Dual Fan Separator within the Universal Waste Management System

Tom Stapleton[1]
UTAS, Windsor Locks, CT.

Dave Converse[2]
UTAS, Windsor Locks, CT.

James Lee Broyan, Jr[3]
NASA Johnson Space Center, Houston, TX

Since NASA's new spacecraft in development for both LEO and Deep Space capability have considerable crew volume reduction in comparison to the Space Shuttle, it is clear that NASA requires a smaller and less expensive commode. The UTAS Universal Waste Management System (UWMS) was designed to address these new constraints, resulting in an 80% volume reduction in the cabin while enhancing performance. Whereas all of the current space commodes use air flow to capture both urine and feces and separate air from the captured air/urine mixture, the UWMS commode and urine fans and the urine separator were combined into a single unit. This unit enables use of a single motor and motor controller, which provides considerable packaging and weight efficiency. In some of the intended platform applications for the UWMS, the urine is pumped to a water reclamation system. The ISS Urine Processor Assembly (UPA) system requires delivered urine to include less than 0.25% air inclusion. Air inclusion in centrifugal urine separators is greatly dependent on its rotational speed. To satisfy this requirement, a gear reducer was included, allowing the fans to rotate at a much higher speed than the separator. This new design, the Dual Fan Separator (DFS) has been designed, prototyped and tested. This paper will outline the studies and analysis performed to develop the design configuration for testing. The studies included a configuration trade study, dynamic stability analysis of the rotating bodies and a performance analysis of included labyrinth seals. NASA is considereing a program to fly the UWMS aboard the ISS as a flight experiment. The goal of the design activity is to elevate the Technical Readiness Level (TRL) of the Dual Fan Separator and determine if the concept is ready to be included in flight experiment deliverable.

Nomenclature

CEV	=	Crew Exploration Vehicle
DFS	=	Dual Fan Separator
EDO	=	Extended Duration Oribiter
LEO	=	low Earth orbit
SLA	=	stereolithography
TRL	=	technology readiness level
WCS	=	Waste Collection System
UCS	=	Urine Collection System
UPA	=	Urine Processor Assembly
UWMS	=	Universal Waste Management System

[1] Research Engineer, Advanced Tech., 1 Hamilton Road, Windsor Locks, Ct Thomas.Stapleton@utas.utc.com
[2] Principal Engineer, Advanced Tech., 1 Hamilton Road, Windsor Locks, Ct Dave.Converse@utas.utc.com
[3]AES Logistics Reduction and Repurposing Project Manager, Crew & Thermal Systems Division, 2101 NASA Parkway, Houston, TX, 77058/Mail Stop EC7.

I. Introduction

Low Earth Orbit (LEO) and Deep Space Habitat vehicles currently being developed by NASA are considerably smaller than the Shuttle and ISS crew habitat volumes. Starting with Skylab there have been at least five waste management systems developed for LEO applications[1]. All of these have required a substantial volume and mass of equipment to try and provide satisfactory crew comfort, cleanliness and performance. The Universal Waste Management System (UWMS) (Figure 1) was designed to offer the performance of the large systems while using 80% less volume.

The UWMS includes human interface features derived from those found in the Waste Management System (WMS) developed for the Extended Duration Orbiter (EDO) in the early 1990's[3,4]. The EDO WMS flew as the primary waste collection unit on the Shuttle four times and it resolved several challenges that occur in microgravity that are extremely difficult to resolve on the ground. Specifically, the EDO WMS allowed determination of the urine airflow rate and suction pressure, and fecal airflow rate to avoid excessive turbulence that results in erratic fecal collection. Additionally the fecal collection canisters and individual fecal bags were modified to improve fecal compaction efficiency by minimizing the spring back of hygiene wipes[5]. The EDO WMS compaction efficiency provides a volume advantage in fecal consumables over existing US and Russian waste collection systems. The UWMS has these key urine and fecal collection attributes and decreases the installed mass and volume of the supporting hardware.

The UWMS consists of two subsystems, the Commode (fecal collection) and the Urine Collection System (UCS). Each depends upon its own fan for air movement to capture waste products and manage odor. The UCS also includes a centrifugal urine separator, which separates urine from the urine air mixture collected by the system. The urine is pumped by the separator to either storage vessels or to a urine processor, depending on spacecraft integration.

