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Kanapathipillai Wignarajah and Eric Litwiller
Enterprise Advisory Services Inc., NASA-Ames Research Center

John W. Fisher
NASA-Ames Research Center

John Hogan
National Space Grant Foundation, NASA-Ames Research Center

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ABSTRACT

Handling and processing human feces in space habitats is a major concern and needs to be addressed for the Crew Exploration Vehicle (CEV) as well as for future exploration activities. In order to ensure crew health and safety, feces should either be isolated in a dried form to prevent microbial activity, or be processed to yield a non-biohazardous product using a reliable technology. During laboratory testing of new feces processing technologies, use of “real” feces can impede progress due to practical issues such as safety and handling thereby limiting experimental investigations. The availability of a non-hazardous simulant or analogue of feces can overcome this limitation. Use of a simulant can speed up research and ensure a safe laboratory environment. At Ames Research Center, we have undertaken the task of developing human fecal simulants. In field investigations, human feces show wide variations in their chemical/physical composition. However, under controlled experimental conditions using healthy adults (e.g. astronauts) fed a standard diet, the variations are likely to be minimal and within statistically acceptable levels. We have prepared a number of simulants using organic chemicals, soy paste (“Miso”) and other materials - particularly those capable of representing the water-holding capacity (WHC) of feces. The chemical composition of this simulant was a better approximation to human feces than previously used analogues. Rheological studies of the simulant are planned to ensure that it simulates fecal material. The emphasis on rheology and WHC is based on the assumption that in space habitats feces will be compacted to reduce volume and/or the water will be removed to safen the fecal waste.

INTRODUCTION

Human feces collection, storage and processing present major problems and hazards even in terrestrial systems. These issues are exacerbated in closed systems (e.g. International Space Station and shuttle) and in microgravity. At Ames Research Center, efforts are underway to develop an improved fecal collection system (also called the Waste Collection System – WCS. The best features of systems ranging from the crude Apollo baggie system to the Russian and American systems for ISS will be selected and optimized for CEV and other future missions. We have also been addressing the need for developing technologies to process feces. A major obstacle to a rapid method for developing the technologies is the inability to perform sufficient numbers of experiments in the absence of an analogue or simulant feces.

Literature review revealed only limited citations of human feces simulant preparation. Efforts under NASA funding have either used monkey or dog feces or chicken litter. Chicken litter, dog or monkey feces are markedly different from human feces with respect to both chemical and physical properties. Chemical and physical properties of human feces are well documented and characterized in medical literature. Often the focus of research using feces is on diagnostics of medical conditions and/or pathological conditions of humans. In some cases, the focus has been on transmission and prevention of diseases amongst humans through intentional/unintentional handling of feces. Safening to reduce or eliminate the hazards of feces can be achieved by sterilization and/or removal of water. On Earth, storage of feces in living compartments is not practiced, but storage is necessitated in space habitats. Storage of human wastes close to humans in a closed system presents potential health hazards from microbes in the feces and from other human pathogens that may thrive on feces during storage. Human feces also release unpleasant odors that though not necessarily known to be hazardous, decrease the quality of life.

WATER CONTENT OF FECES.

Typically feces contains between 65-85% water and 15-35% solids. The variation in the water content is dependent on the speed of passage of the food through the intestine. The longer the residence times of food in the human gut, the greater the water reabsorption and consequently the feces has a lower content. Table 1 has been compiled from literature. Weight of feces per person is dependent on the diet of the individual. Major chemical fractions of feces are provided in Figure 2.

Table 1: Typical variations wet weight, dry weight and moisture content of human feces (Ref. 1)

	Low value	High value
Wet weight of feces of adult fed mixed diet	110 g	170 g
Dry weight of feces of adult fed mixed diet	25 g	45 g
Wet weight of feces of adult fed vegetarian diet	N/A	350 g
Dry Weight of feces of adult fed vegetarian diet	N/A	75 g

Table 2 – Major components of human feces based on chemical composition (Ref. 1)

Fat Content	5-25%
Carbohydrate (Fiber)	10-30%
Nitrogenous material	Less than 2-3%
Minerals (mainly K, Ca & P)	5-8%
Bacterial Debris	10-30%

Most medical texts report that that bacterial debris content is usually around 10-30%. However, Stephen and Cummings (Ref. 2) using a fractionation method reported that the bacterial mass maybe as high as 50%.

