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Waste Collector System Technology Comparisons for Constellation Applications

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ABSTRACT

The Waste Collection Systems (WCS) for space vehicles have utilized a variety of hardware for collecting human metabolic wastes. It has typically required multiple missions to resolve crew usability and hardware performance issues that are difficult to duplicate on the ground. New space vehicles should leverage off past WCS systems. Past WCS hardware designs are substantially different and unique for each vehicle. However, each WCS can be analyzed and compared as a subset of 'technologies' which encompass fecal collection, urine collection, air systems, pretreatment systems. Technology components from the WCS of various vehicles can then be combined to reduce hardware mass and volume while maximizing use of previous technology and proven human-equipment interfaces. Analysis of past US and Russian WCS are compared and extrapolated to Constellation missions.

INTRODUCTION

Human metabolic Waste Collection Systems (WCS) have been present on every manned space vehicle. The WCS is an unglamorous but essential part of any space environmental life support system (ECLSS). However, the WCS often is insufficiently emphasized early in vehicle design resulting in engineering solutions that compromise human performance. Space vehicle WCS capabilities, construction, and technologies have varied substantially and objective comparisons are difficult and not readily available in the literature. However, careful consideration of past WCS technologies is necessary for Constellation vehicles to ensure effective integration of crew human factors and ECLSS equipment requirements. Waste collection is a broadly defined term in habitation systems. This paper defines WCS to the collection of urine, menstrual, and fecal wastes. Collection of emesis and non-metabolic wastes such as excess water, beverages, food wastes, and medical wastes are not considered here but can be compatible with the WCS technologies presented here. Terrestrial metabolic waste collection is straight forward and often use a copious quantity of water, which is unavailable on-orbit. Zero-gravity collection offers substantial challenges in waste separation from the body, unanticipated changes in crew use, capture mechanisms, storage, and/or chemical/physical changes in the waste, once captured. Hardware successfully demonstrated in ground based tests or brief parabolic aircraft flights often experience unanticipated performance compromises in orbit. Failure to completely and effectively capture waste can result in not only unhygienic or aesthetically unpleasing conditions but also result in the spread of substantial quantities of bacterial contamination, noxious odor problems, and crew reluctance to use. Consequently, ineffective WCS operations can result in decreased crew performance. This paper is based on Crew Exploration Vehicle WCS presentation material discussed internally with past WCS project managers at Johnson Space Center in January 2006 (Broyan, 2006).

WCS CONFIGURATION HISTORY

In the 1960s, WCS hardware provided basic collection capability for all-male crews and relied primarily on intimate crew contact for collection. Problems with these devices and crew feedback led to the development of non-contact collection methods in the mid-1970s. The 1980s' regular spaceflights revealed numerous gaps in ground analysis and testing and on-orbit WCS performance. Additionally, mixed gender crews required WCS enhancements for female use and menstrual wastes. In the late 1980s and 1990s, planning of permanent orbiting facilities resulted in the development of longer service life WCS technologies. Despite extensive WCS history and flight experience, each WCS modification requires on-orbit validation due to limited ability to duplicate the unique crew interface and variable waste characteristics artificially on the ground or during short periods of aircraft weightlessness.

Previous and existing US and Russian WCS will be briefly described in terms of capability, hardware description, and crew feedback. Summary tables of major WCS functionality (Table 1) and major WCS hardware characteristics (Table 2) are provided at the end of the section.

MERCURY WCS DESCRIPTION

The six Mercury flights did not exceed 34 hours mission duration and consisted of all-male crews. The crew never left their pressurized suits. Urine waste was collected in an intimate contact prophylactic roll-on cuff urine collection device (UCD). Although a very simple mechanism, the UCD system experienced at least one unexpected in-flight leakage (JSC Life Science Data Archive, 2006). Later Mercury missions allowed transfer of urine from inside the UCD to an external storage bag using a manual syringe pump and enabled samples for medical analysis to be collected. Crew defecation was avoided through the use of a low solids residual diet prior to the flight. The Mercury WCS system is not included in this analysis because its performance issues are unsatisfactory for mixed gender crews and longer duration missions.

GEMINI AND APOLLO WCS DESCRIPTIONS

The ten Gemini missions lasted up to 14 days and consisted of all male crews operating in and outside of their pressurized suits. Gemini developed most of the WCS hardware later utilized on the eleven Apollo missions which lasted up to 12 days, and two Apollo-Soyuz flights. The Apollo hardware has previously been described in detail (Sauser and Jorgensen, 1975) but it is summarized here due to frequent comparisons between Apollo and Constellation missions. The functionally of the Mercury UCD roll on cuff and bag was improved for in-suit operations as the Urine Collection Transfer Assembly (UCTA) and an out-of-suit configuration as the Urine Transfer System (UTS), shown in Figure 1. Apollo 12 and later flights utilized a non-contact Urine Receptacle Assembly (URA). The URA allowed urination volumes of up to 700 ml to be captured. The URA consisted of a hand held cylindrical unit consisting of a hydrophilic screen on the surface to capture the urine and minimize splashing. The urine was retained in a honeycomb filled cavity under the screen. The urine in the honey comb was evacuated overboard when the URA was connected to the vacuum vent system. The URA was a significant improvement because the device was easier to use and clean, however, urine spills were common. The URA pulled the urine into the device with up to 0.01 m^3/minute of air flow. However, the urine velocity vector from the crew was the primary delivery force. The low air flow rate is not suitable for female usage due to the low velocity vector during urination.

Fig. 1 – Apollo Urine Transfer System hardware for out-of-suit operation. Photo illustrates flexible plastic/fabric container, prophylactic roll-on cuff present on many early WCS devices. (Sauser and Jorgensen, 1975).