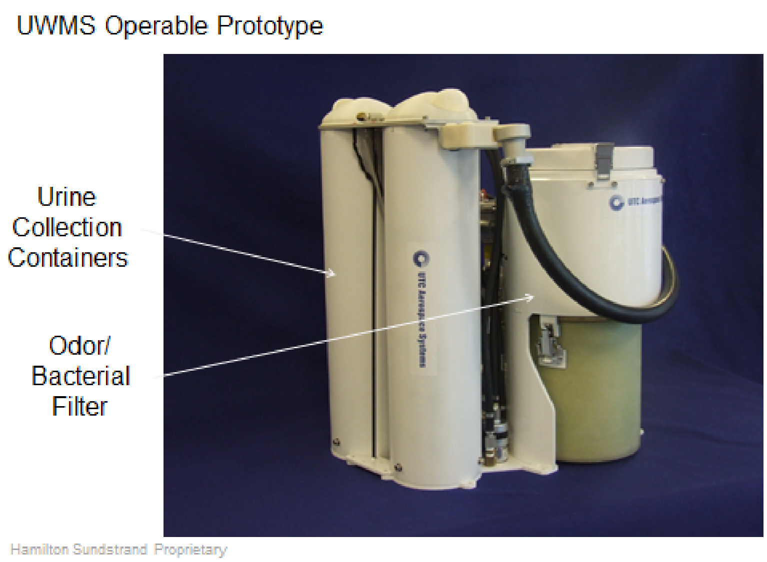

Figure 1

The two air fans and the centrifigul urine separator in the UWMS are combined into a single assembly, refered to as the Dual Fan Separtor (DFS) (Figure 2) . This combination is pivitol in achieving the considerable volume reduction needed. The DFS is driven by a single brushless dc motor (see Figure 1), the impeller diameters are optimized to achieve the expected pressure rise requirement. The previous Urine Fan had predominant high speed requirements to achieve adequate flow and pressure rise. The exact speed is proprietary, but it is several thousand rpm. Unfortunately this was too fast for the speed of the urine air centrifugal separator, so a speed reduction device was necessary to slow the separator shaft speed and increase its torque.

Once the design parameters were understood, a set of concepts were generated and studied to determine which configuration should be developed. Following the down select, the DFS was developed, built and tested (in progress). This effort was completed as an Internal Research and Development (IRAD) effort intended to increase the Technical Readiness Level (TRL) to confidence that allows the DFS to be included in a flight test.

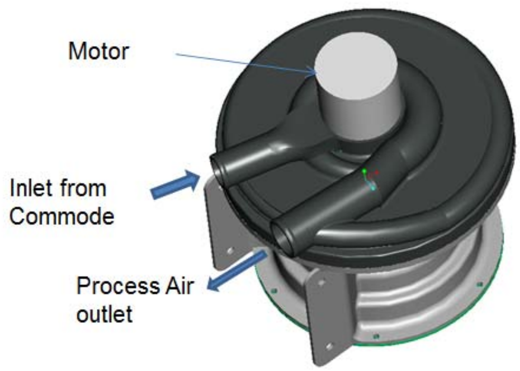

Figure 2

Urine Interface Requirements

As a historical reference, rotary separators can provide very predictable performance in a microgravity environment and have been used many times in life support functions. Rotary separators for urine-air separation were first used on NASA's Skylab WMS and have been used by the Shuttle WMS, and the ISS Russian ACY (toilet). Separating human urine imposes unique requirements on a rotary separator. In considering the final configuration and operating speeds of the urine separator the following design requirements were considered.

Chemical Requirements: Urine density, particulate load, and chemical composition vary widely[6] and urine constituents break down due to microbial action and chemical decomposition. This can form precipitates that can foul rotary separator fluid passages and cause crevice corrosion. Strong acids and oxidizers are often used to prevent precipitation by keeping urine constituents in solution and inhibiting microbial growth. Use of the pretreatment requires very careful selection of high corrosion resistant materials (e.g. titanium and high nickel alloys, and fluorocarbon polymers).