Based on data from Cardon (3), we established that the empirical formula for dry feces (Ref. 4) was:

$C_1 H_{(1.87)} O_{(1.11)} N_{0.2}$

The major variables between feces of humans on a vegetarian diet and those on a mixed diet are the level of fiber and the nitrogen content.

HISTORY OF FECES USAGE AND FECES SIMULANTS

Three major limitations prevent efforts at undertaking laboratory experiments with human feces.

(a) The risks presented to researchers in using human feces that in turn require that researchers complete specialized safety training,

(b) Stringent restrictions on use of human subjects for testing imposed by NASA and the Center for Disease Control (CDC)

(c) Specially designed laboratories equipped and fitted with involving biohazardous facilities in compliance with CDC and OSHA requirements.

HISTORY OF FECES PROCESSING

Efforts at technologies for processing feces have involved the use of monkey feces, chicken litter, dog feces and in rare cases human feces. Some of the limitations of using other animal feces to represent human feces are discussed.

Chicken litter is made up of bedding straw and chicken feces, has high nitrogen content, lower water content (below 40%) and a much higher mineral content than human feces. In addition, the microbial content of chicken litter is low. In this study, the waste considered for pyrolysis was designed for a mixed waste in a fully regenerative life support system. In short duration missions such as in CEV, feces and food wastes are likely to be the major biological components of all solid wastes. There is unlikely to be wastes from crop harvesting, such as straw etc. Thus, the use of chicken litter as being representative of human feces during compaction and/or drying experiments would be a poor choice for our studies at ARC.

In efforts to study biological composting of wastes, dog feces as well as dog food were used in studies at Florida. Medical literature shows major differences in urinary metabolic pathways that would result in differences in chemical composition of feces of dogs and humans. For example, sulfoxidation is a major urinary metabolic pathway in dogs while it is not a significant pathway in humans (5).

Researchers at Umpqua have used refried beans as an analogue for feces. Proximate analysis shows refried beans are very high in protein content. Feces from healthy humans have a very low protein content. Typical analysis of refried beans shows protein content from 25-45% and non-nitrogenous materials of 50-75%, while the protein content in feces is typically below 10 -15%. Thus, even though visually refried beans may appear similar to feces, processing technologies such as mineralization or dewatering using refried beans is not likely to produce results that may reflect how human feces will behave. In future studies, we will attempt to compare dewatering rates in refried beans and human feces.

Other reported efforts include the use of materials such as mashed potatoes, brownie mix, peanut butter and pumpkin pie filling. The reasoning of using these as simulants are not clear, but it does not appear that any of these considered the chemical, physical and water-holding capacity of human feces.

SYNTHETIC FECES

Efforts to produce fecal simulants have been made through NASA-funding and at other organizations such as Kimberley-Clark and other diaper/incontinence garment producing industries. The NASA-funded effort was designed to be chemically representative of human feces. The need for a true fecal simulant is critical for NASA's activities particularly in the interest of enabling the development of technologies to contain and process feces. A commercially available feces simulant based on cellulose was patented as FECLONE™ by Siliclone Inc, PA. Efforts to locate this company have not been fruitful.

Table 3: Fecal simulant developed by Kaba et al. (Ref.6)

Component	Weight (Kg)	% of Total Dry weight
Cellulose	0.60	33
Torpulina	0.43	25
E.coli	0.12	7
Casein	0.17	10
Oleic acid	0.37	20
KCl	0.04	2
NaCl	0.04	2
CaCl2	0.03	1
Total	1.8	100%

Kaba et al (6) reported a fecal simulant developed based on the assumption feces was made up of one third microorganisms and intestinal flora, one third undigested fiber and the balance being lipids and inorganic materials (Table 5).

