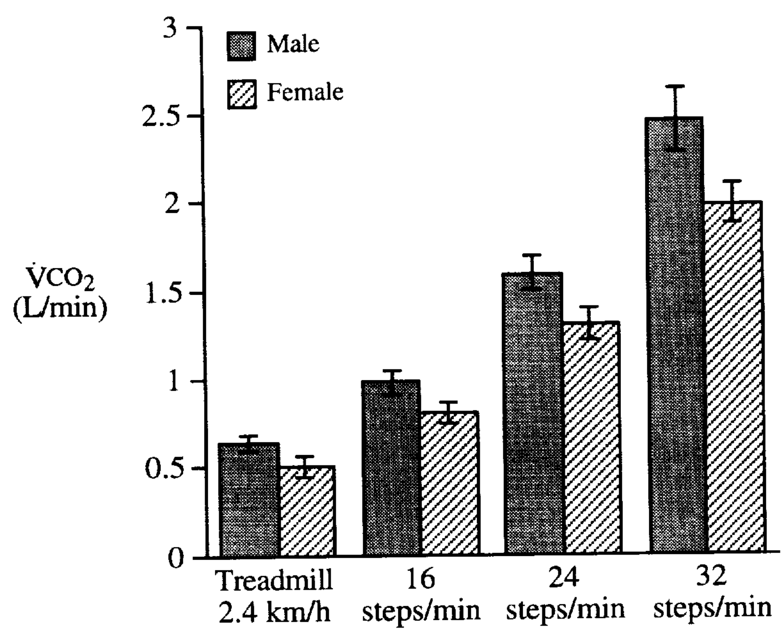

Figure 6. Gender comparisons of $\dot{V}CO_2$ response across exercising conditions.

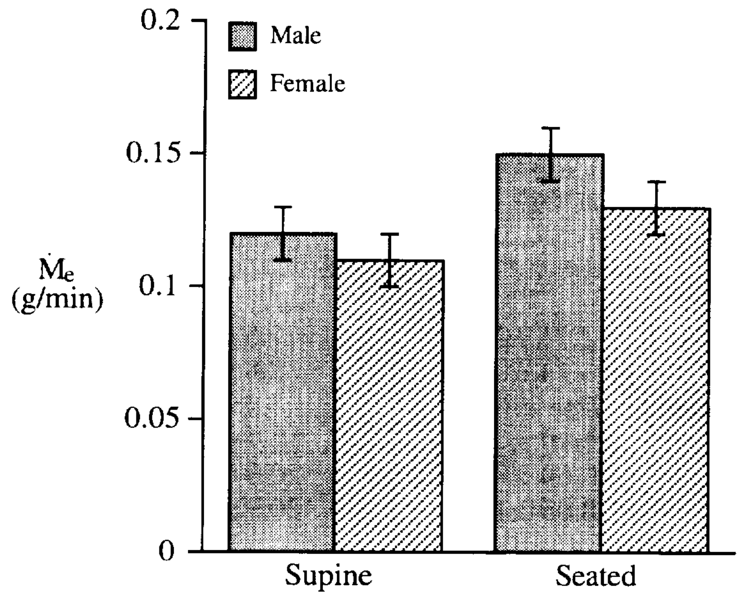

Figure 7. Gender comparisons of $\dot{M}_e$ response across resting conditions.

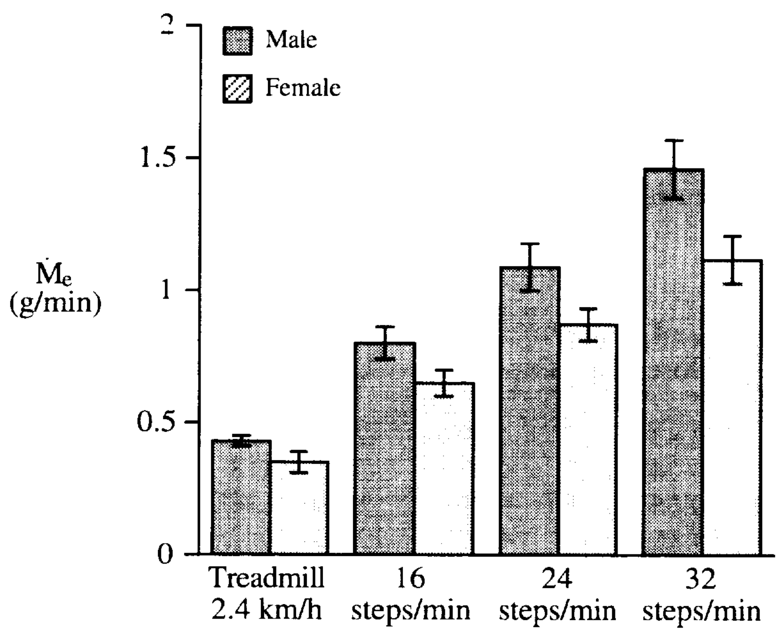

Figure 8. Gender comparisons of $\dot{M}_e$ response across exercising conditions.