Volumetric Requirements: The individual urine void volume (30-1000 ml) and flow rates (5-50 ml/s) are also highly variable. These volumes and flow rates are strong factors in sizing the rotary separator bowl liquid volume and the rate at which it must be able to pump out liquid. Additionally the rotary separator must have sufficient torque capability to centrifugally accelerate a large slug of urine that can collect in the urine funnel hose if air flow is blocked during urination and then the blockage is removed. Failure to size for slug flow has resulted in multiple separator upsets on Shuttle flights.

Particulate Requirements: The air-urine mixture entering the separator is generally only coarsely filtered with a wire mesh screen to prevent large debris from damaging the separator. Finer filtration is generally not possible because of the difficulty of maintaining adequate airflow for efficient capture from the crewman. Hence, the separator needs to handle a large number of small particles from dander and lint in the air.

Pressure Requirements: Urine is transferred from the WMS of all spacecraft to one of three locations: direct overboard venting, a holding tank (for later venting, disposal, or processing), or directly connecting water recovery system. The type of system it connects to is a very important factor in setting requirements for a WMS rotary separator. The rotary separator must be able to generate sufficient pressure rise to deliver urine to the downstream system at a minimum flow rate. Additionally, the rotary separator must not generate a pressure or flow rate that exceeds the capability of the downstream tanks or processing equipment. This is not a static problem because the urine flow rate into the separator and accumulation of liquid within the separator bowl can vary widely over a micturition cycle.

Free Gas Requirements: A rotary separator's primary function is to separate air from urine, but separation is generally not 100%. Urine liquid carry over in the air is generally very unacceptable and is typically defined at the aerosol level. For practical purposes, air entering the urine funnel is well below 100% relatively humidly but becomes near 100% relative humidity due to very large liquid/gas interface interaction. Water loss from evaporation can approach 3% of the urine void volume. Urine will also fully saturate with dissolved gas from this liquid/gas interface and essentially nothing can be done to prevent it. Gas that becomes entrained in the output of the rotary separator and is physically separate from the liquid is termed free gas. Free gas content is strongly determined by the rotary separator design and how it is integrated into the rest of the WMS. For spacecraft that directly vent urine, or automatically drain a tank (Shuttle and Multi-purpose Crew exploration Vehicle), modest amounts of free gas (<20%) is generally not a significant impact. Generally there is a trade that allowing more free gas simplifies rotary separator design and operation and results in less electrical power being required. However when the WMS is connected to a downstream water processing system, rotary separator free gas can be detrimental to water processor performance. This is particularly true for systems that use distillation as part of the water recovery system.

The ISS water processor includes a Urine Processor Assembly (UPA) as an initial treatment for urine. The UPA utilizes a low temperature (~130C) low pressure (~3psia) distillation process. The low temperature is required to avoid the urea present in urine from breaking down into ammonia which is difficult to process with the ISS life support systems. Evaporation of the water from the urine cannot occur until the pressure is lowered in the UPA distillation assembly. Water vapor and non-condensable gas (free gas from a rotary separator) are transferred from the UPA rotary distillation chamber to a concentric condensation chamber with a rotary pump that increases its pressure. The water vapor condenses out to water and the latent heat is recovered, but the non-condensable gas remains in the condensation chamber. During the UPA development testing, it was discovered that the UPA purge pump that removes the non-condensable gas had some significant flow rate challenges that severely limited its capability[7]. Due to UPA development schedule limitations, the purge pump capability limits the influent urine to 0.25% free gas by volume. When free gas exceeds this level, the UPA condensation chamber pressure begins to rise because the UPA purge pump cannot keep up. This results in the rotary pump between the UPA distillation and condensation chambers having to pump against a higher pressure which reduces its flow rate of water vapor. As a result, the overall production rate of the UPA is reduced and can result in unacceptable thermal rise of several UPA components. Hence, the urine free gas level must be kept low to enable integration of the UWMS on the ISS. Operationally, it may be possible to operate the UPA at a different duty cycle or change out UPA components more frequent to account for greater run time on key components and accept up to 2% free gas. For future exploration spacecraft, it should be possible to increase the capability of the purge pump of the UPA or similar systems. However, a flight demonstration on ISS is viewed as a key validation of the UWMS operation and the lower the free gas can be below 2%, the more likely an ISS flight technology demonstration is possible.