Experimental evaluation of water content confirmed 61% water content in the simulant. This was later modified as shown (see Table 4). This new formulation replaced the bacterial composition by yeast and replaced the oleic acid by peanut oil. This is considered justifiable since the main fatty acid in peanut oil is oleic acid ranging from 50-80%.

Table 4: Modification of Table 1 to simplify the fecal simulant (Ref. 7)

	Weight (g)	% of Total Dry weight
Cellulose	380	37.5
Yeast	380	37.5
Peanut oil	200	20
KCl	40	4
Ca(H2PO4)2	10	1
Water for 60%	1500	

Welchel (Ref. 8) patented a synthetic fluid composition made of 15% polyvinylpyrrolidine, 5% psyliium mucilloid and 80% water. By varying the weight percent of soluble to insoluble components, the molecular weight of the soluble component, PVP, and the water content, the viscosities (consistency) of the simulant could be varied from a runny bowel to a normal or constipated situation (see Table 5). This synthetic feces can be adjusted to have a viscosity of between 1,000 to a 40,000 centipoise at 50 revolutions per minute. The dewatering rate can range from 50 to 400 grams per square meter per minute. The dewatering rate is a measure of the ease with which water is released from the compound of interest onto a standard adsorbent. Details of the method used are described in Welchel's US Patent 5356626. Drying rates of the dewatering rates can be predicted from knowledge of the matric potential of water. The dewatering rate reported by Welchel can be used to predict the likely bonding of water to feces. Future studies are planned to obtain details of the strength of bonding of water to feces.

Table 5: Viscosities and Dewatering rates in Human Feces compared with some simple simulants (Ref. 8)

	Viscosity (cps) at 50 rpm	Dewatering rate (in grams per m^2 per min)
Runny feces	3500-5500	Very high
Regular feces	3500-5500	350-400
Pumpkin-pie filling	4040	912
Mashed Potato – 11% solids	1100	650
Peanut butter	20,000	180

Welchel reported that this simulant represented natural feces in dewatering rate and consistency. A shortfall of this fecal simulant is the inability to monitor microbial activity after the processing. The fecal simulant was synthesized using polyvinylpyrrolidene resulting in a much higher nitrogen levels than is typically found in feces. Typically, most of the nitrogenous compounds in feces are released as gaseous ammonia and pyrrole and benzopyrrole (indole and skatole) compounds. In our studies we opted to use the non-nitrogen containing polyethylene glycol instead of polyvinylpyrrolidene to represent the water-holding capacity of feces.

Rheology and water holding capacity of human feces

Rheology is the study of deformation and flow of matter (see Table 1). In food science, it is used to define the consistency of different products. Consistency is described by two components - viscosity ("thickness", lack of slipperiness) and elasticity ("stickiness", structure). Consistency also has a chemical perspective, especially with regard to structures promoting hydrophobicity, hydrophilicity, the presence of hydrogen bonds etc. Thus any analogue or simulant of feces should represent the rheological properties of feces. For CEV and short duration missions, focus in feces processing technologies involve compaction of the waste for volume reduction and/or removal of the water to prevent microbial growth and activity during short duration missions. During long duration missions, combustion and sterilization technologies involving the application of heat may be considered. Therefore, it is important that the chemical composition of the simulant be chemically representative of feces.