Due to the increased mission length, fecal collection had to be addressed. The Gemini/Apollo fecal bag consists of a non-permeable nylon-polyethylene bag with adhesive ring at the top that attached to the crew buttocks, shown in Figure 2. The bag contained an integrated finger cot on the side. There was no air flow and the crew used the finger cot to manually detach the feces and manipulate it into the bag. Wet wipes and tissues were used for cleanup and also placed in the bag. The feces were stabilized by adding a germicidal agent into the bag and manually kneading it through the feces. The bag was rolled up, sealed, and placed in a second vented storage bag. Several configurations of adhesive rings and finger cots were developed and flown. The fecal bag system was marginally functional and was described as very ‘distasteful’ by the crew. The bag was considered difficult to position. Defecation was difficult to perform without the crew soiling themselves, clothing, and the cabin. The bags provided no odor control in the small capsule and the odor was prominent. Due to the difficulty of use, up to 45 minutes per defecation was required by each crew member, causing fecal odors to be present for substantial portions of the crew’s day. Dislike of the fecal bags was so great that some crew continued to use preflight countermeasures and used medication to minimize defecation during the mission. The Apollo fecal bags and a lighter weight UCD type device are still used by Shuttle as contingency devices. The Apollo devices are included in the analysis for comparison purposes but are not recommended for Constellation missions for primary WCS functions due to the overwhelmingly negative Apollo crew feedback.

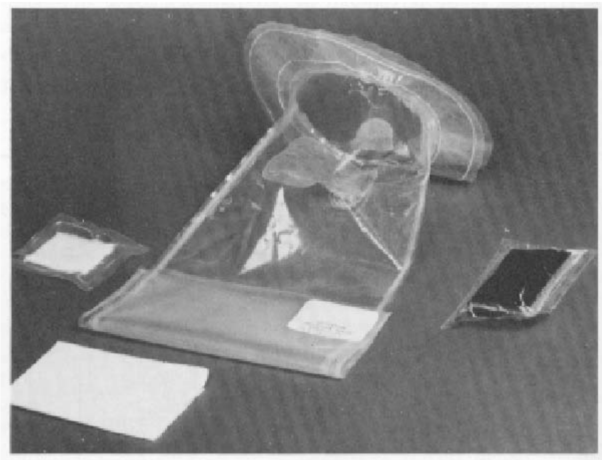

Fig. 2 – Apollo fecal collection bag with germicidal pack and wipes (Sauser and Jorgensen, 1975).

SKYLAB WCS DESCRIPTION

The three Skylab flights lasted up to 84 days and consisted of all male crews operating primarily outside of their pressurized suits. The volume required for waste management was copious by comparison to all other space vehicles. Collection and stabilization of urine and fecal waste for subsequent medical analysis was a primary requirement of the Skylab WCS. Hence, many of the WCS hardware features were oriented toward capturing each crew's waste separately. Skylab provided significant increases in WCS capability and crew comfort through the use of air flow to eliminate intimate crew contact for waste collection (MSFC Skylab Orbital Workshop Vol III, 1974). Air flow was increased to 140 l/min to eliminate previous URA splashing and urine pooling problems. Urine was entrained with airflow through a hose mounted funnel. Urine was separated from the air using rotary separators and collected in individual bags for medical evaluation. Fecal collection used a deployable sit-on seat with air flow entrainment. The crewmember's buttocks formed a seal with the seat. Air flow entered radically below the seat and converged on the bolus, drawing it down into a gas permeable bag mounted below the seat, illustrated in Figure 3. The airflow aided in the separation and capture of the bolus and minimized the need for manual feces manipulation. Individual fecal bags were used and removed for vacuum drying and storing. Air flow was returned to the cabin after odors were removed with a charcoal filter. Both urine and fecal collection systems generally received positive crew comments compared to Apollo although the crew recommended both urine and fecal airflow rates up to 50% higher to improve entrainment. The Skylab WCS was not included in the study because detail component information was unavailable to enable separation of the medical sampling hardware from the collection hardware. However, all following US and Russian WCS systems use air flow entrainment as the primary urine and fecal collection mechanism so this technology improvement is adequately captured in other analyzed WCS.

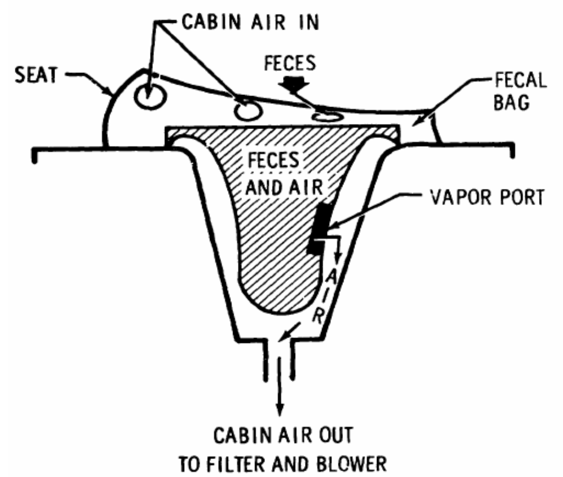

Fig. 3 – Schematic of Skylab WCS seat and bag airflow (MSFC Skylab Orbital Workshop Vol III, 1974).

SHUTTLE WCS DESCRIPTION

The development, operation, and performance of the Shuttle WCS is well documented in ICES publications (Murray, *et al*, 1982), (Winkler, *et al*, 1996). Only a brief overview is provided herein. The Shuttle WCS supports unsuited male and female urine and fecal collection for an average of 16 day missions. The Shuttle WCS is permanently mounted in a wall cavity of the Shuttle middeck for each flight, Figure 4. The Shuttle WCS has limited on-orbit capability and must be removed from the vehicle and disassembled for extensive cleaning and refurbishment between missions. Urine is entrained by airflow into a funnel. A rotary separator separates the urine and delivers it to a waste tank for overboard venting. Air is redirected to an odor/bacteria filter, containing activated charcoal and a membrane filter, and returned to the cabin, as shown in Figure 5. Fecal waste is entrained by airflow under the seat and drawn into a fixed oval tank volume. The tank is sealed and exposed to vacuum between uses to dry the feces and control odors. The tank does not use individual bags but has a single interior tank vacuum cleaner type liner to capture feces but allow air to pass. The relatively large fecal tank is repressurized with cabin gas with each use and that gas volume is lost after every use.