II. Trade Study

The DFS Design assessment began with a well-defined concept. Considering that a full up operational unit was to be developed, it seemed prudent to look at different alternatives. Three concepts were developed during the trade study phase. All three designs included a common fan system, consisting of a set of impellers machined into each side of a single disc. Shrouds were attached to the fan blades to capture the air being translated. One impeller pulls air through the commode, while the other pulls air through the urine separator. Each impeller translated exit air to its own volute. The first two concepts included a centrifugal urine separator that was originally developed for use aboard the Space Shuttle. The remaining concept included a paddle style separator developed for the Sabatier Assembly.

As shown in Figure 3, the impellers mount directly to the fan. The motor shaft continues to a flexible coupling which then interfaces with the gear reducer. Early tolerance studies indicated that assembly without an alignment couple was impossible. The design team became concerned with the rotor dynamic stability of this design due to the rotors low natural frequency and potential for an eccentric rotating mass. This concern encouraged the team to develop Concept 2 which coupled the brushless DC motor and the gear reducer into a single housing.

Concept 2 has definite advantages regarding rotor-dynamic stability. Close coupling speed reducers directly to the motor appears to be an industry standard. A second advantage was that one vendor would be held responsible for delivering an exit shaft to directly drive the impellers and a second shaft to directly drive the separator. The downside of this design solution is that the motor would reside in the airstream having a 100% relative humidity of urine with a pH as low as 2, which is an aggressively corrosive fluid.

Concept 3 used a separator that can operate at the fan speed in effort to remove the speed reduction component. It was believed that the separator had design capability to operate at this speed, but initial studies determined that power consumption at the impeller speed would be excessive.

Completion of the trade study resulted in selecting the initial design with the motor on top spinning the original centrifugal separator as the appropriate solution. The Dual Shafted Motor was dismissed due to the risk of placing the motor into the corrosive pre-treated urine saturated air. The concept with the paddle separator was dismissed because it required too much power operate the unit, as well as the lack of performance data above a much lower operating speed. See Table 1 for a Trade Study summary.

Following completion of the trade study three different areas were explored as part of the detail design phase, including the dynamic stability of the rotating body, fan blade performance and manufacturing techniques.

Configuration Trade Study

Design	Pros	Cons
Entry Design	• Urine Separator is TRL 9 (flight status) • Motor has minimal contact with Urine • An acceptable 150 watt estimated power	• Dynamic stability is hard to predict since it's divided between the motor and speed reducer
Dual Shaft Motor Design	• Urine Separator is TRL 9 • Removal of misalignment Coupling • CDA to supply Motor with Gear reducer integrated • 150 Watt estimated power	• Motor in corrosive airstream of 100% relative humidity of pretreated urine saturated air, having pH of 2 brings concern of damaging dc motor.
RSA Style Design	• Gear reducer and coupling are removed • Can achieve <2% air carry over, as desired for water recovery process	• Separator operating Speed is 4 times greater than other options including the OGA RSA. • Power consumption may exceed 600 watts