Table 5. Mean (±SE) Results Relative to Body Weight (kg) Across Gender and Conditions

	$\dot{V}O_2$ (mL O_2/kg/min)	$\dot{V}CO_2$ (mL CO_2/kg/min)	$\dot{M}_e$ (mg/kg/min)
Males			
Supine	2.71 ±0.26	2.52 ±0.23	1.56 ±0.15
Sitting	3.14 ±0.30	2.86 ±0.27	1.84 ±0.19
Treadmill (2.4 km/h)	9.9 ±0.49	8.39 ±0.59	5.82 ±0.27
16 steps/min	15.19 ±0.65	12.74 ±0.68	8.94 ±0.47
24 steps/min	20.69 ±0.86	20.07 ±0.83	12.17 ±0.59
32 steps/min	28.05 ±1.26	30.98 ±1.43	16.49 ±0.82
Females			
Supine	2.96 ±0.22	2.62 ± 0.19	1.75 ±0.14
Sitting	3.24 ±0.27	2.84 ±0.22	1.92 ±0.17
Treadmill (2.4 km/h)	9.37 ±0.50	7.75 ±0.48	5.52 ±0.29
16 steps/min	15.53 ±0.64	12.84 ±0.52	9.18 ±0.38
24 steps/min	20.37 ±0.91	20.47 ±0.83	12.26 ±0.53
32 steps/min	26.35 ±0.83	30.92 ±0.95	15.64 ±0.48

Table 6. Observed Mean (±SE) Versus Expected Results Relative to Body Weight Across Conditions

	$\dot{V}O_2$ (mL O_2/kg/min)		$\dot{V}CO_2$ (mL CO_2/kg/min)		$\dot{M}_e$ (mg/kg/min)	
	Observed	Expected	Observed	Expected	Observed	Expected
Supine	2.83 ±0.17	4.69	2.57 ±0.15	4.26	1.65 ±0.10	2.73
Sitting	3.24 ±0.20	4.47	2.85 ±0.18	3.93	1.87 ±0.13	2.61
Treadmill (2.4 km/h)	9.65 ±0.35	9.21	8.09 ±0.38	7.72	5.68 ±0.19	5.37
16 steps/min	15.35 ±0.45	14.00	12.79 ±0.42	11.67	9.04 ±0.30	8.17
24 steps/min	20.54 ±0.61	21.00	20.26 ±0.57	20.71	12.21 ±0.39	12.25
32 steps/min	27.48 ±0.79	28.00	31.18 ±0.86	31.77	16.13 ±0.49	16.33

DISCUSSION

This technical paper documents the levels of $\dot{V}CO_2$ and $\dot{M}_e$ that represent the metabolic expenditure of normal daily crew tasks in response to different activities. The results of this investigation will serve as a reference for future investigations in the evaluation of the RCRS and other environmental control systems.

The validity of mean $\dot{V}O_2$ values during each of the conditions is important to examine because the values for $\dot{M}_e$ are calculated from $\dot{V}O_2$ and not reported elsewhere. The mean values for the resting conditions and treadmill walking are approximately 25 percent lower than those reported in the literature [2, 4]. This may have resulted from the low breath volumes during these conditions to which the Q-Plex® may not be sensitive because it is intended to measure air volumes exchanged during moderate to heavy exercise. Mean values of $\dot{V}CO_2$ are similarly depressed at rest and during treadmill walking. The mean results from the stair-stepping activity for all variables are well within expected values as calculated from accepted equations [1, 5].

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13. ABSTRACT *(Maximum 200 words)*

The current environmental control device in the Shuttle uses lithium hydroxide (LiOH) filter canisters to remove carbon dioxide (CO2) from the cabin air, requiring several bulky filter canisters that can only be used once and must be changed frequently. To alleviate a stowage problem and decrease launch weight, the Crew and Thermal Systems Division (CTSD) at the NASA Johnson Space Center has been researching a system to be used on future Shuttle missions. This system uses two beds of solid amine material to absorb CO2 and water, later desorbing them to space vacuum. In this way the air scrubbing medium is regenerable and reusable. To identify the efficacy of this regenerable CO2 removal system (RCRS), CTSD began investigations in the Shuttle mockup. The purpose of this investigation was to support the CTSD program by determining mean levels of carbon dioxide and water vapor production in normal, healthy males and females age-matched with the astronaut corps. Subjects' responses were measured at rest and during exercise at intensity levels equivalent to normal Shuttle operation activities. The results were used to assess the adjustments made to RCRS and are reported as a reference for future investigations in Shuttle environmental control.

14. SUBJECT TERMS

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