Rheological Models

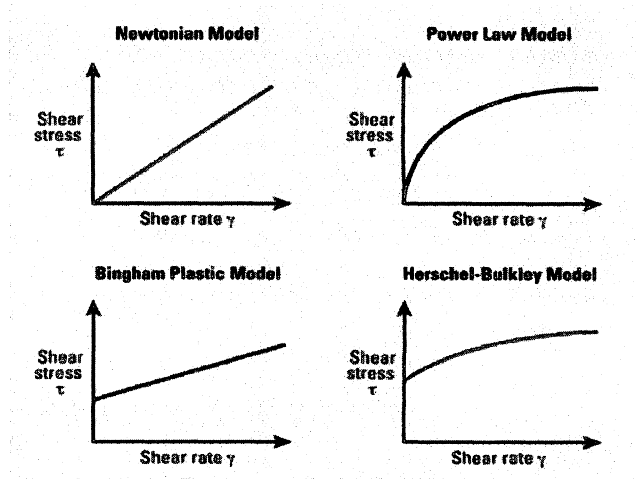


Figure 1- Generalized rheological models of solids and semi-solids

$$\tau = K(\gamma)^n,$$

Where τ = shear stress
γ = shear rate
n = exponent
K = consistency.

Figure 2: Mathematical function showing the Power Law model.

At solid contents lower than 5%, manure is known to behave as a Newtonian fluid (Ref 9) but typical human feces has between 10-20% solids and is predicted non-Newtonian behavior. In fact, it obeys the power law as indicated in the equation above. We plan to test our fecal simulants to ensure that it has the same consistency as reported in literature.

EFFORTS AT AMES RESEARCH CENTER

By critically evaluating previously used formulations and the composition, both physical and chemical, we prepared a number of candidate simulants. The starting chemicals in the synthesis were:

Cellulose $C_nH_{2n-2}O_n$

Polyethylene glycol $H(OCH_2CH_2)_n OH$

Peanut oil CH - COOH

Psyllium powder - Dietary fiber – $C_nH_{2n-2}O_n$

Miso (Soya powder product) -38% proteins; 21% Fats; 20% fiber; 4% minerals

The only biological organisms used were *E.coli* from ATCC collections.

FORMULATION OF SYNTHETIC FECES

We attempted five (5) combinations of synthetic feces as shown in table 6. The goals were to mimic the true water-retention properties of feces and to best fit the chemical composition reported in literature. It is possible that one simulant may be best to study dewatering technology while another may be more representative for studying pyrolytic destruction of feces.

Table 6: Different combinations of synthetic chemicals to represent human feces simulants.

Component	%Wt-Comb.1	%Wt-Comb.2	%Wt-Comb.3	%Wt-Comb.4	%Wt-Comb.5
E.coli	30	30	30	30	30
Cellulose	0	15	15	0	10
Polyethylene glycol	20	20	20	10	5
Psyllium	20	5	0	5	0
Peanut Oil	20	20	20	20	20
Miso	5	5	10	30	30
Inorganics	5	5	5	5	5
Dried Coarsely ground vegetable matter	50 mg	50 mg	50 mg	50 mg	50 mg

Photographic mages of the various synthetic fecal formulations are provided in Figures 3-7 (please see final page of paper). Coloration of fecal simulant was significantly affected mainly by the Psyllium content and to a lesser degree by Miso. For example, in combinations 2 and 3 that had reduced Psyllium the feces was lighter in color. With the addition of Miso at the highest levels in combinations 4 and 5, the brownish color associated with feces was restored. Combination 5 is lighter colored than 5, and this is attributed to the lack of Psyllium.

POROSITY MEASUREMENTS

Porosity measurements are an excellent method to determine air entrapment that in turn can play a role in determining feces processing technology. Interestingly, processed feces when applied to soil was reported to improve porosity through its gluey nature. We plan to undertake porosity measurements of the simulants using the density volumetric method and the Micromeritics Accelerated Surface Area and Porosimeter(ASAP-2010). Assumptions will be made of the specfic gravity of feces from data available in medical literature.

The Micromeritics ASAP instrument provides a second source for measuring the pore dimensions of these simulants. This instrument is designed to measure pore sizes up to 200 nm. Information obtained from these studies will enable us to decide on technologies for feces processing.