The Shuttle WCS has manual mechanical controls that include a slider valve under the seat to seal the tank. The seat is not contoured and some crew have had difficulty in positioning themselves over the relatively small commode hole, resulting occasional unhygienic conditions of the seat and slider valve. Additionally, to increase mission duration, used fecal wipes are not deposited in fecal tank but rather in separate gas permeable individual wet trash bags that are rolled and stored outside the WCS compartment. The fixed volume and inability to maintain or change-out the Shuttle WCS tank on-orbit illustrates an important early design decision that resulted in significant performance decreases as the Shuttle mission changed over the course of the program. A fixed volume on-orbit inaccessible tank is strongly discouraged for Constellation vehicles. There have many issues over approximately 50 missions (Rotter, H. A., 2005) that have required upgrades or minor adjustments to improve performance including separator performance, tank capacity, urine solids precipitation, funnel efficiency, crew fecal use alignment difficulties, unhygienic appearance in tank, airflow depressions, separate wipe disposal, and crew restraint flexibility. Later Shuttle missions incorporated Oxone® tables in the urinal hose assembly to pretreat the urine by lowering the pH to prevent the formation of mineral precipitates in the rotary separators and the breakdown of urea to ammonia.

There have been experiments investigating alternative WCS collections (Thornton, *et al*, 1991) but only complete flight systems are considered in this analysis.

Fig. 4 – Shuttle WCS illustrating smooth minimally contoured seat positioned back from front face. Multiple crew restraint options are provided (thigh bars, hand holds, lap belt, foot restraints, and toe bars). Most crew rapidly adjust to just the toe bar for standing urination or the thigh restraint(s) for seated operation.

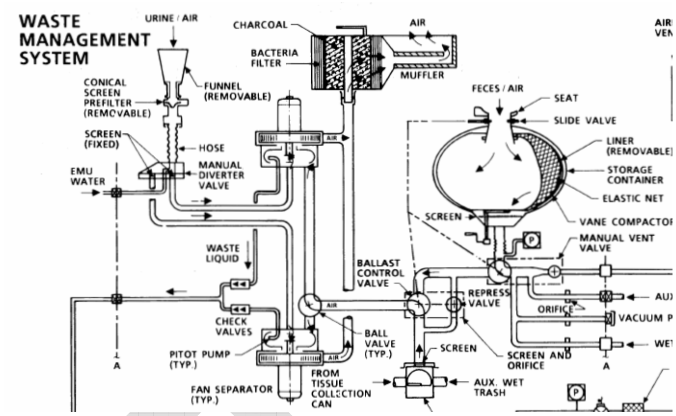

Fig. 5 – WCS flow diagram illustrating redundant fan separators and large single fecal tank. (Goldblatt, L., *et al*, 2002) <I will replace with larger and cleaned up figure in final draft>

US ISS WCS DESCRIPTION

The development, operation, and performance of the Extended Duration Orbiter/Risk Mitigation Experiment operation are well documented in ICES publications (Rethke, D. W., 1990), (Brasseaux, H. J., 1990), (Goldblatt, L., 2002). The unit was originally designed to address Shuttle WCS limitations and have a common design suitable for the Shuttle and International Space Station. Due to ISS maintenance requirements the unit has extensive on-orbit component change out capability, in-line redundancy, and electrical power optimization. The unit is also referred to the US ISS WCS. This paper uses that nomenclature because the Shuttle flight was primarily to validate the new features for ISS. However, due to significant US urine processor performance limitations, the original interface parameters to which the ISS US WCS components were designed to were no longer valid. Due to ISS Program funding constraints that prevented US ISS WCS modification, the ISS Program is currently modifying a Russian Service Module toilet for the ISS US segment.

The primary enhancements in the US ISS WCS, depicted in Figure 6, were support of indefinite mission length, individual fecal bags, compaction of fecal and wipe material, non-vented storage, improved transport of fecal material, larger commode opening, improved female interface, and extensive on-orbit component maintainability. Physically, urine and feces entrainment is similar to Shuttle WCS. However, the hardware is significantly different with the exception of the urinal funnels, as shown in Figure 6. Separate fans for urine and fecal collection, illustrated in Figures 7 and 8, provided more consistent airflow and reduced electrical power. The fecal collection is the most apparent change, as shown in Figure 6. The pronounced seat contours provide a better buttocks seal and improved bolus separation. The distance between the seat and front surface was reduced and notched for improved female funnel positioning. Individual gas permeable fecal collection bags provide a more hygienic and aesthetically acceptable crew experience, were incorporated. Functionally, these bags are similar to those on Skylab WCS and the Russian MIR WCS but have undergone several design iterations to reduce mass and improve performance. After each use the crew releases the bag into the air stream, inserts a plastic lid, and mechanically compact the fecal canister. The ISS WCS flew on the four Shuttle flights as a detailed test object. The unit was flown four times to resolve unexpected performance issues including fecal pop-corning, fecal compaction spring back, check valve performance, and airflow rate modifications. Although the crew indicated that performance was substantially improved over the Shuttle WCS, the fourth and last flight was STS-104 (7A) due to Shuttle Program funding limitations. STS-104 (Goldblatt, L, *et al*, 2002) appeared to solve the all previous crew interface issues and requirements, and received excellent crew feedback. The only improvement suggested was to replace the automated mechanical compactor with a manual compactor.

Fig. 6 – US ISS WCS detailed Test Objective Unit illustrating the front accessible fecal cylinder (behind the stowed foot restraints), contoured seat, and mechanical fecal compactor).