Table 1

-

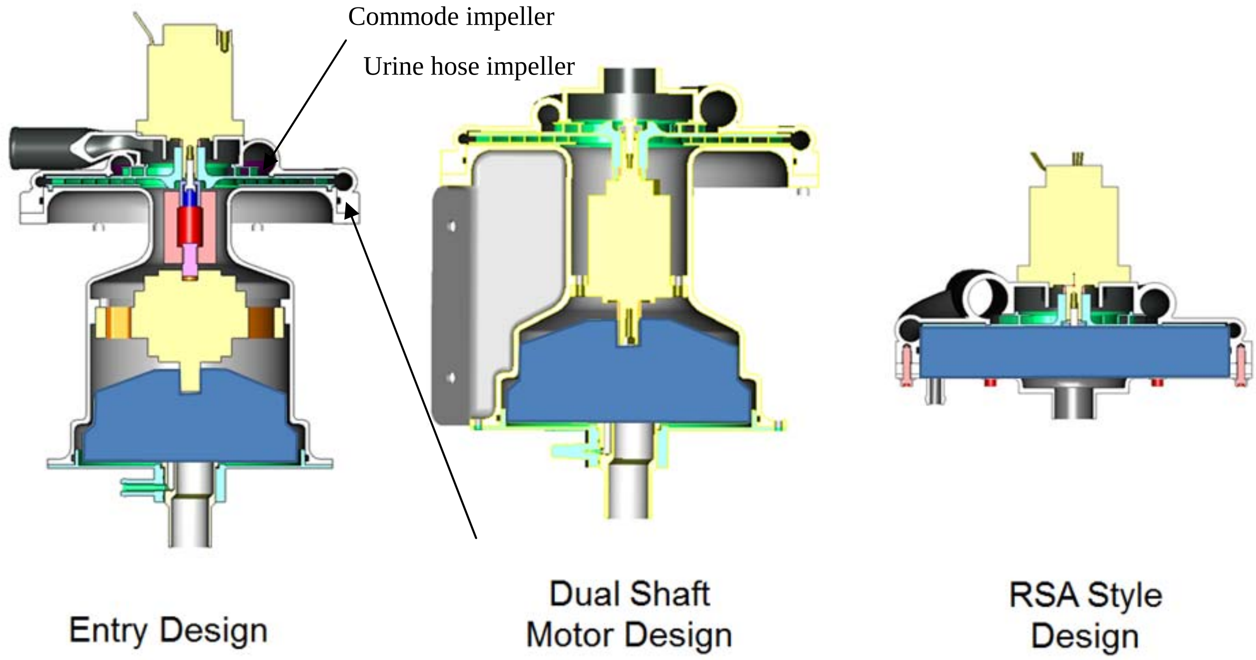

Figure 3

A. Dynamic Stability

An analysis was performed to determine the dynamic stability of the DFS. A major aspect of this assessment is based on the calculation of its critical speed, a property used to determine that the rotating body remains stable while operating at nominal speeds. Critical speed depends greatly on the rotating body's dynamic stiffness, which is the result of material properties, shaft and bearing sectional dimensions and fit tolerance. As defined "The critical speed is the theoretical angular velocity that excites the natural frequency of a rotating object, such as a shaft or gear. As the speed of rotation approaches the object's natural frequency, the object begins to resonate, which dramatically increases system vibration. The resulting resonance occurs regardless of orientation. If the rotational speed is equal to the numerical value of the natural vibration, then that speed is referred to as critical speed." [8] In rotor dynamics a rotating body should operate at least 25% from the critical speed. As a component nears its critical speed the rotating body becomes excited and unstable, causing added wear to the bearing system which results in shortened life.

Suppliers were contracted to perform critical speed analysis on the motor and gear box. With supplied environmental and operating data data a motor and gear box analysis resulted in a calculated critical speed value greatly above the operating speed of the fan impellers. Since these values were well in excess of the DFS rotating speed the team became comfortable that these two aspects would remail dynamically stable. The urine separator has been successfully operated in orbit at rotational speeds three times greater than the proposed DFS speeds, allowing continued confidence.

B. Fan Design

As stated all of the UWMS DFS components are operated by a single motor. The commode and urinal fan operate at one speed and the centrifigul urine separator spins slower. The urine hose fan supplies pressure rise about twice that of the commode fan. Pressure rise is a function of the impellar's outer diameter, causing the urine fan diameter to be 2.5 times larger than commode fan.

As the air exits each impellar it enters its own volute. The volute, in the fan housing, balances pressure through out travel through the conduit. At the exit of the commode and urinal fan, the air is combined and flows to the Odor/Bacteria Filter. The fan design may include an orifice to trim the fan performance so that predicted volumetric air flow is achieved. Achieving aerodynamic efficieny is traditionally determined by the slip gap between the impellar and the housing. Maintaining an acceptable gap becomes costly due to the the number of geometric tolerances that play a role in the final value. A shrouded impeller was considered (Figure 4) as an alternate design. A shroud is attached to each of the impellars, that reside on a single machined disc. The shrouds capture the air as it moves through the fan see Figure 4.