FUTURE EFFORTS – OLFACTION AND ODOUR CONTROL

Olfaction is a chemically based sense (10). Even though there are various reports of odor problems reported as musty, moldy to even one of burnt coffee, only very slight smells have been reported on ISS. There are surprisingly no particular reports on odors from storage of feces – whether there really is no smell emanating from stored feces or whether it is due to the civility and sensitivity of astronauts not wanting to report it is debatable.

Moore et al reported that the compounds associated with fecal odor were hydrogen sulfides, the methyl sulfides and benzopyrrole derivatives(11). Complete analysis of the composition of chemicals off-gassing from feces and showed that the sulfur-containing components were only 2.2% of the total gaseous fraction, while the nitrogenous benzopyrrole compounds were only about 0.3%. Ammonia occurred at 6.3% (12,13).

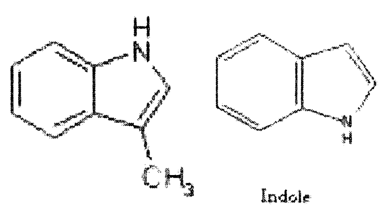


Figure 8 – Nitrogenous Benzopyrrole Compounds – Indole and Skatole

The first phase of testing of the compactor and drying technology will be undertaken using fecal simulants without the malodorous compounds. This will be followed in the second phase by adding the malodorous compounds in the fecal simulants. Once it is established that the technologies of drying and/or compaction perform satisfactorily without hardware malfunction and/or operator function failure, final testing can be completed with limited experiments on "real" human feces.

CONCLUSION

We have developed five (5) separate human feces formulation that are chemically and physically analogous to human feces. The formulations are designed to be representative of water-holding capacity, chemical composition, and consistency of human feces. Additional work is in progress to make quantitative characterization of the physical and chemical characteristics of the simulant with known information about human feces. This effort is an important step in future laboratory work related to methods of feces processing for space habitats.

REFERENCES

1. Ganong W.F. (1983) Review of Medical Physiology 11th Edition. Lange Medical Publication, CA, USA. (1983)

2. Stephen AM and Cummings JH. The Microbial Contribution to Human Fecal Biomass. J. Med. Microbiol. 13(1):45-56. (1980)

3. Cardon JL. and Browner R (1982) Preparation and Analysis of Standardized Waste Samples for Controlled Ecological Life Support Systems(CELSS). NASA-CR#166392, Ames Research Center, CA.

4. Pisharody S, Wignarajah K and Fisher JW. Oxygen Penalty for Waste Oxidation in An Advanced Life Support System. Tech. Paper # 2002-01-2396, 32nd ICES Conference, San Antonio, TX (2002)

5. Wong FA, Lloyd JR and Graden DW. The Metabolism of Etintidine in Rat, Dog and Human. Drug. Metab.Dispos. 18(6):949-953 (1990).

6. Kaba L, Hitchens GD and Bockris JO'M. (1989) Electrochemical Incineration of Wastes. Tech. Paper # 891510.

7. Fisher JW, Pisharody S, Wignarajah K, Lighty JS, Burton B, Edeen M-B and Davis KA. Waste Incineration for Resource Recovery in Bioregenerative Life Support Systems. Tech. Paper # 981758, 28th ICES Conference, Denver, CO (1998)

8. Welchel DN (1994) United States Patent 5356626, October 18, 1994

9. Kumar M, Bartlett HD and Mohsenin NN (1972) Flow Properties of Animal Waste Slurries. Transactions of the American Society of Agricultural Engineers

10. Green S (1994). Principles of Biopsychology, Psychology Press, ISBN-086377-282-1

11. Moore JG, Jessop LD, and Osborne DN (1987) Gas-chromatographic and mass spectrometric analysis of the odor of human feces. Gastroenterology 93:1321-1329.

12. Sato H, Morimatsu H, Kimura T, Moriyama Y, Yamashita T and Nakashima Y (2001) Analysis of Malodorous Volatile Substances of Human Feces. J. Health Science 48(2) 179-185

13. Sato H, Hirose T, Kimura T, Moriyama Y and Nakashima Y (2001) Analysis of Malodorous Volatile Substances of Human Wastes: Feces and Urine. J. Health Science 47(5) 483-490

CONTACT

Kanapathipillai Wignarajah, PhD, Senior Scientist, EASI, NASA-Ames Research Center, MS239-8, Moffett Field, CA 94035-1000.