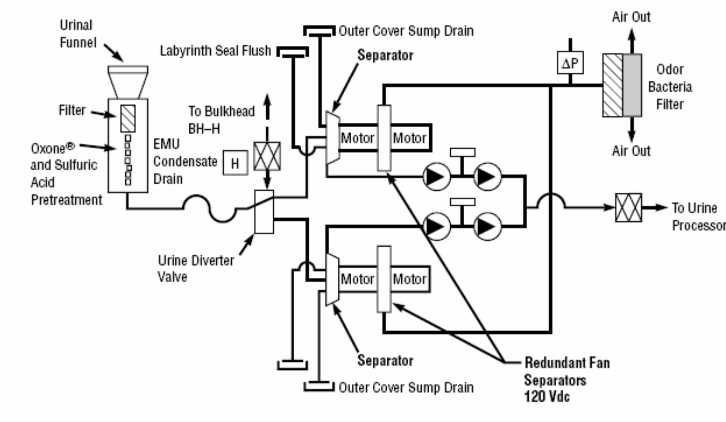

Fig. 7 – US ISS WCS urine collection flow diagram illustrating completely separate air system and redundant fan separators (Wieland, P. O., 1998).

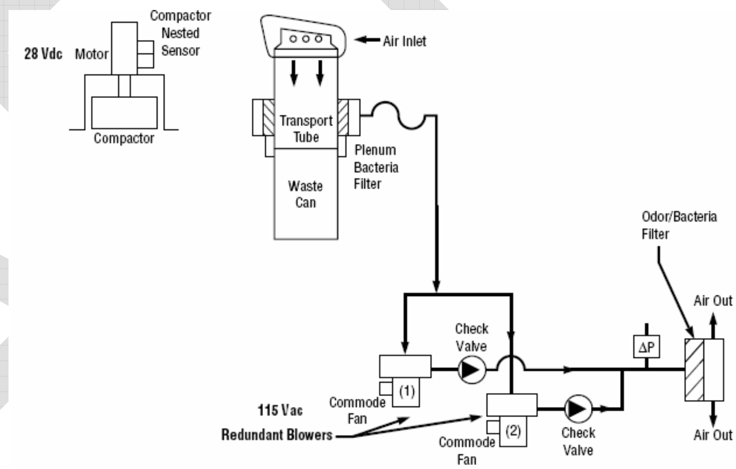

Fig. 8 – US ISS WCS fecal collection flow diagram illustrating separate air path and redundant fans (Wieland, P. O., 1998).

RUSSIAN SOYUZ ACУ DESCRIPTION

The Russian Soyuz toilet (the Russian acronym is Soyuz ACУ) is part of the Soyuz orbital module. A photo of the ACУ components is shown in Figure 9 and a schematic is illustrated in Figure 10. The Soyuz ACУ provides very basic WCS functions for two days from launch to orbital docking and eight hour reentry missions. The system normally remains dormant for up to 180 days on-orbit. However, it was periodically used on MIR for menstrual waste collection during female crewed MIR missions. There is no automation, instrumentation, or fluid transfer, but the system does use air flow to entrain urine, control fecal material, and control odors. Several of the components are similar or use similar technology as the ISS Service Module (SM) ACУ described subsequently. The ACУ operates by the crew standing in the aisle way and manually positioning a combination funnel and fecal receptacle attached to a hose (Museum of Discovery and Science, 2006). The crew can direct the 250 l/min of air to the fecal receptacle or split it between both the urine funnel and fecal receptacle. Air flow is directed through a static separator tank containing polyvinyl formaldehyde foam material, which adsorbs the urine, before exiting a charcoal air filter and fan. A manual squeeze bulb and valve provides urine contingency operations in the event of fan failure, as illustrated in Figure 9.

For fecal collection, a porous bag is placed in the receptacle. Once defecation is complete, the bag is removed, placed sequentially in three bags, and then placed in a wet trash compartment. Based on personal conversations with ACУ trainers, urine collection is acceptable but fecal use is avoided if at all possible with the crew using diet restrictions and preventive measures prior to flight. The system has limited capacity and the history of flight anonymities is unknown.

Fig. 10 – Soyuz ACУ components at Museum of Discovery and Science in Fort Lauderdale, Fl. Illustrates combination funnel and fecal receptacle on left side.

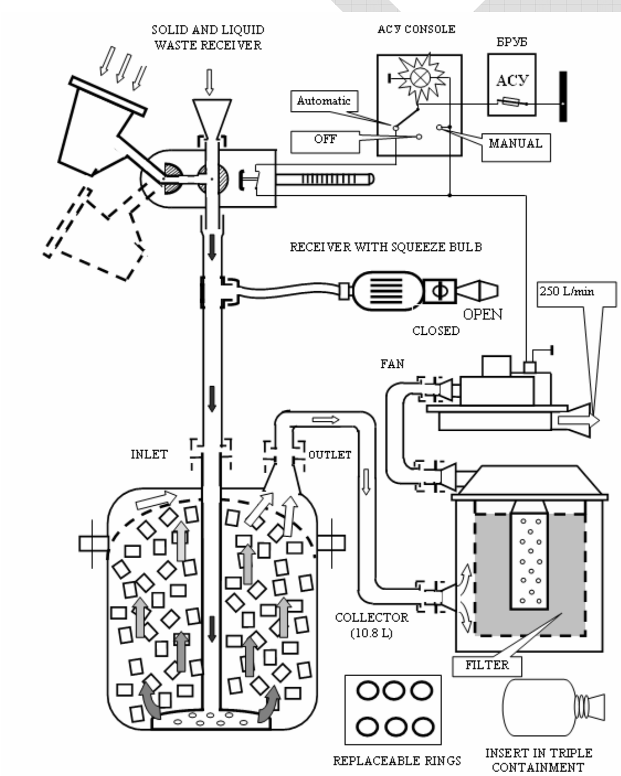

Fig.9 – Soyuz ACУ flow diagram illustrating static separator and combined funnel and fecal receptacle.