The main concern regarding shrouded fan technology is the ability of seals to minimize air from leaking from the air outlet back to the inlet side or from the UCS Fan outlet to the Commode Fan outlet. To prohibit this undesirable air travel, labyrinth seals were chosen as dynamic seals, which are non-contacting and have significant historical use for turbo-machinery sealing.

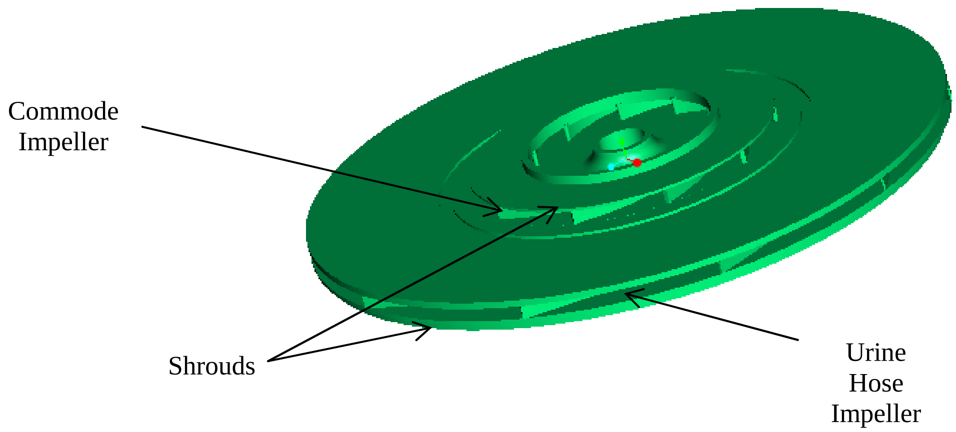

Figure 4. Fan impellar layout.

C. Labyrinth Seal

The labyrinth leals, are dynamic, in that the sealing surfaces do not contact the mating material. "By design, labyrinth seals restrict leakage by dissipating the kinetic energy of fluid flow through a series of flow constrictions and cavities that sequentially accelerate and decelerate the fluid flow or change its direction abruptly to create the maximum flow friction and turbulence." [9] .The ideal labyrinth seal would transform all kinetic energy, into internal energy (heat) in each cavity. This concept originated over 60 years ago and is used widely in turbo machinery. There are a number of factors which contribute to the leakage across the labyrinth seal, most notably the number of teeth, teeth clearance and pressure delta across the seal. <u>Seal Technology</u>[9] by Bruce Steinetz of NASA Lewis supplied the best math model for predicting DFS seal leakage. In the case of the DFS, all the factors had been fixed except for the labyrinth gap and the number of seal "teeth". As shown in Figure 5, there are three labyrinth seals included in the design. Starting at the top and rotating clockwise, they include the Commode Fan Outlet to Commode Fan Inlet, the Commode Fan Outlet to the Urine Fan Outlet and the Urine Fan Outlet to the Urine Fan Inlet.For this exercise a one tooth labyrinth seal configuration was chosen. The impact of the labyrinth seal gap to leakage is graphed in Figure 6. To minimize leakage for seals 1 and 2 (Figure 5) the impeller was shimmed to the motor shaft. To minimize leakage for seals 3 (Figure 5) the Separator Housing was shimmed to the Volute Housing.

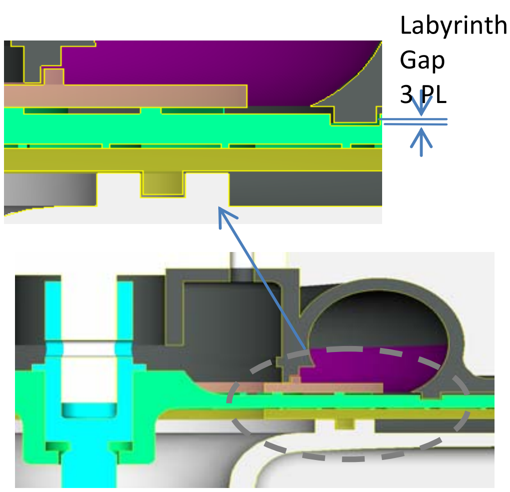

Figure 5. Location of labyrinth seals.