E-mail: wwignarajah@mail.arc.nasa.gov

Phone: 1-650-604-5201; Fax: 1-650-604-1092

ADDITIONAL SOURCES

Here are any additional sources. This is an optional section.

DEFINITIONS, ACRONYMS, ABBREVIATIONS

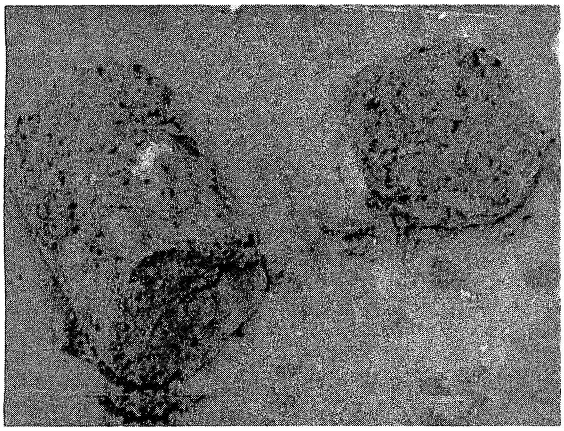
CEV – Crew Exploration Vehicle

ISS – International Space Station

WHC - Water holding capacity

Figures 3-7 : Morphological Appearance of Formulated Synthetic Feces.

Combination 1



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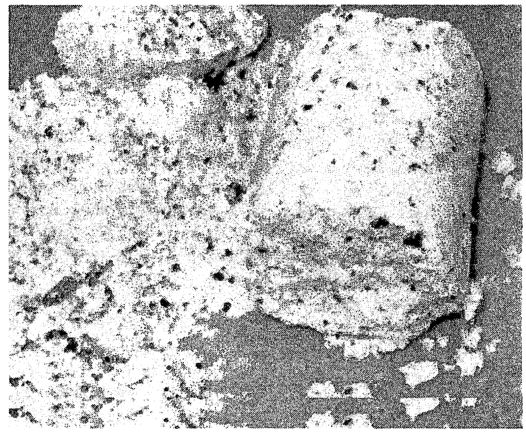

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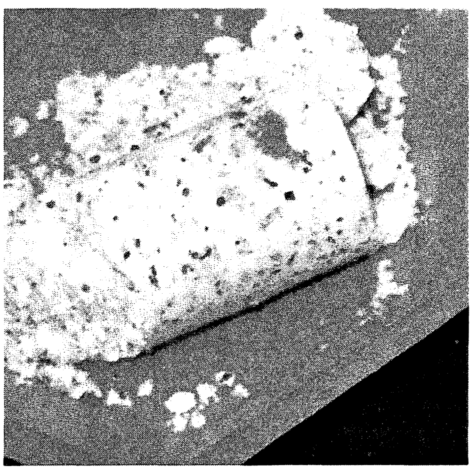

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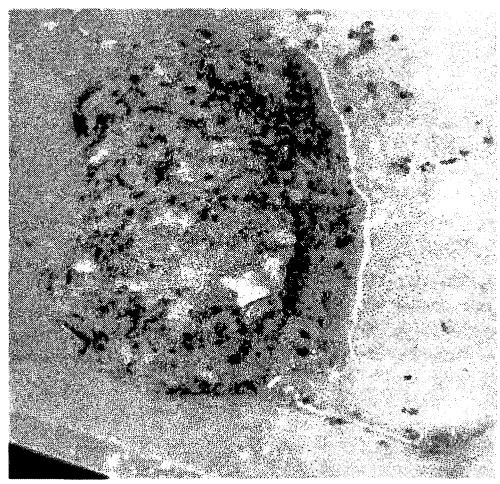

Combination 5