RUSSIAN SERVICE MODULE ACУ

The Russian Service Module toilet (Russian acronym is SM ACУ) is a derivative of the Russian MIR ACУ. The MIR system was similar to the SM system, however, the early MIR system used a series of three static separators. Later, the MIR ACУ was upgraded to replace the static separators with a single rotary separator. The SM ACУ provides long term WCS functions for mixed gender ISS crews in a dedicated compartment, shown in Figure 11. The physics of air entrainment are similar for the SM ACУ and US WCS. The SM ACУ is a distributed system that is not hydraulically integrated with the rest of the vehicle. Generally, fixed tanks are used for pretreat chemical, flush water, and pretreated urine. Figure 12 shows the hydraulic schematic (Broyan, J. L., 2006).

Urine is air entrained in a funnel which passes through a course particulate filter. The urine is pretreated with a mixture of deionized water, sulfuric acid, and chromium trioxide to reduce the pH to 1.3 to 2.0 (Holder, D. W., 2003). The pretreated urine is removed by a rotary separator and is delivered to a urine storage bladder tank. When the urine tank is full, it is removed and drained into the Progress Rodnik tank. Special one-use funnel inserts are used to accommodate female menstrual waste.

Fecal waste is collected in a fixed canister with a seat mounted on top. The seat uses radial air flow and individual fecal bags functionally similar to the US ISS WCS. The crew defecates into the porous bag, places wipes in the bag, and then releases the elastic cord attaching it to the seat and closes off the fecal bag. Air flow draws the bag to the bottom of the fecal tank. The tank has a capacity for 21 defecations. When the fecal tank is full, the seat is removed and the tank capped, removed and placed in the Progress. There is no compaction of fecal waste.

Fig. 11 – Service Module ACY compartment illustrating urinal funnel (yellow item on left) and seat/fecal receptacle on lower right (NASA photo archives).

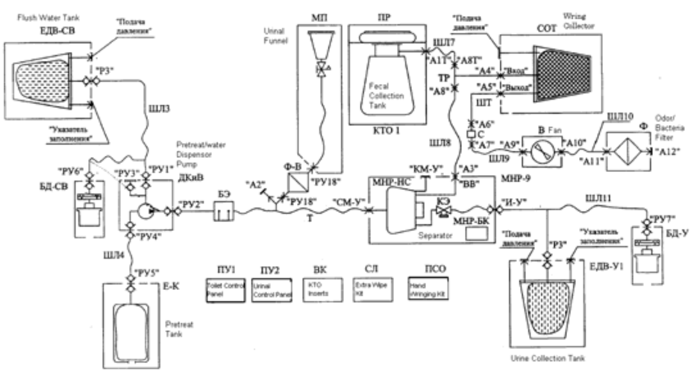

Fig. 12 – Service Module ACY flow diagram. (Broyan, 2006). <I will make image larger and cleanup format.>

The ACY components require a significant amount of maintenance as they are replaced regularly and frequently with the majority of the system being replaced within one year. Sufficient quantities of spares for all ACY components and consumables are maintained on orbit at all times or ready for Progress launch. Maintenance has been performed only by Russian crew. Maintenance is understood to be relatively easy, but time consuming. The ACY has received positive crew feedback for ease of use, is comparable to the US ISS WCS, and preferred over the US Shuttle WCS. The ISS Program is currently adapting a SM ACY for use in a single US rack in the US segment. The US segment ACY will be integrated with potable water and urine fluid buses with modifications to Figure 12.

WCS COMPARISON

ANALYSIS METHOD

As reviewed above, WCS hardware systems differ substantially because of the wide range of the state of technology and past design mission parameters including: crew size and gender, vehicle volume, mission duration, and reliability requirements. Table 1 summarizes the major functional characteristics of each vehicle.

Table 1. Previous and existing WCS major functional characteristics.

		General System		Urine Collection	Fecal Collection	Analysis	
	Vehicle	Air capture	Female Crew	Crew Feedback	Crew Feedback	Included	Known System Detail
US	Mercury	n/a	n/a	neutral	n/a	No	n/a
	Gemini	n/a	n/a	leaked	very negative	No	n/a
	Apollo	n/a	n/a	adequate	very negative	Yes	Good
	Skylab	Yes	possible	positive	neutral	No	n/a
	Shuttle	Yes	Yes	positive	neutral	Yes	Good
	US ISS WCS	Yes	Yes	positive	positive	Yes	Good
Russian	Soyuz	Yes	Yes	positive	negative	Yes	Derived
	MIR	Yes	Yes	unknown	unknown	No	n/a
	Service Module	Yes	Yes	positive	positive	Yes	Good

Comparing one vehicle's WCS against another does not result in a fair comparison. This paper proposes that a more objective method is the comparison of fluid technologies required to provide basic WCS functionalities. The technologies can be applied to any WCS and include urine capture, fecal capture, air handling, and urine pretreatment. The definitions of each technology are as follows:

- Urine capture encompasses the collection from male and female crew including menstrual wastes.
- Fecal collection is collection of solid and loose stool.
- Air handling includes movement of air and capture of odor during waste collection. Air handling hardware can be common for both fecal and urine collection.
- Urine pretreatment is not included in urine capture because it represents the ability to stabilize urine for longer duration missions and water recovery but introduces additional chemical handling hazards within a vehicle.

Five vehicle WCS, indicated in the right column of Table 1, representing the range of technology, hardware implementation, and available detail, were analyzed. The major hardware characteristics are listed in Table 2 by material technology.

Table 2. Analyzed major WCS hardware characteristics by material technology.