D. Manufacturing

For testing purposes the Fan Volute and Separator Housing models were developed and built, using Stereolithography (SLA). The sealing surfaces were machined as needed. The impeller and shrouds were machined from titanium, the shrouds were bonded in place. As mentioned above labyrinth seal performance depends greatly on the space of the gap between the shroud and housing. Due to difficulty in controlling tight tolerance in the nonmetallic SLA sealing surfaees and difficulty controlling the Labyrinth Seal geometry testing was not completed at the writing of this paper.

The original impellar design was to braze the shrouds in place. Materials Engineering determined that the 100% relative humidity urine/air mixture, with a pH as low as 2, would corrode the braze material. At that point the bonding solution was chosen. The team learned that this solution presented unique challenges, including difficulty in controlling sealing surface tolerance. Different techniques will be explored as the design moves toward a flight design. The review may include welding, diffusion bonding and mechanical connectors.

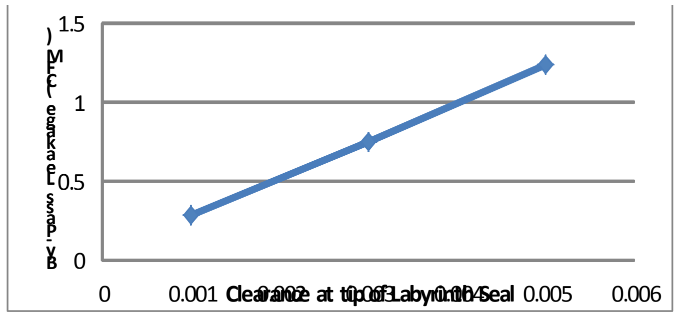

Figure 6. Inner commode seal leakage as a function of gap <will fix graphic>

III. Conclusion

The Dual Fan Separator design effort discussed in this paper brought considerable fidelity to the design, including an understanding of how Labyrinth Seals works and an ability to analyze their performance and determine their geometric dimensions. Another needed advance was understanding the elements that determine the dynamic stability of a complex rotating body, and how this altered the design to be more stable and predictable, such as removing the flexible couple. One of the goals of this activity was to prove the labyrith seal performance. Due to difficulty in maintaining the tolerance control that is necessary to achieve the desired sealing, this did not occur. The forward work, that is currently underway is to rebuild the Impellar Assembly with the intent of achieveing the needed dimensional control.

References

[1]Broyan, J. L., "Waste Collector System Technology Comparisions for Constellation Applications," 2007-01-3227, 37^{th} International Conference of Environmental Systems, Chicago, IL.

[2]Stapleton, T. J., Baccus, S., Broyan, J. L., "Universal Waste Management System Development Review," , xxxxxx, 43^{rd} International Conference on Environmental Systems, Vail, CO.

[3]Winkler, H. E., Cerna, N. F., Rotter, H. A., Ouellette, F. A., Hoy, D. M., Brasseaux, H. J. "Shuttle Orbiter Environmental control and Life Support System-Flight Experience," 961334, 26^{th} International Conference on Environmental Systems, Monterey, CA.

[4]Rethke, D. W., Steele, J. W. "Collection and Containment of Solid Human Waste for Space Station," 901393, 20^{th} Intersociety Conference on Environmental Systems, Williamsburg, VA, 1990.

[5]Goldblatt, L., Neuman, M., Chhipwadia, K. S., Brasseaux, H. J., "International Space Station Waste Collector Subsystem Risk Mitigation Experiment Design Improvements," 02ICES-166, 32^{nd} International Conference on Environmental Systems, San Antonio, TX, 2002.

[6]Broyan, J. L., Cibuzar, B. R., "Development of an In-line Urine Monitoring System for the International Space Station," 09ICES-0298, 38^{th} International Conference of Environmental Systems, Chicago, IL.

[7]Holder, D. W., Hutchens, C. F., "Development Status of the International Space Station Urine Processor," 2003-01-2690, 33^{rd} International Conference on Environmental Systems, Vancover, BC.

8 Wikipedia The Free Encyclopedia, "Crtical Speed" http://en.wikipedia.org/wiki/Critical_speed

9 add labyrinth seal reference