	US			Russian	
Vehicle	Apollo	Shuttle	Shuttle EDO/RME	Soyuz	Service Module
General System					
Total mass [kg]	Varies	75	111	25	113
Total volume [m^3]	Varies	0.34	0.34	0.10	0.74
In-line redundancy	No	Yes	Yes	No	No
On-orbit maintainable	n/a	No	Yes	No	Yes
Number of major components	6	11	16	6	16
Urine Technology					
Capacity [L]	no limit	no limit	no limit	10.8	22 / tank
Intimate contact	Yes	No	No	No	No
Separation technology	n/a	Rotary	Rotary	Adsorber	Rotary
Menstrual Compatible	No	Yes	Yes	Yes	Yes
Pretreat Technology					
Pretreat chemical	n/a	Oxone	Oxone	n/a	Sulfuric acid + hexavalent chrome
Pretreat delivery	n/a	Manual daily tablet	Manual daily tablet	n/a	Automatic liquid injection
Urine disposal	Vent	Vent	Vent	Tank	Tank
Fecal Technology					
Capacity [defecations per unit]	1	112	21	1	21
Individual bags	Yes	No	Yes	Yes	Yes
Comode opening diameter [cm]	~15	~10	~20	~15	~15
Crew manipulation	Yes	No	No	Yes	No
Compaction	n/a	Limited	Yes	No	No
Fecal Disposal	Trash volume	Fixed tank	Replaceable canister	Trash volume	Replaceable tank
Over board vent	Yes	Yes	No	No	No
Fecal Stability	germicide	vacuum	breathable filter	No	sealed tank
Air Technology					
Urinal air flow rate [l/min]	n/a	283	382	120	250
Fecal Airflow Rate [m^3/min]	n/a	453	424	120-250	400
Common fan	n/a	Yes	No	Yes	Yes
Odor Control	No	Yes	Yes	Yes	Yes
Bacteria Control	No	Yes	Yes	No	No

Technology categories were assigned to detail component mass, volume, capacity, and service life. WCS components that contact the indicated material were included in that technology. Consumable mass and volumes were normalized by their service capacity for components that stored waste. The long term change out of components due to service life was not addressed in this analysis but should be in longer term lunar surface WCS analysis.

This analysis presents data using direct mass and volume comparisons derived from the existing vehicle parameters. The application of the equivalent system mass (ESM) approach (Levri, J. A., *et al*, 2003) is left to future applications of specific spacecraft missions where the nuances in mass equivalences can be tailored for the particular study. The use of ESM is more applicable to assessing the impact of WCS selection on interfacing waste processing systems (Drysdale, A., 2004). The differences between WCS electrical power usage and lost atmospheric gas should produce relatively minor differences from these results. Furthermore, this analysis treats each hardware system as it exists and does not account for possible mass or volume enhancements that may be possible with redesign, except at the end where extensions of WCS technologies to Constellation are discussed. The use of wipes, tissues, and gloves is fairly consistent between Shuttle WCS, US ISS WCS, and SM-ACY. Specific wipe data could not be located for Apollo so it was considered 50% higher than current average usage rates due to the negative crew feedback about the difficulty in maintaining hygienic conditions.

Data Source Descriptions

- Apollo UCD and fecal bag data was drawn from current Shuttle mission data. Both items are manifested as contingency items.
- Shuttle WCS data was based on current Shuttle mission planning data, structures qualification data, and personnel conversations with a former Shuttle WCS project manager (Mathew Fritz).
- US ISS WCS data was based on previous mission planning data, CDR data package, and personnel conversations with a former US ISS WCS project manager (Ketan Chippwadia).
- Soyuz ACY data was based on analysis of web based information from (Museum of Discovery and Science, Fort Lauderdale, FL), extrapolation of Service Module component data, and engineering estimates.
- Service Module ACY data was based on NASA's digital information management system, manifest information, and data exchanged from 1999 to 2006 during US-Russian technical interchange meetings (Broyan, J. L., 2003-2006). Missing component information was completed with engineering estimates.

For all systems, the mass and volume remaining after component categorization, such as structure, and electronics, was proportionally distributed to the four technology categories. Detailed WCS components data was categorized into appropriate material technology categories. The individual components were applied to the typical lunar CEV mission. The lunar CEV mission considered a crew of four and a total mission duration of 18 days (nominal and contingency). Metabolic waste generation was assumed to be seven micturitions per crew per day and 1.5 defecations per crew per day. These values are higher than planned for ISS, which were 6 and 1.0 respectively, to account for higher crew variability that can occur on shorter missions. Therefore, a CEV-like system must accommodate up to 504 urinations and 108 defecations per mission.

Figures 13 and 14 show the results of analysis of detailed component mass and volume data analysis applied to a lunar type CEV mission.

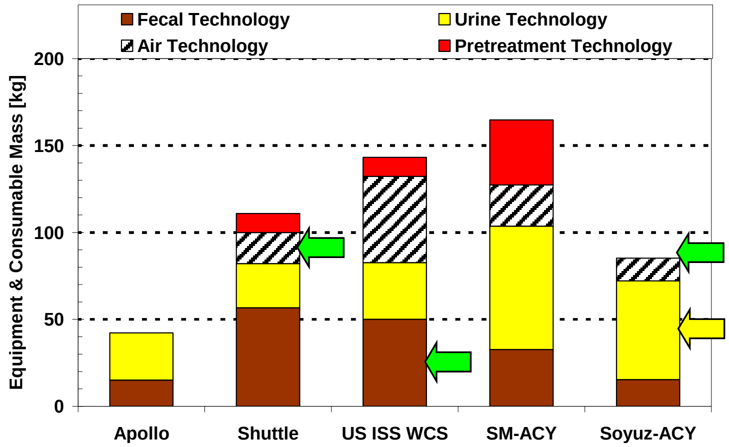

Fig. 13 - Mass of existing WCS technologies scaled to typical lunar CEV mission. Illustrates the wide variety in technologies implemented in space vehicles. WCS material technologies are represented individually and in the total system.

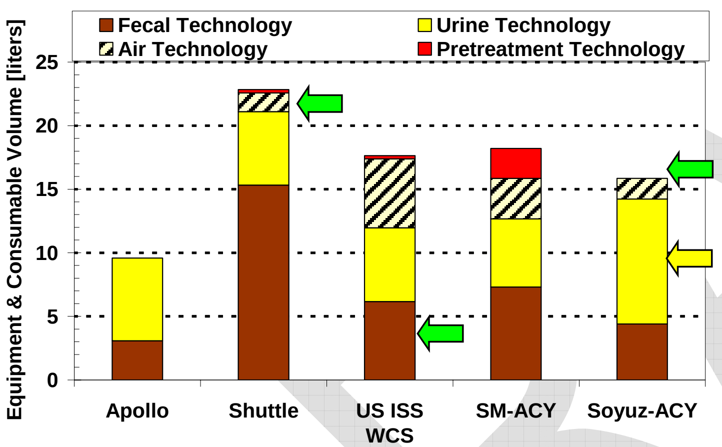

Fig. 14 - Volume of existing WCS technologies scaled to lunar CEV mission.

It is necessary to look at both the mass and volume results concurrently to draw conclusions. The arrows point out specific technologies that will be discussed in the extension to Constellation missions section. The following broad interpretations and explanations on the results can be made:

- Not surprisingly, Apollo has the lowest overall mass and volume. However, it has the fewest crew interface accommodations and consequently has the most unsatisfactory crew interface.
- Apollo WCS and Soyuz ACY do not use pretreatment, so there is no pretreat mass and volume impact. The Shuttle and US ISS WCS pretreatment technologies are the same Oxone® tables. The tablets are small and concentrated and are mounted in a hose section that has limited mass and volume impact. The SM ACY uses liquid chromic acid. The larger mass and volume result for the flush water and pretreat tanks, the pretreat pump, and associated instrumentation that have a significant penalty for a short mission duration.
- The Apollo WCS does not have air handling so there is no mass and volume impact. The Soyuz ACY has a small fan and associated low airflow. The Shuttle WCS, US ISS WCS, and SM ACY all have comparable air flow rates. The larger US ISS WCS air technology results from the redundancy requirement imposed and separate urine and fecal air handling systems. The separate air handling systems reduce electrical power consumption, since a smaller fan can operate for just urination. However, separate air handling systems are a significant mass penalty for short mission durations.
- The Apollo WCS uses an individual UCD for every micturition, which is a different approach than one the Apollo crew could use all day. Soyuz ACY has a static separator that requires a fixed ratio of absorber material to urine. The Soyuz ACY static separator is currently non-vented and not regenerated. If the Soyuz ACY static separator was able to regenerate, the savings would be substantial. The Shuttle and US ISS WCS have comparable urine and technologies because both utilize redundant rotary fan separators. The SM ACY is comparable in urine technology but only has a single rotary separator.
- The storage of fecal waste is a substantial portion of WCS weight. The Apollo and Soyuz ACY systems include only the consumables for manually removing and containing the fecal waste. The Shuttle WCS is volumetrically large, not only because of the large oval tank but also the mechanical linkages required to operate it. The US ISS WCS is comprised of the transport tube, fecal canister, and compactor. As noted in the STS-104 debrief, the compactor was recommended to be removed. The SM ACY is primarily the fecal storage tank. An analysis of only fecal storage hardware was performed to help distinguish the differences between technologies for longer Constellation surface missions. The CEV selection of WCS should consider compatibility with longer duration missions. The mass and volume analysis results of just the fecal storage methods are presented in Figure 15.

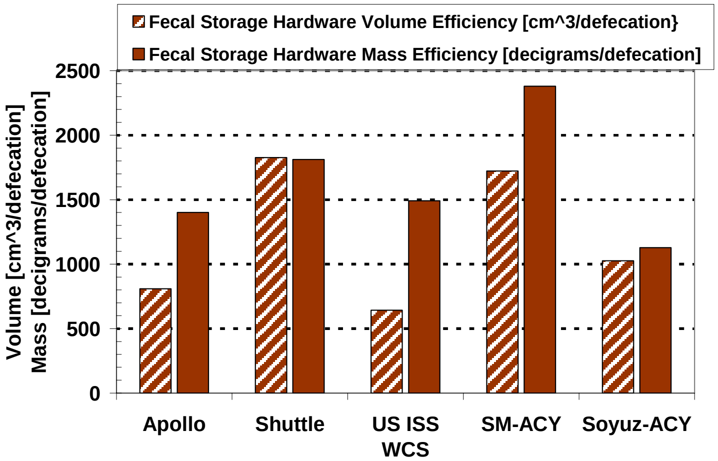

Fig. 15 - Mass and volume efficiency of existing WCS technology fecal storage efficiency. Illustrates the dramatic differences in volume between systems that compact and do not compact fecal waste.

Apollo relied on manual rolling of the fecal bag for compaction. Shuttle relies on a relatively flexible elastic webbing material that 'gathers' the waste rather than compacting it. Additionally, the Shuttle WCS tank does not accommodate wipes and other 'paper products' in the current application. The US ISS WCS achieves an effective compaction of the fecal and wipe material. It provides the lowest storage volume, reasonable mass allocations, and a good crew interface. The RS SM does not provide compaction but does collect fecal wipes so it has a slight penalty over the Shuttle WCS. The Soyuz is comparable to Apollo bags because the waste is also manually compacted. The Apollo or Soyuz interfaces are both poor crew interfaces.

<u>Extension to Constellation missions</u>

As stated earlier, there are often numerous performance issues between ground and simulated zero-g performance and orbital WCS experience. The existing WCS systems have several good crew interfaces and technologies and future Constellation WCS applications should strongly consider them. The crew physical interface and urine/fecal capture physics are critical and should remain unchanged for Constellation. The hardware 'behind the seat and funnel' is more flexible for the incorporation of technology enhancements. The above analysis indicates that no one WCS approach has the best combination of technologies. It is proposed that the best WCS technologies could be combined to provide a robust proven crew interface and reasonable mass and volume characteristics for each technology area. For example in reviewing Figures 13-15, the following individual technologies provide the best mass and volume:

- Air Technology: The Shuttle air handling system has the lowest mass and volume primarily due to its common urine and fecal fan (combined fan/separator motor assembly).
- Urine Technology: Rotary separators are very mature technologies (Shuttle and ISS US WCS) and have reasonable mass and volume. However, they are the weak link in any system. Separators need to be protected from particles, menstrual waste, precipitates, unplanned liquids and mechanical damage from launch/landing loads. However as discussed subsequently, the Soyuz ACY urine collection has potential to address the rotary separator weaknesses.
- Pretreat Technology: The chemical Oxone® is the only on-orbit US experience and the mass and volumes are reasonable for short missions. However, if a static separator were successfully developed, the pretreatment system is not required. Its deletion would remove a hazardous material from the crew volume. However, depending on the system design, pretreat may still be required to maintain stability during dormant periods.
- Fecal Technology: Although the Apollo system provides the lowest mass and volume, the fecal crew interface is considered unacceptable for maintaining cabin hygiene. The fecal collection of the US ISS WCS is recommended due to its low total volume, storage efficiency, suitability for longer term missions, and ability to transfer stored waste between vehicles.

These basic technologies could serve as the starting point for a Constellation WCS. Several improvements are possible and could warrant additional research and design:

- The Shuttle air handling system is acoustically loud and a single quieter US ISS WCS fan could be used.
- If a static separator were able to be regenerated through periodic overboard venting or other means, its volume could be comparable to the Soyuz ACY urine collector. Absorber and capillary separators could both be developed for this application. The static separator tolerates particulate and menstrual loading so a particulate filter is not required, further reducing mass and air pressure restrictions. Additionally, the Apollo URA could be modified to allow female use. The modified URA could then function as a low mass contingency device, rather than UCDs. For lunar surface operations where partial gravity is available, the static separator could be replaced with simpler baffled tanks for separation, collection, and storage prior to treatment. Depending on the water recovery technology selected, urine pretreat may be required to be added.
- The US ISS WCS fecal system is applicable to both zero and lunar partial gravity and would allow commonality and transport of wastes between the transit and the surface missions. It is recommended to maintain the US ISS WCS fecal collection seat characteristics, airflow and general bag volume. However, improvements in the bag, if the 30.5 cm bolus length requirements can be reduced to more representative values, canister, and compaction

method are areas of possible mass and volume reductions.

Figure 16 illustrates one possible concept using the technologies and enhancements above. The crew would urinate into a Shuttle style personal funnel with US ISS WCS air flow characteristics. A common fan US ISS WCS, odor bacteria filter, and air muffler would provide the required airflow. Urine would be separated and captured in a new static separator prior using Apollo-like overboard venting. The static separator would have sufficient capacity to hold urine during non-vented periods. No pretreatment or particulate filtration would be required. Feces would be collected in an US ISS WCS based system with its air flow characteristics. The canister would be modified for the vehicle geometry. Urine contingency storage could be accomplished with a modified URA type device for direct vent to vacuum. Contingency fecal operations would use the US ISS WCS fecal bags in an Apollo like application with additional wipes and gloves. If the static separator development does not lead to satisfactory performance, it could be replaced with a rotary separator, particulate filtration, and pretreat.

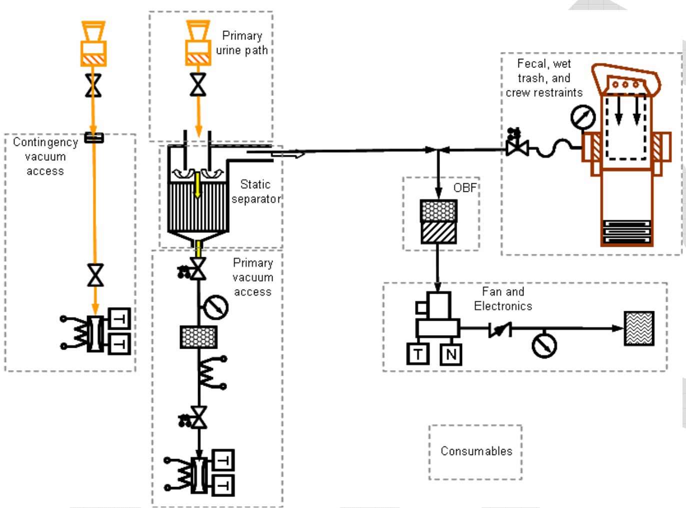

Fig. 16 – CEV Concept based on use of best exiting WCS technologies.

The change out of just a few urine components would allow for the transition from a zero-gravity transit WCS to partial gravity surface WCS. Maintaining commonality would provide robustness in sharing spares and consumables across Constellation vehicles.

CONCLUSION

As previous WCS experience has indicated, it is difficult to accurately predict and test new WCS to crew interfaces. Existing WCS have good interface options that should be used for future missions to minimize the possibility of unexpected on-orbit performance. The analysis using the four WCS technologies, encompassing urine, fecal, air, and pretreat, provides a means to objectively select the best characteristics of each and utilize them as a starting point for Constellation mission WCS. However, the analysis should not only drive to reduce mass and volume. Early design selections should allow future mission flexibility by including hardware commonality between vehicles and the ability to transport waste between vehicles, unlike the Shuttle WCS fixed tank. Finally, and most critical is to seriously consider crew feedback on human factors, odor control, and mission flexibility. Failure to completely and effectively capture waste can result in unhygienic conditions, spread of substantial quantities of bacterial contamination, noxious odor problems, and crew reluctance to use. Consequently, ineffective WCS operations can result in decreased crew performance. Past mature US WCS hardware from Shuttle and US ISS WCS have incorporated a rigorous process of post mission crew debriefs to understand issues and concerns followed with implementation of numerous hardware improvements that have been validated during subsequent flights. These mature WCS interfaces should be used for Constellation.

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DEFINITIONS, ACRONYMS, ABBREVIATIONS

АСУ	Ассенизацио нно- санитарное устройство roughly translated as the Russian Waste Management System. For purpose of this paper it is equivalent to the US acronym WCS
CEV	Crew Exploration Vehicle
ECLSS	Environmental Controls and Life Support Systems
ESM	Equivalent System Mass
ISS	International Space Station
JSC	Johnson Space Center
MSFC	Marshall Space Flight Center
NASA	National Aeronautics and Space Association
SM	Service Module
STS	Space Transportation System
UCD	Urine Collection Device
UCTA	Urine Collection Transfer Assembly
URA	Urine Receptacle Assembly
US	United States
UTS	Urine Transfer System
WCS	Waste Collector System